Research Topics

New ideas in performance science

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New ideas in performance science

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Editorial: New ideas in Performance Science

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Editorial on the Research Topic
New ideas in Performance Science

1 Introduction

This Research Topic was launched to serve as a compendium of forward-looking contributions from basic and applied research, outlining recent developments, novel ideas, and directions within the fast-growing field of Performance Science. This interdisciplinary research field encompasses topics and approaches from diverse domains, and provides insights into fundamental skills, psychological and physiological mechanisms, and outcomes of performance activities and experiences (e.g., Cotterill, 2017; Mugford and Cremades, 2018; Murphy, 2012). Scientific advances in Performance Science foster performance by enabling the development of innovative interventions tailored toward aspects of education, training, health, and wellbeing across domains of human performance (e.g., Bégel et al., 2024; Sevdalis and Wöllner, 2016; Williamon, 2004).

The 17 contributions comprise: Thirteen Original Research articles, two Opinion articles, one Hypothesis and Theory article, and one Review article. Collectively, these articles showcase the breadth and depth of Performance Science, by providing insights into human performance across a broad spectrum of activities and contexts. The intersection of scientific disciplines (e.g., psychology, cognitive science, human movement science, musicology, anthropology, medicine), performance domains (e.g., sport, music, dance, education), and scientific methodologies (e.g., neurophysiological, psychophysical, behavioral) pursues evidence-based knowledge with relevance for scientists and practitioners alike. The disparate nature of these component disciplines and the widespread applications in contexts far beyond academia make Performance Science a radically interdisciplinary area of human knowledge (e.g., Collins et al., 2011; Danielsen et al., 2023; Tod and Eubank, 2020).

2 Overview of articles

The featured contributions can be classified into four thematic areas (Figure 1)[1]: Performance foundation (i.e., individual differences and skills); Performance preparation (i.e., teaching and learning); Performance execution (i.e., delivery and interaction with co-performers and audiences); and Performance context (i.e., historical, societal, and cultural contexts within which performance is embedded). We will now introduce these one by one.

2.1 Performance foundation

Individuals come to performance situations equipped with their own backgrounds and skills. Contributions in this category focus on timing behavior in rhythmic tasks, acoustics of vocal performance styles, and the neuroscience of academic performance.

By comparing beat alignment abilities of active musicians to those of inactive musicians and non-musicians, Spiech et al. find that active musicians possess significantly stronger beat alignment abilities, with years of formal musical training as the only significant predictor of beat perception.

In a systematic review on Spontaneous Motor Tempo (SMT) in healthy adults, Desbernats et al. highlight that the reference means for SMT are far from universal; rather, a range of SMT values exists, and many factors modulate them. The authors discuss these modulators according to a classification as intrinsic factors pertaining to personal characteristics (e.g., pathology, age, effector, expertise) and extrinsic factors pertaining to environmental characteristics (e.g., physical training, external constraints, observation training, type of task).

Kim investigates the dynamics of intentional sensorimotor desynchronization by asking participants to tap increasingly ahead of a metronome cue. An adaptive-frequency oscillator model captures tapping performance, revealing that desynchronization is governed by the non-linear dynamics of rhythmic coordination.

Bruder and Larrouy-Maestri examine highly trained female classical singers' ability to adjust their vocal production to various styles including their own formal training area (as an opera aria, pop song, or lullaby). Distinct acoustic profiles emerge, implying that singers can indeed produce contrasting performances. In a subsequent perceptual experiment, lay listeners' high accuracy in recognizing the performed singing style confirms singers' proficiency in performing in operatic style, and their versatility when delivering lullaby and pop performances. This performance competence is, however, not linked to singers' formal training levels.

Xu et al. record electroencephalogram (EEG) during resting state, working memory, and general intelligence tasks, in college students with different levels of academic performance. Their results reveal a reduction in alpha-band activity (8–9 Hz) connecting the frontal and occipital lobes in low-performing students, compared with high- and average-performing students, in the general intelligence task. Possible explanations include fatigue, anxiety, and cognitive effort.

2.2 Performance preparation

Performance skills are mainly acquired through training. Several articles aim at enhancing our understanding of the mechanisms sustaining efficient teaching, and the importance of learning and practice for optimized skill acquisition.

Combining perspectives from ecological psychology and embodied cognitive science, Miura and Seki demonstrate how physical touch has beneficial effects on motor skills learning in

1 Figure 1 uses visual materials from vectorportal.com (boot, CC-BY 4.0) and rawpixel.com (ball, CC0 1.0) that have been modified for the present use.

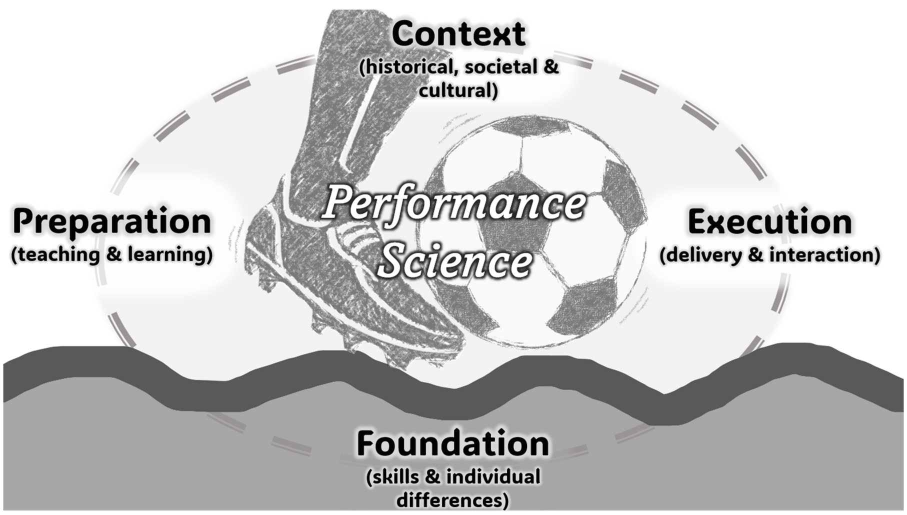

FIGURE 1
A conceptual framework of Performance Science, indicating four interconnected thematic areas. Taking soccer as an example in the performance domain of sport, for the actual performance execution, performance can be prepared under a learning regime. This occurs within a societal, cultural, and historical context, based on a foundation of an individual skillset.

classical ballet. Specifically, touch becomes an effective way of embodying teachers' verbal instructions.

Tuyà Viñas et al. investigate the effects of decision-making on movement variability and passing accuracy in high-level female soccer players, during an elastic band resistance task. Adding decision-making to a forward-backward movement task with ball and elastic resistance increases the movement variability of defenders, but not of attackers. Attackers' passing accuracy, on the other hand, is reduced. Deliberate consideration of decision-making constraints may thus enhance soccer training.

In a study on expert percussionists' choices between left- and right-hand sticks for sight-reading of timpani parts, Bacon et al. demonstrate a prominence of two overall strategies ("dominant-hand lead" and "alternating") when rhythms are stable, and notation is as expected. However, as excerpts become more musically and/or visually challenging, sticking choices amongst percussionists tend to diversify.

Moen et al. present a study utilizing Bio-Electro-Magnetic-Energy-Regulation (BEMER) therapy to enhance recovery in elite female soccer players on game nights characterized by taxing peaks in physical load. Continuous sleep monitors reveal substantial disturbance in sleep following game nights, which may be alleviated by persistent use of BEMER therapy.

2.3 Performance execution

A number of contributions focus on aspects of actual performance delivery. These involve interactions between co-performers and between performers and audiences, with an emphasis on flow and bodily expression.

Zielke et al. investigate the precise musical features that induce or disrupt flow in music performance. They find that the proportion of performance time spent in flow significantly correlates with self-reported flow intensity. This provides a novel intrinsic measure of flow. The authors further analyze music scores and performed melodies, finding that stepwise motion, repeated sequence, and a lack of disjunct motion are common to flow-state entry points, whereas disjunct motion and syncopation are common to flow-state exit points.

Gibbs et al. assess inter-subject correlations in heart rate variability and skin conductance, measured in novice and expert players of Central-Javanese gamelan music. Whereas, expert players exhibit greater physiological synchrony when playing traditional pieces over (stylistically unfamiliar) improvised playing, novice players show the opposite pattern. Furthermore, in traditional playing, these physiological measures relate negatively to a self-report measure of shared flow, whereas the association is positive for improvised playing.

Vukadinović advocates a deeper appreciation of performative aspects of hair and hairstyle as a means of expression in dance. As such, hair can be suppressed (as in the "aesthetics of order" found in the classical ballet bun); used decoratively (as in the ponytails of Broadway and Ballroom dancers); used metaphorically, to express, for example, strength, sensuality, and freedom (as in the long, loose hair of contemporary flamenco dancers); or used instrumentally, to enhance the spectator's perception of liveliness, vibrancy, and stillness.

D'Amario et al. examine the effects of perceived voice-matching with a co-performing singing partner and the complexity of the singing task (unison and canon) on body motion. The authors collect upper-body movement of advanced choristers singing duos along with a recording. Results show that the settings perceived as least together relate to extreme differences between the spectral components of the sound. In addition, compared to canon, singing in unison promotes more periodic movements, more open upper-body posture, and more distance from the music stand.

2.4 Performance context

How performance is defined, how it is achieved, and how it is assessed strongly depend on the context in which it manifests. Several studies focus on the historical, societal, and cultural environments that underpin performances.

Hadar and Rabinowitch tackle the social dynamics characterizing different musical genres. They select four genres occupying an extensive continuum of music performance and transmission styles, from strictly orally transmitted and/or notated to fully improvised music. Their new framework examines the social meanings of musical performance styles in terms of structural sparseness, flexible social roles, cultural non-conformity, and creative freedom.

Upham et al. investigate fans' Twitter engagement during live-streamed concerts of the K-pop group BTS, analyzing the content patterns in 1,200 tweets. Postings during these performances appear to be principally directed toward fellow fans and audience members. Individuals choose to share their excitement and check in with other concert attendees, to construct a collective and interactive concert space and create a richer experience.

Based on Ecological Systems Theory, Thuany et al. conceptualize the factors contributing to runners' performance. Their holistic approach allows the identification of environmental determinants which otherwise have been limited to individual characteristics (e.g., in physiology, genetics, and biomechanics).

Finally, Lee et al. compare research interests and trends in soccer-related journal articles published before vs. during the COVID-19 pandemic. A new focus on developing fast-paced, highly efficient training sessions emerged as a response to imposed constraints, along with a switch in focus from head injuries to lower-limb injuries and new concerns about the economic impact of the COVID-19 pandemic.

3 Concluding remarks

The present Research Topic illustrates the diversity and creativity of research approaches within the advancing field of Performance Science. The interconnected thematic areas of foundation, preparation, execution, and context depicted in Figure 1 can serve as a conceptual framework for research within different performance domains, be it music, dance, sport, or education. Individual differences and skills, teaching and learning, implementation and interaction dynamics, and contextual characteristics can all be considered essential components in the conceptual architecture of performance. This applies to novices as well as to expert performers. Furthermore, the fact that performance domains are directly related to everyday contexts and experience naturally imbues Performance Science research with high degrees of ecological validity, and applicability in wider contexts and across individuals.

To investigate such complexity, future research will benefit from transdisciplinary dialogue across scientific domains and thematic areas. The current Research Topic represents merely a glance into the possible future of Performance Science (cf. Filho and Basevitch, 2021). This glance is far from exhaustive; for example, research on performance in the healthcare sector, the workplace or sport coaching was not fully represented. Yet, we envision that theoretical frameworks, methodologies, and findings from the Performance Science domains covered in this Research Topic may also prove useful within these knowledge areas (cf. Aoyagi et al., 2012; Sandars et al., 2022; Schiavio et al., 2019). Finally, although the contributions to this Research Topic focus mostly on achieving specific goals and performance outcomes (e.g., delivering a concert, executing movement sequences, or rehearsing routines), performance scientists should not neglect the health and wellbeing of performing individuals, which may indeed be compromised in multiple ways during pursuits of human performance (cf. WHO, 2024; Williamon and Antonini Philippe, 2020).

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Dynamic touch for embodying teacher's verbal instruction: Implications from classical ballet

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1. Introduction

Teaching a motor skill in physical education involves the teacher's visual and verbal demonstration (Ryan et al., 2016). This often accompanies physical contact from the teacher to the learner (Choi and Kim, 2015). For example, imagine a classical ballet lesson where the teacher teaches the beginner learner how to stand correctly. First, the teacher stands correctly and verbally explains how to position the body. Next, the teacher touches the learner's body and corrects their alignment and form. When teaching other techniques, some teachers push the body part of the moving learner and change their movement trajectory. Thus, for teaching motor skills, touch often occurs from the teacher to the learner, and its primary role can be described as a mechanical effect on the learner's body.

In this article, however, we contend that touch has cognitive significance for learners, that is, the embodiment of the teacher's words from the perspective of cognitive and movement sciences. Among many physical contacts, we will focus specifically on learner-to-teacher touch, for example, when the learner pushes the teacher's arm to ascertain the stiffness of the joints. We discuss that without it, the problem of the symbol merry-go-round is likely to occur.

2. Symbol merry-go-round in ballet lessons

Learners (especially beginner learners) often encounter several problems in ballet lessons. Learners must learn how to subtly control muscle tension and engagement levels; however, for several reasons, it is difficult to estimate the state of muscle activity by watching the teacher's kinematics (e.g., the trajectory of movement, velocity, and acceleration). First, the adjustments in the level of muscle activity do not always accompany kinematic changes. For example, when adjusting poses or techniques for expressive nuances (e.g., lightness vs. strength), the kinematics do not change much, but muscle tension and engagement levels do. Second, the skill requirement of ballet is high. Warren and Cook (1989, p. 30) state, "The hand must appear relaxed at all times." Note that they do not say that the hands must always be relaxed, instead, it must always "appear" to be so. This requirement implies that the better the teacher's movements are during the ballet, the more confused the learner will be about the muscle tension and engagement levels.

Moreover, as the level of muscle tension and engagement is difficult to convey through kinematics, the teacher is compelled to describe it verbally. This is when the problem of the symbol merry-go-round (Harnad, 1990) is likely to arise. This problem has been pointed out in embodied cognitive science, which regards human cognition as being formatted in sensorimotor experience (and the neural systems used for it) rather than independent of the body and behavior (Glenberg, 2015; Fincher-Kiefer, 2019). Harnad (1990) and Glenberg (2015) illustrate this problem with the example of learning Chinese from a Chinese/Chinese dictionary. Imagine that someone who does not speak Chinese lands at an airport in China and would like to know the meaning of a Chinese word on a signboard. They look up the meaning in their Chinese/Chinese dictionary; however, the word is rephrased in other Chinese words, and they have to search further for its meaning in the dictionary. However, repeating this makes no sense to them, as the symbols are simply rephrased. This means that symbols divorced from something outside the symbol system (e.g., sensorimotor experience) do not provide meaning.

Consider a specific example where you will understand the word "love" only using an English/English dictionary. In the dictionary (Merriam-Webster, n.d.), love is defined as "strong affection for another arising out of kinship or personal ties". Then, you search "affection" and find that it is defined as "a feeling of liking and caring for someone or something". No matter how often you repeat this process, it will not lead to an understanding of the meaning of love, unless some words in the dictionary are connected to your sensorimotor experience.

Fincher-Kiefer (2019, p. 84) points out the possibility that experts have a rich sensorimotor experience of their skills. Therefore, the language they use to express these skills are more embodied than in a novice. This suggests that the more experienced the ballet teachers are, the richer variations of embodied words they use in the lesson. Beginner ballet learners may receive many words from their teachers, but the words can easily cause a symbol merry-go-round because learners may have little bodily experience associated with them. Conversely, beginner learners may require relevant sensorimotor experiences to embody the teacher's verbal instruction.

3. Embodiment by touch

3.1. Language and bodily experience

We propose learner-to-teacher touching in a way that is called "dynamic (effortful) touch" in ecological psychology (Gibson, 1966; Turvey and Carello, 2011; Carello and Turvey, 2016) as a means of stepping off the symbol merry-go-round. Dynamic touch involves moving an object dynamically to determine its physical properties. For example, to ascertain the weight of something, we can toss it, receive it, or shake it in our hands to perceive the weight more accurately than by simply holding it (Gibson, 1966). Our proposal for learners is to dynamically and gently move the teacher's body to embody their instruction. The ballet teacher could, for example, demonstrate a defined arm posture and allow the learner to manipulate their forearm to explore muscle tension.

To provide a rationale for our proposal, we introduce the behavioral and neuroscientific evidence showing that language comprehension and bodily experience are related (for a systematic understanding, please see Fincher-Kiefer, 2019, chapter 5). For example, Glenberg and Kaschak (2002) reported that comprehending a sentence that describes an action in one direction (e.g., "close the drawer" means the direction away from the body) is facilitated by hand movement that is compatible with that action. This is known as the action–sentence compatibility effect (ACE)[1]. Studies on children have shown that physically manipulating objects related to the reading material enhances their reading comprehension (Glenberg et al., 2004, 2007). A neuroimaging study demonstrated that while one processes words referring to face, arm, and leg actions (to lick, kick, and pick), the brain regions that are active during actual actions of those body parts activate (Hauk et al., 2004).

Kontra et al. (2015) reported interesting evidence that bodily experience (i.e., the dynamic touch of an object) deepens the understanding of physics concepts. They tested whether the understanding of physics concepts (torque and angular momentum) is facilitated by bodily experience. In their experiment, participants either (1) held and moved a device made from bicycle wheels to experience torque and angular momentum or (2) observed someone doing it. They found that the participants who moved the device understood the physics concepts better (obtained a better score in the post-test) than those who observed it. In addition, the follow-up neuroimaging experiment revealed that the better score was explained by the activation of sensorimotor brain regions when they reasoned about angular momentum.

The aforementioned studies show that language is grounded in the body (i.e., embodied) and that actual touch facilitates the embodiment and deepens understanding of the subject. This suggests that it is essential for beginner ballet learners to touch the teacher dynamically to embody the teacher's words effectively.

1 There is controversy over the reliability of some versions of the Glenberg and Kaschak ACE, most notably Morey et al. (2022). Nonetheless, a recent meta-analysis (Winter et al., 2022) concludes that the effect is small but reliable.

3.2. Embodiment in ballet lesson

Let us explain what can be known by dynamic touch itself. As observed in many ballet skills, subtle control of muscle tension and engagement, while the kinematics do not change significantly, can be regarded (although not exclusively) as adjusting the level of muscle cocontraction. Cocontraction refers to a situation where the agonist and antagonist muscles are active simultaneously (Latash, 2018). The level of cocontraction corresponds to the level of joint stiffness, defined as a ratio of the force applied to a joint from outside to an angle at which it is flexed or extended. Increased cocontraction results in increased joint stiffness because the muscles firmly pull the bone from both sides of the joint.

It is difficult to determine the level of cocontraction from the kinematics because one can change the level of cocontraction without changing the kinematics. However, joint stiffness can be perceived by dynamically moving the joint from the outside, meaning that the level of cocontraction can also be perceived by dynamic touch.

As a practical example, the following approach may be helpful. Let us consider the case of embodying the teacher's verbal description of the muscle tension and engagement level of arms such as during poses. First, the teacher reproduces the level of muscle tension of the arm as good and bad examples. Then, the learners hold the forearm of the teacher with one hand firmly and try to push, pull, or sway it in various directions. Any touch should be forceful enough to move the joints of the person being touched. When swaying the arms, the learners should sway them rhythmically to the extent that they move at least a few centimeters. By doing this, the learners can learn about the appropriate cocontraction level around the teacher's elbow and shoulder joints. Comparing good and bad examples will help one to better understand the correct level. The teacher's verbal description corresponds with the learner's sensorimotor experience through dynamic touch, allowing the teacher's words to become embodied in the learner. The same approach can be applied to the legs during poses such as an arabesque or retire.

We do not recommend touching a moving body such as in turns because it can be dangerous. Experienced ballet teachers can reproduce the stiffness of the arms and legs in turns (e.g., pirouette and piqué turns) while standing still without actual rotation. We recommend that the learner touch them dynamically.

4. Discussion

Although this article covered a limited situation in ballet lessons, it has provided an essential perspective for beginner learners to step off the symbol merry-go-round and embody the teacher's words by dynamic touch. We consider this to be significant in two ways. First, while the positive effects of physical contact in dance pedagogy have been often discussed (Assandri, 2019; Hermans, 2021), the use of dynamic touch from learner to teacher has not been discussed. This may be partly because touching teachers is culturally and socially discouraged. However, learner-to-teacher touch has some substantial benefits for skill learning, as explained in this article. How dance educators can incorporate this into the field must be thoroughly discussed elsewhere.

Note that the learner-to-teacher dynamic touch is not the only solution for the symbol merry-go-round problem. The teacher-to-learner touch can also act on the learner's sensorimotor experience. However, dynamic touch is significant in enabling active and exploratory information acquisition. In ballet lessons, because teachers tend to give information unilaterally to the learner, active information acquisition is considered essential from a pedagogical perspective (Culp et al., 2020). Active learning in physical education needs further study, and this article provides insight into it.

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Beat alignment ability is associated with formal musical training not current music playing

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The ability to perceive the beat in music is crucial for both music listeners and players with expert musicians being notably skilled at noticing fine deviations in the beat. However, it is unclear whether this beat perception ability is enhanced in trained musicians who continue to practice relative to musicians who no longer play. Thus, we investigated this by comparing active musicians', inactive musicians', and nonmusicians' beat alignment ability scores on the Computerized Adaptive Beat Alignment Test (CA-BAT). 97 adults with diverse musical experience participated in the study, reporting their years of formal musical training, number of instruments played, hours of weekly music playing, and hours of weekly music listening, in addition to their demographic information. While initial tests between groups indicated active musicians outperformed inactive musicians and nonmusicians on the CA-BAT, a generalized linear regression analysis showed that there was no significant difference once differences in musical training had been accounted for. To ensure that our results were not impacted by multicollinearity between music-related variables, nonparametric and nonlinear machine learning regressions were employed and confirmed that years of formal musical training was the only significant predictor of beat alignment ability. These results suggest that expertly perceiving fine differences in the beat is not a use-dependent ability that degrades without regular maintenance through practice or musical engagement. Instead, better beat alignment appears to be associated with more musical training regardless of continued use.

KEYWORDS

beat perception, active musicians, inactive musicians, nonmusicians, machine learning, musical training, beat alignment

1. Introduction

1.1. Background

Practice is said to make perfect, but do you remain perfect if you stop practicing or do you lose it if you do not use it? Humans' ability to master a variety of skills has fascinated psychologists and neuroscientists for decades, culminating in a vast domain in and of itself (Ericsson and Charness, 1994; Sternberg and Grigorenko, 2003; Feltovich et al., 2006; Chi et al., 2014), spanning everything from sports (Shea and Paull, 2014) and dance (Calvo-Merino et al., 2005, 2006, 2010; Orgs et al., 2008, 2018) to beer and wine tasting (Tempere et al., 2019; Hinojosa-Aguayo et al., 2022). These impressive abilities are often described as the result of extensive practice and effort (Sloboda et al., 1996; Lehmann et al., 2018). Of particular interest to this work is how these factors impact musical expertise (Sloboda, 1991; Lehmann et al., 2018) and more importantly, whether they have a lasting effect once the practice comes to an end.

Musicians refine a number of different perceptual, motor, and cognitive skills to play their instrument(s) with fluency (Sloboda, 1991; Lehmann et al., 2007). Psychologically, this manifests in musicians outperforming nonmusicians in discriminating different pitches (Kishon-Rabin et al., 2001; Tervaniemi et al., 2005; Micheyl et al., 2006), tapping to rhythms (Franěk et al., 1991; Repp and Doggett, 2007; Chen et al., 2008; Skaansar et al., 2019), and remembering auditory stimuli (Pallesen et al., 2010; Cohen et al., 2011; Talamini et al., 2018). With the advent of neuroimaging tools, many studies have now shown that these differences manifest in a host of functional and anatomical changes to the brain as well (Amunts et al., 1997; Brattico et al., 2001; Imfeld et al., 2009; Jäncke, 2009; Dawson, 2014; Criscuolo et al., 2022). While there are clearly many investigations in the literature comparing musicians and nonmusicians, fewer break the dichotomy down into different types of musicianship and when they do, the results are often mixed. For instance, some studies have compared professional to amateur musicians and nonmusicians (Kauffman and Carlsen, 1989; Gaser and Schlaug, 2003; Hove et al., 2010; Krause et al., 2010; Repp, 2010; Mikutta et al., 2014; Appelgren et al., 2019), early- vs. late-trained musicians (Watanabe et al., 2007; Bailey and Penhune, 2010, 2013; Steele et al., 2013; Bailey et al., 2014; Shenker et al., 2022), and active vs. inactive musicians (Hanna-Pladdy and Gajewski, 2012; Bonde et al., 2018; Romeiser et al., 2021). This last classification of active vs. inactive musicians is especially important for investigating how ingrained these musical abilities truly are—do they dull without regular maintenance or are they set in stone once perfected?

One foundational musical ability is beat perception, the ability to detect temporal periodicities in musical rhythms (Schulze, 1978; Nguyen et al., 2018). The behavioral literature comparing beat perception in musicians and nonmusicians is somewhat mixed (Madsen, 1979; Rammsayer and Altenmüller, 2006; Grahn and Rowe, 2009; Mosing et al., 2014) with clear individual differences present (Grahn and McAuley, 2009; Grahn and Schuit, 2012). Specifically, musicians have been shown to be more accurate in judging tempo (Madsen, 1979) and beat alignment (Grahn and Schuit, 2012) as well as displaying better rhythm perception (Rammsayer and Altenmüller, 2006) and greater subjective experience of the beat, but only when one was present (Grahn and Rowe, 2009). Conversely, some of these researchers have found no difference between musicians and nonmusicians on similar rhythmic tasks like rhythm discrimination (Grahn and Brett, 2007), temporal generalization (Rammsayer and Altenmüller, 2006), beat strength tasks (after an outlier was removed; Grahn and McAuley, 2009), or musical aptitude in general once genetic influences were accounted for Mosing et al. (2014). This could be due to the multidimensionality of rhythmic abilities in general, with many different perceptual, cognitive, and genetic factors contributing (Mosing et al., 2014, 2016; Bartholomew et al., 2015; Hambrick and Tucker-Drob, 2015; Wesseldijk et al., 2019; Fiveash et al., 2022; Niarchou et al., 2022). However, another factor that could potentially distinguish differences in beat perception between musicians that has remained largely unexplored is whether rhythmic abilities change through continued music playing or devolve when discontinued.

1.2. The present study

Therefore, the present study was conducted to investigate possible differences in beat perception between active and inactive musicians and nonmusicians. We hypothesized that trained musicians who continue to play music regularly would be able to discriminate finer deviations from the beat (hereafter referred to as "beat alignment") than nonmusicians and, to a lesser degree, inactive musicians who no longer play their instruments. A working hypothesis based on the "use it or lose it" principle of brain plasticity (e.g., Shors et al., 2012) further suggests that inactive musicians may simply revert to a previous stage of the ability, though it is unclear whether this stage is comparable to or more advanced than nonmusicians. Alternatively, sufficient musical training may cement heightened abilities regardless of regular rehearsal or other metrics of musical engagement. Conversely, greater musical engagement (reflected in regular playing) could be a result of greater beat alignment ability since those with lesser ability may be discouraged from continued playing.

As a follow-up control analysis, we also investigated the role of other demographics and musical engagement factors like years of formal musical training, number of instruments played, and regular music listening habits. This also served to determine whether any effect of currently playing music could be confounded by or even better explained by our other measured variables.

2. Materials and methods

2.1. Participants

To this end, we analyzed beat alignment ability scores obtained with the Computerized Adaptive Beat Alignment Test (CA-BAT; Harrison and Müllensiefen, 2018a,b) for previous studies by Spiech et al. (2022, in preparation)[1] and Spiech et al. (2022b,c). CA-BAT scores were used either as a covariate or grouping variable while demographics information was simply used to characterize our samples (see Supplementary material 1 for an exhaustive list of all variables collected in the other three studies). In accordance with our ethics protocol approved by the Department of Psychology's internal research ethics committee at the University of Oslo (reference number 8131575), participants provided informed consent and were compensated with gift cards of varying value. Data from 97 unique participants (46 women, 50 men, seven left handed participants) recruited for three past studies on beat synchronization to challenging "groovy" beats (Spiech et al., 2022, in preparation, see footnote 1; Spiech et al., 2022b,c) was used in this analysis. One individual did not report demographic information and we used the mlim R package (Haghish, 2022) to impute the missing observations for the machine learning regressions. Participants were 27.2 years old on average (range: 18–56, SD: 6.1 years) and listened to music for an average of 17 h per week (range: 1–84, SD: 15.1 h).

First, we classified participants into Active Musicians, Inactive Musicians, and Nonmusicians using their self-reported instruments played, musical training, and weekly music playing. Active Musicians ($N=48$) were classified as any subjects who reported playing music weekly (M: 5.7, range: 1–27, SD: 5.9 h). Active Musicians reported receiving 10.4 years of formal musical training on average (range: 0–34, SD: 7.6 years) and played a variety of instruments (29 stringed instrumentalists, seven percussionists, four brass instrumentalists, 18 pianists, 11 vocalists, and nine other instrumentalists including electronic music producers). Inactive Musicians ($N=27$) were classified as any subjects who reported *not* playing music weekly but had either received some musical training or reported being able to play an instrument. Inactive Musicians had an average of 5.4 years of formal musical training (range: 0–20, SD: 5.033 years) with nine playing stringed instruments, two playing percussion, five playing brass instruments, 12 playing piano, and one singing. The remaining

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participants ($N=21$) reported having no musical training nor having learned to play any instrument and were thus classified as Nonmusicians ($N=21$). These group characteristics are depicted in Table 1 below.

2.2. Procedure

For the purposes of comparing uniform data, only the information from the custom-made musicianship questionnaire (results of which are summarized in section 2.1) and from the CA-BAT were used. All three experiments began with participants filling out the demographics and musicianship questionnaire. Specifically, they provided their age, handedness, gender, years of formal musical training (specified as formal training involving a teacher or tutor), hours of weekly music playing, hours of weekly music listening, and type of instruments played (stringed, percussion, brass, piano, voice, and other which included electronic music production). Hours of weekly music listening along with type and number of instruments played were included as measures of musical engagement since more regular exposure to music and familiarity with more instruments could indicate greater musical interest. In Spiech et al. (2022, in preparation, see footnote 1) and Spiech et al. (2022b), the CA-BAT was completed at the end of each experiment whereas it was completed midway through the experiment in Spiech et al. (2022c) as part of the counterbalancing scheme. Potential effects of participant fatigue on CA-BAT performance were assessed and deemed unlikely, see Supplementary material 2 for details.

The CA-BAT is a reliable and valid psychoacoustic test that measures participants' ability to discriminate fine differences in the timing of a musical beat (Iversen and Patel, 2008; Grahn and Schuit, 2012; Leow et al., 2014; Ross et al., 2018; Harrison and Müllensiefen, 2018a,b; Tranchant et al., 2021; Spiech et al., 2022b,c). The CA-BAT achieves this by playing 25 short musical clips with overlaid beep tracks. Each clip is played twice, once with the beep track aligned to the beat and once where the beep track is misaligned (by a constant proportion) to some extent. Participants are then asked to select the clip where they thought the beep track was aligned to the beat. The degree of misalignment is determined to some extent by participants' accuracy where correct responses result in smaller misalignments on the subsequent trials and incorrect responses result in greater misalignments. Owing to item response theory and its adaptive design (i.e., correct responses result in smaller differences between beep tracks while incorrect responses result in greater differences), the test itself only takes around 10 min to estimate a participant's beat alignment ability.

2.3. Statistical analysis

First, a Kruskal–Wallis rank sum test (a nonparametric one-way analysis of variance) with Beat Alignment Ability as the dependent variable was used to assess Musicianship (Active vs. Inactive vs. Nonmusician) group differences (Kruskal and Wallis, 1952). Follow-up two-tailed Welch's independent samples *t*-tests were then used to test for differences in Beat Alignment Ability between groups because the variances between groups were expected to be unequal (Delacre et al., 2017). These tests were corrected for multiple comparisons using the false discovery rate (FDR, Benjamini and Hochberg, 1995). Second, to investigate the degree to which any of these differences could be related to disparities in musical training, we repeated the same tests with Years of Formal Musical Training as the dependent variable. Data analyses were carried out in R version 4.1.3 (R Core Team, 2013) using the "ez" and "effectsize" packages (Lawrence, 2011; Ben-Shachar et al., 2020) and results were visualized using the "ggplot2" package (Wickham, 2016).

Lastly, to fully explore the relationships between demographic and music-related variables with Beat Alignment Ability, we performed a generalized linear regression with all measured variables (participants' age, gender, handedness, years of formal musical training, number of musical instruments played, number of hours of weekly music playing, and number of hours of weekly music listening) as independent variables to predict CA-BAT scores. However, we expected the music-related variables to be highly correlated with one another, potentially running into multicollinearity problems, so we additionally employed non-parametric and non-linear regression models with Gradient Boosting Machine (GBM, Friedman, 2001), Random Forest (RF, Breiman, 2001), and Extreme Gradient Boosting (XGBoost, Chen et al., 2015; Chen and Guestrin, 2016) algorithms. Tree-based algorithms such as GBM, RF, and XGBoost are *not* prone to collinearity and can effectively rank the importance of the predictors based on reduction of residual deviance or gains in other loss functions, while taking interactions between the variables into account. In this way, we sought to identify the most important factors related to beat alignment ability by extracting estimated variable importance from the model to further examine whether state-of-the-art non-parametric machine learning models would confirm the results of the generalized linear regression analysis or identify effects masked by multicollinearity.

The variable importance was estimated by the loss function gains in the process of constructing the trees. Interpreting variable importances is not necessarily analogous to correlation or regression coefficients. Instead, they can be conceptualized as variables that feed the model with unique information to improve its performance. To simplify the interpretation of variable importance, they are often scaled by dividing all estimated variable importances by the value of the variable with the highest importance. Therefore, the scaled variable importance can range from 0 to 1, ranking the importance of the predictors to the model. We used the h2o.ai software to carry out the machine learning analysis (Click et al., 2017).

TABLE 1 Summary statistics of the different Musicianship groups.

Musicianship group	Number of participants	Hours played weekly	Years of formal musical training	Number of instruments played	Gender	Age
Active musicians	48	5.7 (1–27)	10.4 (0–34)	1.7 (1-4)	19 women, 29 men	27.4 (18–56)
Inactive musicians	27	0	5.4 (0–20)	1.1 (0-2)	15 women, 12 men	27.1 (20–45)
Nonmusicians	21	0	0	0	12 women, 9 men	26.5 (20–39)

For hours played weekly, years of formal musical training, and number of instruments played, the first values represent the group average while the values in parentheses are the range.

3. Results

The Kruskal–Wallis test with Beat Alignment Ability as a dependent variable revealed a significant effect of Musicianship [$\chi^2(2) = 6.783$, $p = 0.034$, $\varepsilon^2 = 0.071$]. FDR-corrected follow-up two-tailed Welch's independent samples *t*-tests revealed that Active Musicians exhibited moderately greater Beat Alignment Ability than Inactive Musicians [$t(39.442) = 2.213$, $p = 0.050$, $d = 0.56$] and even greater Beat Alignment Ability than Nonmusicians [$t(33.82) = 2.337$, $p = 0.050$, $d = 0.63$]. Inactive Musicians' Beat Alignment Ability, on the other hand, did not differ from that of Nonmusicians [$t(46) = -0.087$, $p = 0.931$]. These results are displayed in Figure 1 below. However, when this same analysis was conducted with three outliers removed (subjects with Beat Alignment Ability scores more than ±2.5 standard deviations from the dataset's mean), the omnibus effect was diminished to a trend [$\chi^2(2) = 4.818$, $p = 0.090$, $\varepsilon^2 = 0.052$] and no *post hoc* pairwise comparisons survived multiple comparisons corrections (all corrected *p*-values > 0.144) so this result should be taken with caution.

Unsurprisingly, Years of Formal Musical Training also differed between Musician groups as revealed by a Kruskal–Wallis test [$\chi^2(2) = 44.690$, $p < 0.001$, $\varepsilon^2 = 0.470$]. FDR-corrected follow-up two-tailed Welch's independent samples *t*-tests demonstrated that all groups differed from each other with the largest differences being both musician groups having substantially more musical training than Nonmusicians [Active Musicians: $t(47) = 9.448$, $p < 0.001$, $d = 1.93$; Inactive Musicians: $t(26) = 5.621$, $p < 0.001$, $d = 1.53$], indicating that our grouping factor accounted for a difference. However, Active Musicians also had more Years of Formal Musical Training than Inactive Musicians [$t(70.997) = 3.378$, $p = 0.001$, $d = 0.77$], potentially confounding our findings about music playing and necessitating the subsequent regression analyses.

In order to rule out this potential confound, we consulted our generalized linear model's results. The regression analysis had an R^2 of 0.147 and mean residual deviance of 0.820 and showed that only Years of Music Training was a significant positive predictor of Beat Alignment Ability. Thus, after accounting for the variance explained by Years of Formal Musical Training, it seems that Hours of Weekly Music Playing had no bearing on Beat Alignment Ability. Table 2 presents the coefficients, standard errors, *p*-values, and standardized coefficients of the GLM predictors. The pairs plot in Figure 2 demonstrates the correlations between all of the variables. As expected, many of the music-related variables were significantly correlated which could potentially introduce multicollinearity issues for the generalized linear model, necessitating our machine learning regressions.

Fine-tuning the GBM, RF, and XGBoost models confirmed that the linear model was not confounded by multicollinearity problems by providing similar evidence. Extracting and rescaling the variable importance measure from the models revealed that Years of Formal Musical Training was the most important predictor of Beat Alignment Ability, explaining more of the variance compared to Number of Instruments Played, Hours of Weekly Music Listening, and particularly, Hours of Weekly Music Playing. The mean residual deviance of the fine-tuned GBM, RF, and XGBoost models were 0.65, 1.00, and 0.70, respectively. This indicates that the GBM model was the most accurate, followed by XGBoost and RF because the lower the mean residual deviance, the lower the prediction error and thus the more accurate the model. As shown in Table 3, Years of Formal Musical Training was the single most important predictor for all models, confirming the results of the generalized linear model, while handling the potential multicollinearity issues.

4. Discussion

In this study, we compared the beat alignment abilities of active musicians to those of inactive musicians and nonmusicians. We found

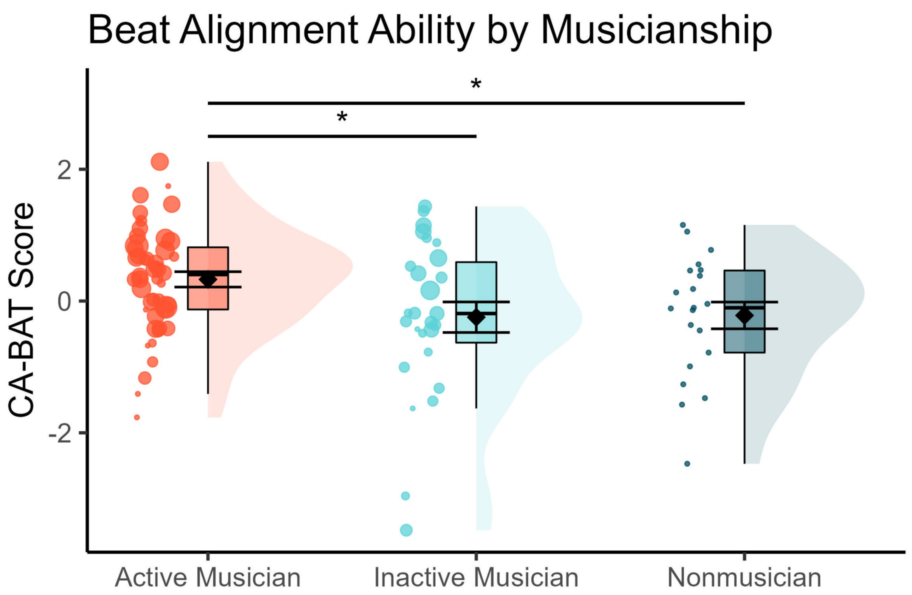

FIGURE 1
Raincloud plots displaying Beat Alignment Ability scores by Musicianship. Dots are individual subject scores and are scaled in size relative to years of formal musical training while large diamonds are group averages. Error bars represent standard errors of the mean. The boxplots' thick black lines correspond to the group medians, hinges to the first and third quartiles, and whiskers to the most extreme value no further than 1.5 times the interquartile range. Asterisks depict statistical significance at $p<0.05$.

TABLE 2 Output of the generalized linear model. Only Years of Formal Musical Training was significant, indicating that with more years of formal musical training, CA-BAT scores increased and that once this was accounted for, no music-related or demographic variables had any impact.

Predictor	Coefficient	Standard Error	*p*-value	Standardized Coefficient
Age	0.006	0.019	0.322	0.036
Handedness	0.322	0.382	0.400	0.084
Gender	−0.207	0.219	0.348	−0.103
Years of formal musical training	0.046	0.020	0.024*	0.335
Hours of weekly music playing	−0.002	0.020	0.938	−0.009
Hours of weekly music listening	0.006	0.007	0.406	0.087
Number of instruments played	0.022	0.134	0.871	0.021

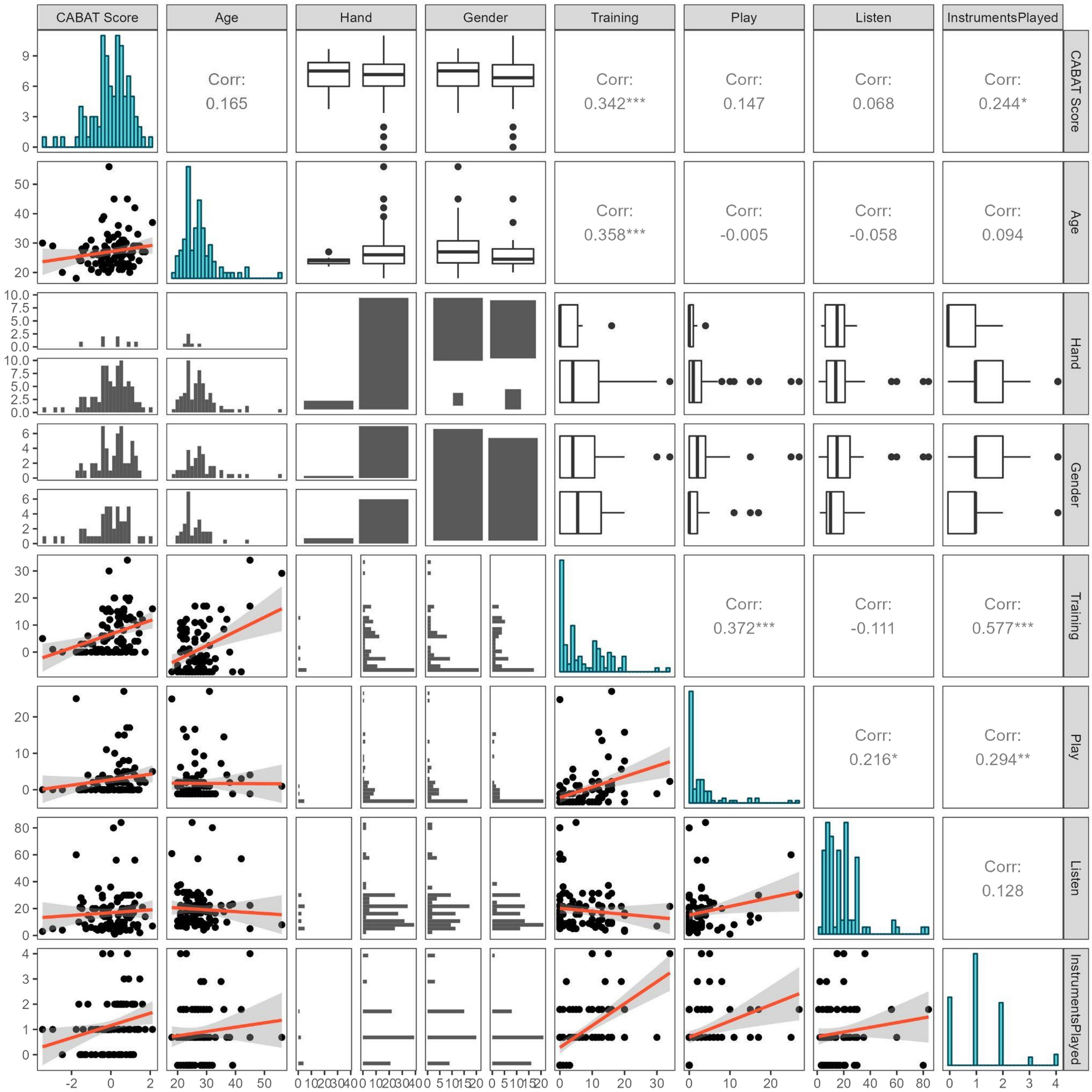

FIGURE 2
Pairs plot demonstrating the correlations between all of the different variables used in the regression analyses. As expected, and potentially troublesome for linear regression, many music-related variables were correlated with each other.

that active musicians possessed significantly greater beat alignment abilities than both inactive musicians and nonmusicians (the latter two groups performed similarly on the CA-BAT). However, the distribution of years of formal musical training differed between groups, possibly

TABLE 3 Scaled variable importance of GBM, RF, and XGBoost models.

Variable	GBM	RF	XGBoost
Years of formal musical training	1.00	1.00	1.00
Age	0.65	0.92	0.60
Hours listened weekly	0.61	0.83	0.88
Hours played weekly	0.33	0.53	0.60
Gender	0.14	0.24	0.07
Number of instruments played	0.12	0.31	0.45
Handedness	0.01	0.08	0.09

Looking at the ranking of the variable importance indicates that Years of Formal Musical Training is the most important predictor of beat alignment for all machine learning models. Furthermore, Hours Played Weekly was relatively less important to all models, once Years of Formal Musical Training, Age, and Hours Listened Weekly are taken into consideration.

confounding the observed beat alignment differences. The subsequent generalized linear regression indicated this had indeed occurred; years of formal musical training was the only significant predictor of CA-BAT scores. To ensure that the generalized linear model was untainted by multicollinearity problems arising from our significantly correlated music-related variables, we employed three different machine learning regressions that are not prone to these concerns in order to rank the importance of our predictors. All three machine learning regressions confirmed this was the case; years of formal musical training dwarfed all other music-related and demographic factors. These findings suggest that more musical training is associated with better beat alignment even without regular rehearsal.

This explanation falls in line with common notions of expertise where practice enhances ability (Ericsson and Lehmann, 1996; Sloboda et al., 1996). The active musicians in our sample received more years of formal musical training and likely accrued more hours of beat perception refinement through their continued engagement with their instruments, resulting in better performance on the CA-BAT than both their inactive counterparts and nonmusicians. However, these marginal effects of continued practice were superfluous for sharpening beat alignment since the regression analyses demonstrated that years of formal musical training sufficiently explained differences in CA-BAT scores. Thus, it seems that with enough training, the neural circuits for beat alignment could become hardwired and continued musical engagement is not necessary to preserve the ability.

A part of this picture could be that people with better beat alignment might be more motivated to stick with musical training for more years, further exercising their rhythmic skills. This is supported by Albert Bandura's self-efficacy theory where one's beliefs about one's competencies influences subsequent motivation and performance (Bandura, 1982, 1997). This has already been shown in the context of music performance (McPherson and McCormick, 2006; Hendricks, 2016) and so it could potentially apply to lower level musical abilities as well. It seems logical that better beat alignment could result in more of Bandura's "mastery experiences" while training, which then motivates them to pursue more formal musical education and learn more rhythmically challenging pieces in a virtuous circle. Indeed, this explanation is consistent with genetics studies that have found interactions with or no effect of practice on musical aptitude and achievement (Mosing et al., 2014; Hambrick and Tucker-Drob, 2015; Wesseldijk et al., 2019).

As to the absence of differences between active and inactive musicians, methodological aspects should also be considered. For example, it could be that the CA-BAT may not be sensitive to finding beat perception differences that arise from musical engagement factors like regular playing. Moreover, the CA-BAT measures the ability to detect fine-grained phase offsets and this is often not necessary for many instruments in a variety of musical traditions. Indeed, the perceptual center (when a sound's onset is perceived) has been shown to vary considerably depending on a number of musical qualities (Danielsen et al., 2019), how it is measured (London et al., 2019), and genre expertise (Danielsen et al., 2022). It is possible that only highly trained musicians develop an enhanced beat perception ability that generalizes across sounds well enough to be observed in the beat alignment measured by the CA-BAT. Said another way, the CA-BAT may not be ecologically valid for untrained listeners. Other rhythmic tests should thus be employed to investigate whether this may have been the case.

Additionally, the CA-BAT's two-alternative forced choice design introduces cognitive demands on working memory that may explain dissociations with beat tapping and production abilities (Bégel et al., 2017; Fiveash et al., 2022). These cognitive demands could be correlated with latent educational or genetic variables, that is, more years of formal musical training could be associated with more years of education in general or certain genetic predispositions (Bartholomew et al., 2015; Mosing et al., 2016). The latter could not be studied within the framework of the present study. However, with genetics alone explaining roughly 13%–16% of beat synchronization abilities (Niarchou et al., 2022), for example, this may explain why the predictors in our generalized linear model only explained about 15% of the CA-BAT scores' variance.

A substantial limitation of this study is that our dataset did not contain potentially important details about participants' musicianship because it was not the focus of the original studies where the data was collected. One such detail is the age that musical training began. A sensitive period for musical ability has been proposed (Penhune, 2011; Bailey and Penhune, 2013); early-trained musicians have been found to exhibit greater sensorimotor synchronization performance (Watanabe et al., 2007; Bailey and Penhune, 2010; Bailey et al., 2014) and executive functioning (Chen et al., 2022) alongside neuroanatomical differences (Amunts et al., 1997; Imfeld et al., 2009; Steele et al., 2013; Bailey et al., 2014; Shenker et al., 2022). It could be possible that only early-trained musicians (who could then accrue more years of formal musical training overall) develop an enduring beat perception while those who began their training outside of the sensitive period may either fail to cultivate better beat perception than nonmusicians or lose any gains they may have made after they stopped playing music. In our study, it is unclear to what extent our results are driven by early training so further experiments are needed to rule this out.

We also did not collect information regarding the type or quality of the formal training received. Given that musical training was the single most important predictor of CA-BAT scores we measured, it would be interesting to explore the quality of this training in future studies. For instance, it is conceivable that more intense training (i.e., more hours spent practicing) could induce more enduring beat perception abilities later in life. Furthermore, some types of musical training (e.g., private lessons, training in large or small ensembles, rigorous self-teaching) may be better or worse at enhancing beat alignment. Finally, certain musical styles and traditions require more precise beat timing than others (e.g., math rock requires better timing abilities than ambient soundscapes) so musicians trained in these genres could plausibly develop enhanced beat perception to meet their needs. Longitudinal and intervention-based studies manipulating and controlling for these various factors should thus be carried out to conclusively rule out the influence of these variables.

Finally, despite our clear instructions that formal musical training required supervision, two participants may have misunderstood what constitutes formal musical training and responded with an inordinate number of years. Removing them from the analyses, however, did not change the overall pattern of results and even when more extreme exclusion criteria were employed (see Supplementary material 3 for details).

In conclusion, from our sample of nearly a hundred participants, we found that better beat alignment ability was associated with more years of formal musical training and that this relationship dwarfed any potential effect of currently playing music. This was confirmed using both a conventional generalized linear model as well as nonlinear and nonparametric machine learning regressions that are not prone to the multicollinearity issues that may arise while measuring typically intercorrelated musical variables. However, since our model only captured roughly 15% of the variance in our data, future work is needed to tease out the exact nature and causal relations of these variables. This could include using other rhythmic tests, genetic information, longitudinal designs, and more detailed demographics questionnaires (e.g., type of musical training and age at which musical training began). Further, to definitively rule out potential pre-selection effects found in previous work (i.e., innately talented musicians continue training longer than those without such talent), intervention studies are needed to test whether training can improve the rhythmic abilities of participants of varying natural skill.

Data availability statement

Publicly available datasets were analyzed in this study. This data can be found at: https://osf.io/d6mje/?view_only=d0910426b5eb481d9cff1850c4f874f6.

Ethics statement

The studies involving human participants were reviewed and approved by Internal Ethics Committee, Department of Psychology University of Oslo reference number: 8131575. The patients/participants provided their written informed consent to participate in this study.

Author contributions

CS conceived the study and carried out the statistical analyses and data visualizations with EH. CS wrote the first draft of the manuscript. TE, BL, AD, and EH all provided feedback and revised the manuscript. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fpsyg.2023.1034561/full#supplementary-material

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The varying social dynamics in orally transmitted and notated vs. improvised musical performance

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Musical performance can be viewed as an intricate form of social behavior. Accordingly, the rich diversity of existing musical styles and traditions may reflect distinct modes of social interaction. To gain a better understanding of the relations between musical style and social dynamics, we have formulated a framework for dissecting different genres of musical performance according to key social criteria. In particular, we contemplate on the continuum ranging from strictly orally transmitted and notated to fully improvised music, and its relation to general compliance with social norms and structure, borrowing key concepts from tight-loose theory, a powerful paradigm for studying societal behaviors and tendencies. We apply this approach to analyze four distinct prominent musical genres, providing a detailed mapping between musical style and social dynamics. This work highlights important factors that link between musical performance and social interaction, and will enable future experimental unraveling of social aspects of musical performance as expressed by different musical styles and practices.

KEYWORDS

tight-loose theory, musical genres, improvisation, social interaction, musical performance

Introduction

Different styles of musical performance demand varying levels of accuracy and planning (Davies, 2001; Thom, 2020). Thus, notated and orally transmitted music, compared to improvised music, for example, requires a high level of alignment between players, careful compliance with written notes and instructions, and a systematic level of playing that adheres to the composer's intentions (Thom, 2020). Given that musical performance can be considered as a complex form of social interaction (D'Ausilio et al., 2012; Keller et al., 2014; Robledo et al., 2021), it stands to reason that performance styles should associate with congruent forms of social dynamics. In particular, we would like to propose that whether music performance is based more on notation and oral tradition or more on improvisation, may correspond to the degree of adherence to more general social norms displayed by the social dynamics incorporated within the music-making.

To examine and develop this notion we analyze several established traditions of music performance with respect to distinct criteria of social dynamics along the axis ranging from tight to loose social compliance with norms, a framework originally developed for studying societal behavior (Pelto, 1968; Gelfand et al., 2011). This analysis brings us closer to understanding joint music-making as a social phenomenon and its relations to particular forms of social dynamics.

We wish to emphasize that our main aim was to capture varied social dynamics that underlie different types of musical performances and to strengthen our theoretical understanding of this phenomenon. To this end we chose four different musical traditions that serve to exemplify the social components of joint music performances. Therefore, rather than providing a comprehensive musicological or ethnomusicological account of the musical genres explored, we focus on particular tendencies of music engagement that they represent with an emphasis on their underlying social dynamics. We thus intend to treat each musical genre as an ideal prototype of a particular mode of musical interaction. These include: (1) Western classical; (2) Hindu music; (3) Jazz; (4) Free jazz improvisation. These four musical genres span a broad representational array of performance conditions which allowed us to explore an extensive continuum of orally transmitted versus improvised traditions, along the lines of Kay (2016):

> "If freely improvised music and creative jazz lie at one end of a spectrum, then the other end would inevitably be secured by Western classical music, where there is variation only in the interpretation of a defined composition. I would place North Indian raga music in the middle of the spectrum: it balances in harmony the best attributes of classicism, retaining the continuity of past and tradition while respecting artists' intuitive and improvised interpretation of the present" (p. 10).

We therefore wish to further explore the continuum proposed by Kay (2016) and to add an analysis of the social structures underlying it.

Mapping between performance attributes and social structure

Western classical music

Western classical music encompasses an era stretched over 1,000 years of diverse styles and traditions originating in the Latin plainchants of the Roman Catholic Church. The chants did not include any musical instruments which were forbidden by the church, and were exclusively monophonic (Taruskin, 2010; Levy et al., 2022). Though writings and drawings from that time imply the existence of secular instrumental music, which is believed to have incorporated polyphony, no remaining notated scores have been found to confirm this hypothesis (Taruskin, 2010). Modern writings about the performance of plainchants (e.g., Berry, 1979; Brunner, 1982) highlight the essentiality of maintaining an authentic performance, one that is consulted with experts of medieval music and is not bound to mainstream assumptions regarding this tradition (Brunner, 1982). Such historic approaches, which remain alert for novel directives to uncover authentic traditional musicianship, imply a broader social influence of a millennium-practiced musical tradition. In other words, it illuminates additional possible structures presumably remaining untouched, other than the musical ones (e.g., the social structures between the players and/or the players and audience, see more in Small, 1998).

The first secular music documented is known to be the Troubadour songs, sung by poet-musician knights. Located in today's modern France, Aquitine, this elite tradition emerged, introducing love and knigtly songs (Taruskin, 2010). Though not bound to religious controls, according to Taruskin (2010), this musical style reflected strong social norms of feudalism and hierarchy, with its harmonious and ideal poems.

Although presumably existing well before, polyphony became a central practice in European music only during the 12th century (Taruskin, 2010; Frobenius et al., 2022). This period also marks the establishment of meter and notation as essential components of composition and performance (Taruskin, 2010). The next musical form created during the 13th-14th century was the French Motet. The Motet, a vocal composition that emerged as a Latin religious practice but cultivated to include secular branches, enabled composers to further elaborate harmonic techniques, and complex writing of several melodies including text (Taruskin, 2010).

From the secular motets of Dufay Guillaume de Machaunt, a renowned composer of the 13th century, Western classical music evolved into the early Renaissance period, giving rise to the famous pieces of Du Fay, which included masses, magnificents, motets and hymns, which imported English harmonic techniques and styles. A century later, the form of the Mass reached a peak, represented by one of its famous composers, Josquin des Pres (Sanders et al., 2022). In that time the Ordinary of the Mass was established including the Kyrie, Gloria, Credo, Sanctus, and *Agnus Dei*. Later Renaissance gave rise to the Madrigal form and mostly branched into either vocal work or compositions of instrumental dances. The Renaissance era fostered several performance practices. e.g., *cantare super librum* (Bent, 1983), that at first historical sight might be understood as types of improvisation. However, a closer examination of this type of performance revealed that what was casually considered by some researchers as a spontaneous and free expression (Ferand, 1957), was in fact "music fully or sufficiently conceived but nevertheless unwritten" (Bent, 1983, p. 378). Bent (1983) therefore argued for a more subtle definition for inventing musical lines on the spot, one which reflects the extremely sophisticated and strict set of rules underlying such musical practice. Bent's approach emphasizes the strict nature not only of orally transmitted music, but also of the music that had greater degrees of freedom, i.e., *cantare super librum.* Such historic accounts support our central argument about the strict musical and social characters implicit to Western classical music. Conversely, Broude (2020) linked the shifting of *cantare super librum* practice from being solely improvised to exclusively notated to the rise of music-printing industry, the increase in amateur musicians who could not improvise counterpoint lines sufficiently and mostly related to our piece: to the materialization of the construct of "art works" (Broude, 2020).

1,600 to 1750 marks the Baroque era, represented iconically by the compositions of Johan Sebastian Bach and George Friedrich Handel. During the Baroque period the seeds of modern harmony and orchestration were planted, along with the idea of the modern orchestra and modern opera (Taruskin, 2010). Largely influenced by Italian music, the idea of solo voice for instruments was born. This is exemplified in Bach's Cantatas. Handel's famous "Messiah" oratorio represents a peak of compositional advancement as well as religious topics performed in secular halls.

This accentuates the expansion of music to additional realms of society. However, at the same time demonstrates the strong religious ties it continues to maintain to this day. The excitement and interest in different instrumental timbres and arrangements, e.g., the trio sonata, influenced composers' attention and appreciation of the violin, which was considered the highest rank of all instruments

(Sanders et al., 2022). This is highly notable in Vivaldi's various violin concertos and sonatas. Different musical forms emerged, giving rise to great versatility and styles during the 17th–18th centuries, such as the Concerto and Fugue for example. The latter not only implies the centrality of instrumental music but also facilitated the emergence of novel compositional structures and techniques, e.g., deploying repetition of themes, exposition, change of key and more. However, the techniques mentioned flourished into their full potential during the Classical era, where structural clarity, symmetry and stability gained centrality over textural intricacy.

The Classical era was stretched between three different styles: the first, "Reform opera" (as in Gluck's famous Orfeo ed Euridice), focused on the opera's drama rather than on the singers' solos. The second style evolving at the time related to the centrality of keyboard work. Moving from the harpsichord to the clavichord emphasized the emergence of great pieces such as Carl Philip Emanuel Bach's keyboard sonatas. As mentioned above, this was also influenced by the significance of the Sonata form at the time (Mangsen et al., 2022). Along the centrality of piano-playing, various improvisational practices flourished in the Classical era, e.g., the Cadenza, the Fantasia and the prelude (Goertzen, 1996). According to Goertzen, while the Fantasia was a well-established practice, often reviewed and mentioned in concerts' programs, the prelude remained somewhat in the margins of Western music. Goertzen claimed that one of the social-cultural movements that influenced the diminishing of such improvisational practice pertains to the rise of printed music and printed programs, leaving the spontaneously crafted parts of classical performance sealed in the past. The third musical style peaking at the time was the symphony (Larue et al., 2022). Originating in the Greek work "sounding together," this musical style symbolized a new mode of relatedness and social balance in music (Larue et al., 2022). Along with being part of the Catholic service, in its early format, symphonies were present at different venues and concert halls: from official ceremonies to private concerts held in palaces and residencies of the local aristocrats (Larue et al., 2022). Represented iconically with Joseph Haydn, Wolfgang Amadé Mozart and Ludwig van Beethoven's symphonies, this form has also bridged Western music into the Romantic era.

With Beethoven's later work, along with composers such as Hector Berlioz, Franz Schubert, Frederick Chopin, Clara and Robert Schuman and many others, Western classical music entered the Romantic period. Key features of this time included greater emphasis on emotional expression, as opposed to the previous period's focus on clarity and structure (Taruskin, 2010). At the same time, orchestras became bigger, and the harmonic structures and arrangements became more intricate and diverse. On the social level, Romanticism emphasized the "I," calling for expressiveness and individualism, however, this "I" very quickly grew into the "big I" or, "We," identifying a national component within the musical culture (Taruskin, 2010). The late 19th century gave rise to novel compositional exploration such as the symphonic Lieder, as indicated in Gustav Mahler's symphonies.

The early 20th century is characterized by the emancipation of basic harmonic structures such as scales and form, as represented by Claude Debussy's contributions on the one hand, and Igor Stravinsky's compositions on the other. Later periods of the 20th century incorporated many complex post-war and cold war influences (Taruskin, 2010; we will not be covering those in this article). The migration of many composers (e.g., Schoenberg, Stravinsky, Bartók, Hindemith, Krenek, Korngold, Milhaud and more) to America as a consequence of Hitler's regime, influenced the meeting between European and American styles, which had a profound effect on the history of Western music (Taruskin, 2010).

Though it would have been of great significance to explore the delicate changes that have evolved in form and style throughout the Western classical eras, we focus on more fundamental aspects witnessed along the stretch of a millennium of Western classical music, i.e., on the constant presence of some kind of hierarchy (e.g., between players, instruments, styles), clear compositional forms, and a literate notation from as early as the 9th century. All the styles and iterations mentioned above have evolved from the establishment of defined musical roles between players (even if these roles are exchanged – this would be scripted by the composer), which we believe have created a distinct social matrix between the players.

At the same time, in Western culture, improvisation is popularly considered as branching out from strictly notated music. However, up until 150 years ago, the basic skills of any musician equally included performance, improvisation and composition (Moore, 1992). Indeed, improvisation was a fundamental part of Western Classical music evident over different eras: Renaissance, Baroque, Classical and early Romantic music. Moore (1992) raised the question of how improvisation suddenly vanished during the 19th century and pointed at the lack of research on this striking phenomenon. As mentioned, one reason was that musicians became more specialized in specific roles (i.e., composer versus instrumentalist; Moore, 1992; Bailey, 1993; Goehr, 1994). However, perhaps the crucial driving force for notated music becoming predominant in Western society from the 19th century onwards was its embracement by the upper class, while improvisational music came to be regarded as less prestigious and was associated with the lower social classes (Moore, 1992; Fischlin and Porter, 2020). Thus, notated music became a symbol of social status, superseding other previous cultural functions of music making, such as creating communities and allowing a free, improvisatory relationship between performer and audience. As a consequence, musicians were increasingly encouraged to focus on composing music for the elite. Even musicians belonging to the margins of society at that time, now found an opportunity for acceptance in higher social circles, by emphasizing their compositions (Moore, 1992). Concomitantly, improvisation was pushed out of the mainstream of musicological research (Moore, 1992; Monson, 1996; Fischlin and Porter, 2020).

Perhaps the most crucial motivation for the transition from improvisation to notation in Western music was the effectiveness of notated music in preserving strict social hierarchies and values (Moore, 1992; Goehr, 1994; Small, 1998). Thus, it seems that the vanishing of musical improvisation in Western Classical music around the 19th century was closely tied with contemporary social structures, thus is indicative of a strong link between musical style and its social underpinnings.

Hindu music: Hindustani and Carnatic traditions

Prior to separating into its two central streams of Carnatic music and Hindustani music around the 12th and 13th centuries, Hindu music can be traced 2,500 years back, in the chant and utterances of the Vedic period: devotional hymns sang to the gods, also called *Samaveda* (Gowrishankar, 2022). The Hindustani stream is traditionally divided into four periods: Delhi sultanate, Mughal period, the Colonial era and Modern Hindustani. All four eras present rich musical developments with key musicians greatly influencing the establishment of diverse styles and forms. The Carnatic stream is acknowledged with four main periods as well: Vijayanagar period, Pre-Trinity period, Trinity period and Post-Trinity period. The Trinity period is considered the golden age of Carnatic music, referring to three great composers who substantially innovated the ragas and talas, establishing new forms of Carnatic music (Vijayakrishnan, 2007; Gowrishankar, 2022).

Though we will not be able to encompass the vast musical traditions evolving at different times, it is of great interest for us to realize that throughout almost a millennium the Hindu music of both streams preserved its connections with its ancient origins while innovating with ragas and other forms (Nettl, 2014; Gowrishankar, 2022). The magnitude and domination of the traditional aspects in Hindu music, we believe is fundamental to the social context created by Classical Indian performance. As specified by Nooshin and Widdess (2005), it does not only influence the players' adherence to their musical role (e.g., leader or accompanist of the raga improvisation), but also creates strong expectations among the audience.

While the Northern tradition, i.e., Hindustani classical music stemmed from several ancient influences such as the ancient Persian tradition *Musiqi-e assil*, the Southern branch. i.e., Carnatic classical music, evolved under the influence of the reformative *Bhakti* movement (Vijayakrishnan, 2007). Unlike Hindustani music, Carnatic music emphasizes vocal music, whereas instrumental music is secondary and inspired by vocal characteristics (Vijayakrishnan, 2007). In addition, this branch did not incorporate any exclusive instrumental forms (Gowrishankar, 2022). Remaining unaffected by Islamic conquest of the Northern part of India, as well as departing from any Persian influences, the Carnatic stream remained truthful to ancient Hindu traditions. On the other hand, the Hindustani stream was conceived as a synthesis between traditions, the religious and the secular (Nettl, 2014). The three vocal streams identified with Hindustani music are *Dhrupad*, *Khayal*, and *Thumri.* Under the rule of Delhi Sultanate, important musicians such as Amir Khusrau evolved, who is identified with establishing and formalizing some of the basic tenets of Hindustani music. Though differing in many social and historical factors, the two branches do share some similarities in terms of forms and performance styles, i.e., the *Raga* (scale) and *Tala* (cyclic rhythmic pattern), though they developed differently in each stream – the Hindustani or the Carnatic (Nettl, 2014). An additional aspect shared by both Hindustani and Carnatic streams relates to the pre-determined roles of the musicians in the music ensemble (Nettl, 2014): the melodic soloist (present in both streams); and the accompaniments: string instruments (Sitar or violin); and a set of drums (*Tabla*). In all streams of Indian music, the soloist is considered the group's leader and is almost exclusively engaged in improvising. The other players provide a rhythmic and drone basis, and at times participate in structured moments of improvisational dialogues with the soloist (Nettl, 2014). While in the Carnatic stream the voice gained great centrality, in the Hindustani music the instruments were more salient in the musical performance (Vijayakrishnan, 2007). Pertinent to our discussion of possible social structures embedded in varied musical traditions, are the strict roles of soloist versus accompanist, which remained untouched throughout almost three millennia.

When discussing the evolution of Hindu music, one should take into account the subtlety in which issues of social class are entwined within the performance and musical relationships of the musical tradition (Clayton and Leante, 2015; Alaghband-Zadeh, 2017). In Hindustani music, according to Clayton and Leante (2015), this social aspect can manifest either in pre-determined roles specific to the performance (e.g., soloist; accompanist; or listener), or in matters relating to the underlying relation between the players (e.g., teacher-student; family members). In this respect, the authors highlight several historical changes occurring throughout the 19th century, one of them illustrated by many musicians of *Sāraṅgī*-playing families becoming solo singers and henceforth abandoning their accompanying instrument due to its association with low-status. Alaghband-Zadeh (2017) shows how ancient and active practices of "active expert listeners" in North Indian performances, preserve aspects of class, roles and aristocracy among the relationship between the players as well as between musicians and their audiences.

In her attempt to define the nature of Hindustani music, McNeil (2017) argues that the Hindustani musical tradition was interpreted inaccurately by western researchers, who used western terminologies and ontologies of improvisation and notation, thus imposing a binary system of thought that does not apply to Hindustani music. McNeil highlighted the difficulty in translating the term improvisation, which represents different realities and varied aspects of musical creativity in each culture. The segregated approach, typical to Western theory of music, fails to include central parts of Hindustani, as well as Persian and Arabic music, according to McNeil (2017). In his ethnographic exploration of his personal journey into Indian music, Kay (2016) compares performing a *Raga* to painting a portrait of a well-known and beloved personality that was not completely pre-planned. In other words, Kay captures in his description the traditional as well as the creative aspects of performing classical Indian music.

Nooshin and Widdess (2005) explained that both Iranian and ancient Hindu music did not theorize the term improvisation, but musicians rather dedicated some parts of the musical performance as responsibilities of the performers. The authors specified however that nowadays, the two main Classical Indian streams (i.e., Hindustani and Carnatic music) differ in that sense. While Hindustani musicians use terms such as *Bandis* and *Gat* to refer to pre-composed and relatively unchanged parts, and *Upaj* and *Khyal* as indicating innovative parts of the players, modern Carnatic music seems to allow a rougher distinction between pre-composed music, *Kalpita* (or sometimes known as *Kriti*), and music that is created on the spot, *Kalpana*.

Several authors have highlighted the emotional component of Hindustani classical music (Nooshin, 2003; Nooshin and Widdess, 2005; Pudaruth, 2016). According to Pudaruth, Hindustani music is "always making reference to and depicting some emotions outside itself… a music comprising various 'channels', through which a wide range of human emotions can be expressed" (p. 6). Creativity and emotional expression, she concludes, are essential for engaging in the Hindustani musical tradition. Pudaruth further explains that in Hindustani aesthetics, the artistic experience entails reaching a unique emotional state called *Rasa*. The *Rasa* is differentiated from a more daily experience of emotions in that it allows the beholder to experience the emotion in full, thus inducing a euphoric or ecstatic feeling of bliss. In those moments, the beholder becomes unified with the art form: there is no separation between knower and known, and there is no egocentric consciousness (Pudaruth, 2016). Thus, Hindustani music focuses on reaching a contemplative, transcendental and even spiritual state of mind.

Instead of the dualistic terms of improvisation and notation (the former does not even exist as a word in any of the languages used in India), McNeil (2017) framed her discussion about Hindi music performance, using the terminology of *Vistaar* and *Badhat,* suggesting feelings of expansion or growth, and *Upaj* and *Andaaz*, emphasizing creativity and novelty. Hindustani music, McNeil explains, incorporates only mild references to fixed structures, or what she conceptualizes as "seed ideas." These seeds are manifested in three possible layers, defined by the raga itself, the song's structure and the rhythmic patterns (*Tala*). Using culinary metaphors, McNeil explained that the challenge of the Hindustani musician is to realize the methods and strategies appropriate to the musical context that will allow them to complete the preparation of only "half-baked" musical materials. In other words, the so-called fixed elements of Hindustani music are only preliminary entities, which are subjected to varied interpretation and manifold possibilities to evolve. McNeil's conceptualization of seed ideas not only serves the author in establishing strong arguments for understanding Hindustani music within an appropriate language and cultural context, but also helps distinguish this type of musical creativity from Western improvisation. As specified by McNeil, the *seeds* are present in the performance from the very start and are raised to their mature, developed potential, through the creative process unraveled by the musician, a process of expansion and growth. On the contrary, in Western music, musical elements such as the harmonic and melodic structure do not function as encapsulated primary forms, only waiting for the musician to bring them into life (hence the seeds) but reveal themselves as fixed musical structures that the musicians can play around with, stretch, expand, rebel and work against, to a certain extent (Berliner, 1994; Monson, 1996; Hadar and Amir, 2021).

Jazz

Jazz was born in the U.S. in the early 1920's, featuring a musical approach that highlights improvisation and creative processes, and specific artistic styles that include structural, rhythmic, melodic, harmonic and timbrical elements influenced partially by African American religious music (Lewis, 2002). It is important to note that not all jazz styles have the same emphasis on improvisation. The basic ingredients of a jazz tune (known as a standard) include: (1) a melody (usually referred to as head), and (2) a harmonic progression, usually referred to as changes (Berliner, 1994). The rich repertoire of jazz standards incorporated a diversity of musical influences, such as spirituals, marches, rags and popular songs (Berliner, 1994).

The common approach to a standard is playing the head in the opening and closing of a performance and playing solos in between, usually rotating between all members of the band. This, however, is only the basic way jazz players use the standard for their improvisatory exploration. The basic structure itself is often altered and personalized by the players, and even by the same player, after performing the same piece for many years (Berliner, 1994). For example, players often change the tonic (i.e., choose a different key to elicit new timbres), or occasionally alter the melodic feature to add more tension or to create different instrumentations. In addition, players make subtler changes to the basic structure, by using repressed or exaggerated vibrato; emphasizing slurring or tonging; adding accents in different places and finding novel sounds and timbres with their own instruments. Thus, jazz combines structure with improvisational content. The improvisational *solo* represents the main platform for freedom and exploration, and the structural choices hold a level of flexibility and a means for the musician to personalize their performance (Berliner, 1994).

In her expansive investigation of the music of African American culture, Monson (2007) established important links between the musical genre of jazz and the consolidation of the cry of Black people for equity and recognition. Monson poses critical questions such as:

> "What effects, direct and indirect, did the struggle for racial equality have on aesthetics, the sense of mission musicians brought to their art, the diversity of music played and composed, and the symbolic meanings attached to the art form? What role did world affairs, especially African independence and anticolonialism, play in how African Americans came to envision their political and cultural liberation? In what ways did the ideas of aesthetic modernism mediate between music and politics?" (p. 4).

Thus, jazz has played an important social role of bringing forward the voice of African American people to the forefront of the musical scene (Bailey, 1993; Berliner, 1994; Monson, 1996, 2007). However, it seems that another form of improvisation, free jazz improvisation, was necessary for breaking through musical norms and past traditions.

Free jazz improvisation

In free jazz improvisation[1] performers do not establish any pre-determined frames or idioms to guide their joint playing. Free jazz improvisation evolved during the late 1950's, as a post-war tradition (Pras, 2015) that rejected former jazz conventions, such as bebop, New-Orleans jazz and swing (Lewis, 2002; Pras, 2015). Those years set a historic landmark in the evolution of improvisation, and a point of intersection of culture, history, and music (Lewis, 2002). The tension between two social sectors gave rise to the novel trend: one representing African American culture, where jazz had originated; and the other subscribing to Western European movements, attempting to elide the fundamentality of Black culture to the formation of free jazz improvisation (Lewis, 2002). Within this heated atmosphere, the new musical genre was conceived as a strong rebellious musical medium (Lewis, 2002; Pras et al., 2017).

These significant years had a worldwide influence on the state of jazz and improvisation, leading to free jazz improvisation being incorporated and integrated into different musical traditions (Fischlin and Porter, 2020). Fischlin and Porter (2020) provide an international

1 For the purpose of the current research, we treated "Free jazz improvisation" in its ultimate manifestation: as freed from any musical idiom or convention. We wish to acknowledge that along its evolution, this genre grew to incorporate various musical expectations, both from the audience's perspective, as well as from the players themselves (Pras, 2015). However, as in the rest of this study, we focused on the salient tendencies of this genre, with the intent to capture the underlying social structures associated with it.

and multi-cultural view of how societies dealing (present and past) with colonialism, war and trauma use improvisation to build their independent voices and sense of freedom in a reality of terror and domination. Emphasizing the association between improvised musical genres and marginal socio-economic sectors of society, the authors capture the powerful strategies improvisation offers minorities to resist and fight oppression and hierarchal social structures.

In their collection of essays (Fischlin and Porter, 2020), the authors describe varied communities around the world, where improvisation was used as a strategic tool to provide individuals with an opportunity to reflect on the social structures perpetuating their ongoing suffering. Through the artistic practice of improvisation, they explain, people might find novel ways to express themselves and broaden their horizons, within restrictive and difficult environments, or in the authors' words, improvisation elevates "the responsibility to act creatively and in concert with others to reclaim a public common under attack" (p. 11).

Zim Ngqawana's Exhibition of Vandalism (Vos, 2020) for example, invited the audience to experience the consequences of social-political realities in South Africa, through engaging in a healing ritual of musical improvisation, a musical ritual that concurrently emphasizes destruction, reconciliation and growth. In this improvised response to vandalism, the players played both intact and vandalized instruments together, thus representing the distorted and convoluted social situation faced by the musicians. It should be noted that while free jazz improvisation seems to emphasize the individual and, at times marginal voices of society, and to promote modernism and breaking of rules and norms, other modes of improvisation also exist, such as from East Asian origins, which seem to highlight, instead, the musician's connections to their cultural traditions. For example, when a musician performing classical Indian music is adhering to the sacred structure of the *raga* their playing (Pudaruth, 2016).

We commenced our paper by describing the complex histories of four musical genres (i.e., Western classical; Hindu music; Jazz; and Free jazz improvisation), while highlighting salient social intricacies pertaining to each genre. In the following part we will further deepen our examination of the social layers embedded in each musical genre. We will first set the stage for our central discussion regarding the social aspects of musical interaction (i.e., 'A social lens to music'). We shall then focus our discussion on the social components as reflected in the genre's placement along a continuum ranging from orally transmitted and prearranged music, to improvisational traditions. Next, we will introduce the Tight-Loose (i.e., T–L) framework, which we will deploy to examine the possible social meanings underlying various musical styles. In this respect we will specify four societal parameters, which capture the music's behavior along the T–L continuum (i.e., structural sparseness; flexible social roles; cultural nonconformity; and creative freedom). Finally, we will summarize our findings in a Table 1 and discuss different possible consequences of the genres' level of T–L on the social dynamics afforded between musicians (e.g., common group membership vs. tolerant group membership).

A social lens to music

Though music is a social phenomenon, deeply embedded within a social and a cultural frame (Small, 1998; Cross et al., 2019) some historical and musicological accounts tend to treat music as a stand-alone, independent experience, not acknowledging to a sufficient extent its intricate ties with human histories and social events (Small, 1998; Taruskin, 2010). Nevertheless, many theorists examined various social aspects of music from different perspectives and foci (Small, 1998; DeNora, 2003; Finnegan, 2007; Taruskin, 2010). Small's theorization regarding musical performance as representative of larger social dynamics, is highly pertinent to the social lens we apply in this article. Small argues that the mere concert hall venue already establishes a set of hierarchies and sub-groups by inviting a very delimited and elite part of the society and by separating the audience and players in a precisive way: seated in different parts of the hall and even entering and exiting the hall from different doorways, depending on the type of ticket purchased. Small (1998) compared between the social event of contemporary classical music (i.e., taking place in prestigious concert halls) to the completely contrasting close and intimate social event created in Rock festivals during the 1960s and 1970s. While the former gave rise to strangers sharing a physical space, yet remaining distant and alien to one another, the latter enabled new societies to evolve: groups of people who immersed in the music and with one another in a boundless and free manner. Most relevant to this piece is Small's assertion that "those taking part in performances of different kinds are

TABLE 1 Portrayal of each musical style according to 4 categories of social tightness/looseness and the average score reflecting overall looseness.

	Western Classical	Indian Classical	Jazz	Free Jazz Improvisation
Structural sparseness	•	●	•	●
Flexible social roles	•	•	●	●
Cultural nonconformity	•	•	●	●
Creative freedom	•	●	●	●
Overall looseness	•	●	●	●

looking for different kinds of relationships, and we should not project the ideals of one kind of performance onto another" (Small, 1998, p. 49), featuring Small's fundamental belief that different social values underlie diverse musical performances.

In a similar vein, Finnegan's (2007) seminal work set forth the social and political structures of amateur, local music making, as reflected in a case study of the musical culture of the British city of Milton-Keynes. Through a detailed examination of the town's musical life, Finnegan uncovers the strong social structures shaping the seemingly mundane musical events, which allow the local musicians to connect to their heritages and tradition on the one hand, and to influence the social changes and growth on the other.

Various authors among both Hindustani and Carnatic musical traditions discussed the social (Weidman, 2012) and political (Alaghband-Zadeh, 2017) representations embodied in Hindu music. Weidman (2012), for example, provided an ethnographic point of view, when reflecting on her experience of learning Carnatic music as an apprentice of her violin teacher. Such unique mode of relating, she explains, enables implicit knowledge of class, gender, and social identity to be learnt by the apprentice on sensorial and bodily levels, transcending musical mastery *per-se*. In relation to Carnatic music scholarship, Weidman accentuates the tacit knowledge of values such as social belonging, social hierarchies, and power imbalances, conveyed through the apprentice-music teacher relationship.

Several writers highlighted the unbreakable link of Jazz and free jazz improvisation to underlying social dynamics (Heble, 2000; Gazit, 2015; Liberatori, 2019). Heble (2000) presented his evolutional course of thinking of jazz playing as embedded in social structures. Firstly, Heble emphasized (mainly) black people's ethnical and political motivations as giving rise to jazz and free jazz improvisation, as part of their social struggle for becoming emancipated from the control, hegemony and expectations of white men. However, later, the manifestations of these improvisational genres became postmodern attempts to abandon any ethical responsibility towards the audience. In that sense, Heble understands free jazz improvisation as promoting an isolation of previous social expectations. Moreover, he accentuates the ability of jazz and free jazz improvisation to evoke novel musical forms and expressions, which possibly, eventually may subscribe to alternative social forms and dynamics on their own.

Interestingly, the establishment of music therapy as a profession in the 40s and 50s of the 20th century gave rise to numerous perspectives about the social and psychological aspects of music (Bruscia, 1998; Aigen, 2005). One important more recent theoretical contribution relates to the use of music in everyday life (Ansdell, 2014), and music's inseparable connections to people's social lives, and to the centrality of Community Music Therapy (CMT) (Stige et al., 2010). CMT focuses on the contextual and ecological meanings of music therapy, unravelling its social-cultural centrality beyond and above the music therapy room.

We will now turn to contextualizing our discussion within a musical spectrum stretching from prearranged and orally transmitted music, to highly improvisational and free genres.

Prearranged vs. improvised music performance

In accordance with different ideas about music as deeply situated within the social matrix of life, we wish to examine the social dynamics of music performance as a consequence of the specific musical tradition it embodies, along a continuum, ranging from fully orally transmitted or notated, pre-composed and pre-arranged music to fully improvised. Although this continuum does not include all characteristics of each genre and is not central to all genres, we believe it is essential for the understanding of the social components afforded by musical interaction. Inspired by different researchers who placed different musical traditions along this continuum, [e.g., Nettl (1974) who studied improvisation or Moran (2017) who focused on the cognitive aspect of orally-transmitted compared to improvised performances], we similarly, place varied styles of performance along the orally transmitted-improvised spectrum, which assisted us in identifying key social components on which we center our discussion.

Prearranged music

In Western Classical Music, prearranged music consists of performers communicating the semantic structures and identified features (e.g., themes, idioms, dynamics) of an existing musical piece (Thom, 2020). In this sense, according to Thom, the performer is expressing not only their individual musical intentions, but to a large extent also the composer's original intentions, executing the piece in a recognizable manner. Thom (2020) further suggested that Western classical music entails close adherence to the performance plan, and rapid and decisive return to it in the event of an unintended deviation (e.g., a missed note or a cracked tone during singing). This reflects an underlying value of following the strict rules and orders created by the composer, which are reinforced by audience expectations (Thom, 2020). Indeed, any deviation from the ongoing musical plan will reconfirm the original aim and intention of the composer (as presented in the musical form), through the performer's effort to seek the shortest way to get "back on track."

Such a view of music as a formal form of art *per se* independent of any extra-musical context can be traced back to the Romantic era. This resulted in music becoming aligned as 'artwork' with its earlier predecessor, the plastic arts (Goehr, 1994). Goehr explained that these advances in the 18th century had two main influences on the artistic evolution of music: (1) music became independent of extra-musical contents such as religion, and began to be defined and understood as pure art; (2) musicians shifted their emphasis from mere "performance" of music (which could adopt different styles and purposes) to the final product (i.e., composition) of the artistic form, the artwork, submitting to the standards of the plastic arts.

The significance of music being divided into distinct and separated categories of "artwork" (compositions) and "performance," focusing mainly on the finalized concrete object, is highlighted by different thinkers (Moore, 1992; Bailey, 1993; Goehr, 1994; Small, 1998; Benson, 2003; Thom, 2020). Moreover, Goehr further argued that all musical genres nowadays are framed within the context of "artwork" regardless of how they were initially conceived or if their originators considered themselves as composers. For example, in Baroque music, many pieces incorporated significant improvisatory sections, which during the 19th century consolidated as finalized compositions or as "artworks." Only few musicians to date practice and perform improvisation in Western Classical pieces (e.g., Dolan et al., 2013). According to Goehr, John Cage's famous piece 4′33, for example, was not intended by the composer as a precomposed musical work, but rather as a musical performance which bared metaphoric and conceptual significance.

Improvisation

As opposed to prearranged music, musical improvisation consists of the instantaneous and spontaneous creation of music. Improvisation may exhibit varied degrees of musical freedom: from the expansion of existing prearranged musical elements to the generation of a new piece altogether on the spot (Nettl, 1974; Bailey, 1993; Berliner, 1994). The act of improvisation is shared by nearly all cultures and societies (Nettl, 1974; Rommen and Nettl, 2020), and underlies, for example, European vocal and instrumental ornamentation from the 16th to the 19th centuries, Indian ragas, Arab mawals and modern jazz standards.

Though manifested somewhat differently across diverse genres and cultures, improvisation seems to consistently present a certain everchanging balance between tradition and innovation, as stated by Racy (2000):

> "Improvisation constitutes a merger between the familiar and the novel. It is described as an appropriate balance between satisfying musical norm and departing from it, perhaps an intermediary between compliance and defiance. In some traditions, a successful improviser must strive both to be on the innovative or exploratory edge, as well as to pre-serve the authenticity of the music." (Racy, pp. 306–307).

Interestingly, Bailey (1993), who interviewed improvising musicians, noticed that many of them are reluctant to use the explicit term "improvisation," and preferred "playing," sometimes adding the specific idiom of their specialty: "playing jazz" or "playing Flamenco," while others overtly mentioned their avoidance of the term. Bailey ties this behavior with the somewhat illusive, ephemeral, and random connotations attributed to "improvisation," which could undermine for musicians the perceived preparedness, scholarship, training, and investment involved in such practice, according to Baily.

Nooshin and Widdess (2005) claimed that the blanket term of improvisation fails to represent the immense diversity of creative performance styles existing worldwide and embedded in various cultures. Similarly, we argue that the continuum ranging from oral and notated music to improvisation represents different practices in different cultures, and is closely attached to culture-specific social practices, needs and dynamics. To appreciate this diversity, we consider the four example musical traditions reviewed above with respect to the social contexts connected to each genre. Through this analysis we will gain a more refined appreciation of some deeper differences between diverse musical traditions and their social significance. It is important to note that some of the genres incorporate highly diverse types of improvisations and styles, however we shall focus on the central tendencies of each tradition and their respective social structures.

In order to examine the social nature of prearranged versus improvised genres, we shall now deepen our discussion by introducing and incorporating the T–L framework.

The tight–loose paradigm in music performance

As illustrated above, the diverse genres that have evolved of musical performance reflect in many ways the political, cultural and social backgrounds and conditions, within which they emerged. However, it is challenging to compare between them due to the distinct features of each musical form and the complexity of the historical and societal context, in which they exist. In order to better align the intricate social structures underlying musical performance, we adapt the *tight-loose paradigm* used in the social sciences to the domain of music performance (Rabinowitch, 2022) as a framework for analyzing the relations between different modes of musical performance from a social perspective.

Tight–Loose theory (T–L theory, for short) was developed as a means for characterizing the essence of cultural disparities between societies (Pelto, 1968; Gelfand et al., 2011). The theory maintains that although all societies exhibit social norms, some tend to more *tightly enforce* these norms, prioritizing social order and obedience over openness and creativity. Other societies display more *looseness*, exhibiting greater openness and adaptiveness to norm violations (Gelfand et al., 2006, 2021). This single variable has proven to very effectively encapsulate important differences between distinct societies, and to serve as a valuable predictor of a variety of large-scale complex social behaviors and phenomena, as diverse as Covid-19 casualty rate (Azevedo et al., 2022; Gelfand et al., 2022) and religious beliefs (Jackson et al., 2021).

From a musical point of view, we posit that different musical traditions afford varied degrees of tightness/looseness. In particular, we identify four societal parameters, intrinsic to the music, that we suggest determine the level of tightness/looseness within each musical genre. These include *structural sparseness*, *flexible social roles, cultural nonconformity*, and *creative freedom*.

Structural sparseness

Nettl (1974) suggested the term *structural density* to conceptualize improvisation by placing all genres, Western and non-Western, on one continuum, focusing on the density of the pre-structured elements of the improvised performance, or in Nettl's words: "the musical models" (p. 12). While Baroque and Jazz music present a denser appearance of prearranged musical elements, Persian, Arabic and Indian music reveal a more sparse and open presence of binding musical scripts. Nettl argued that while performances incorporating thick and dense structures tend to vary less and enable limited freedom to the performers, performances which lack this kind of density provide more freedom of creativity to the players. Our theoretical analysis refines and expands Nettl's notion of the density continuum. We argue that different modes of performance induce respective levels of social freedom that may extend beyond the musical interaction itself, affecting both listeners and performers. Applying the T–L paradigm to Nettl's structural density concept, suggests ascribing more tightness to musical genres that closely follow pre-determined notation (i.e., Western Classical), and more looseness to musical genres that are structurally more flexible and sparse (i.e., Hindustani, and free improvisation).

While Nettl focused on the density of the pre-determined structural components alone, we wish to expand the density paradigm to include further aspects that relate to the social structures represented in the musical performance. Several studies have discussed the social nature of both notated (D'Ausilio et al., 2012; Keller et al., 2014) and improvised (Robledo et al., 2021) music-making. As a natural operationalization of human social coordination and interaction, the study of musical ensembles provides a powerful opportunity to delve into the foundations of such music-based social behavior (Keller et al., 2014; D'Ausilio et al., 2015).

Flexible social roles

Different musical traditions endow players with varying flexibility in fulfilling their hierarchical role in the performance (e.g., soloist, accompanist, first violinist, second violinist). These roles may be fixed or interchangeable between players. When applying the T–L paradigm to this category, we attribute more tightness to musical genres that pre-determine fixed roles between the players (i.e., Western Classical and Hindustani classical music), and more looseness to musical genres that are more flexible in determining which player plays which part in a certain musical piece. Another aspect of social roles relate to the social class associated with the musical genre. As explored above, various genres are embraced or represented by different social classes in different historical eras.

Cultural nonconformity

Cultural nonconformity can introduce different levels of strictness regarding the level of commitment players are expected to exhibit towards their musical tradition. How far does the musical genre tolerate extending and bending the musical norms while playing or improvising? What are the cultural expectations of the audience? In this category we ascribe more tightness to genres presenting high conformity and commitment to predetermined norms of performance (i.e., Western Classical and Hindustani), whereas genres that support a greater alteration of the original form and harmonic context are considered looser (i.e., jazz and free jazz improvisation).

Creative freedom

The level of creative freedom expressed within the musical experience also varies across genres. Different musical traditions permit or prohibit varying levels of alteration in rhythm, melody, harmony, dynamics, timbre. Applying the T–L paradigm to the concept of creative freedom, we associate more looseness with genres that approve of alterations and innovations on the spot (i.e., Hindustani, jazz and free jazz). In contrast, Western Classical music exhibits more tightness in this respect.

In addition to the four aforenoted social criteria, we wish to introduce another barometer for capturing the nature of T–L among the four musical traditions: Common Group Membership (CGM). The overall depiction for each music style, displayed in the last row of Table 1, provides a relative positioning of that musical genre along the tight-loose continuum, with Western Classical music representing the tightest form of performance, and Free Jazz Improvisation being the loosest. The explicit categorization approach that we have demonstrated allows to use reasoning for performing such mapping, and to make predictions about the extent to which engagement in each musical style may affect broader aspects of social interaction. To illustrate this, we consider CGM as a feature of social interaction and conceive a hypothesis about the degree of CGM expected to be found in each form of musical performance. In other words, we wish to use our theory as a possible explanation for various in-group and out-group behaviors (Cross et al., 2019), and more specifically to utilize the level of T–L associated with each musical genre as a predictor for the quality of CGM. This analysis expands on our previous predictions regarding the effects of joint music making on CGM levels (Rabinowitch, 2022). According to Rabinowitch (2022), while tight aspects of music (e.g., the music's rhythmic structure) can influence musicians' higher levels of CGM (which include both positive and negative effects), it is the looser aspects of music (e.g., interpretation and improvisation) which mitigate the negative effects of CGM (e.g., blind obedience and conformity), and therefore increase the groups' level of Tolerant Group Membership (TGM). We propose that while tighter musical genres are expected to evoke higher levels of CGM, improvisational genres will associate with lower levels of CGM and higher levels of TGM. Later in the discussion, we shall further elaborate on the levels of CGM/TGM afforded by the various musical traditions and genres.

Next, we shall depict the *musical* T–L characteristics (i.e., the societal components) of the four musical genres discussed so far (Western Classical; Hindu music; Jazz; Free Jazz Improvisation). In addition, Table 1 provides a simplified illustration of the quality of each societal component as well as the overall nature of the four societal components (i.e., how tightly or loosely they manifest within each musical genre).

Mapping different musical traditions to tight-loose social tendencies

As an example for how to characterize different musical traditions and compare between them in terms of tight-loose social tendencies we describe a preliminary mapping of different musical styles according to the social parameters we have introduced, positioning them on to the T–L continuum. We portray each of the musical traditions from low to high along the 4 social categories, *structural sparseness*, flexible *social roles, cultural nonconformity*, and *creative freedom* (Table 1). This framing is based on our overall familiarity with the different musical styles and on informal interviews that we have conducted with professional performers from each genre. It thus provides a general qualitative T–L charting of the music styles that could later on be fine-tuned, for example, through questionnaires and expert judgements.

When focusing on the *structural sparseness* of each musical structure, one can notice there is no clear gradient from tight to loose. *Western Classical* performance receives the lowest characterization on structural sparseness due to its closed, notated, and highly restricted form. *Hindustani music*, exhibits more spacious musical structures than *Jazz* music. This is due to the tighter adherence to jazz standards, even during improvisation. Although Hindustani music abides to extremely strict guidelines (e.g., a particular Raga or Makam), most of the musical structures are created on the spot, while referencing the pre-determined musical materials as foundational elements, rather than a form. Free jazz improvisation receives the highest account on structural sparseness, as this genre does not exhibit any pre-determined structural restrictions.

Flexible social roles displays a clear gradient (Table 1), growing from the strictest social roles, manifested in *Western Classical* performance, to the loosest within *Free Jazz Improvisation*. While in *Western Classical music* the roles of musicians are entirely predetermined by their seat in the orchestra or role in a chamber music ensemble,[2] a free jazz improvisation performance does not impose any social restrictions on the players and allows them to continuously negotiate the leadership over the performance. This was nicely demonstrated by Hadar and Amir (2021) who studied joint improvisations between jazz and free improvisors. One of their key findings relates to the wide range of relationships enabled between performers of this genre. Hadar and Amir (2021) specified seven different types of relationships present among jazz and free improvisors, emphasizing the players' tendency to rapidly switch between close intimately, to "fighting" and "teasing" each other on stage.

From similar considerations, we considered *Jazz* performance also high on flexibility of social roles. The lenient roles experienced in jazz performance was highlighted by additional researchers (Berliner, 1994; Monson, 1996; Aigen, 2013) and seems to play a major role in this musical genre. *Classical Indian* performances do not follow pre-specified partitures, thus providing a wider basis for musical choice, also on the social hierarchy dimension. However, following strong traditions and performance conventions, this genre shows a tendency to assign players with the traditional roles ascribed to their instruments, and even when these constraints are relaxed, a clear plan for switching roles is predetermined, and is never spontaneous.[3] Another point to consider relates to the social class, in which the respective musical genre had evolved. For example, while nowadays both Western classical music as well as jazz and free jazz improvisation are associated with elite and bourgeoise parts of society (Small, 1998), the genres originated in quite differing political ecologies. Both Western Classical music and Hindu music originated in religious practices, and to date subscribe to the original musical forms to a certain extent. In contrast, Jazz and Free Jazz Improvisation originated in secular and rebelling societies.

On a different note, one should consider the influence of the players' musical proficiency on the social interaction enabled between them. While this component is relevant to all musical genres to a certain extent, clearly, the more restrictions and cultural conformity the players are subjected to, the greater skill level they have to develop. This subscribes both to the social layers associated with classical genres as well as to the possible competition and feeling of hierarchy and estrangement between the players, as pointed out by Small (1998). Nevertheless, studies about jazz players (Berliner, 1994; Hadar and Amir, 2021) revealed the great emphasis jazz players place on their musical partners' professional level, and their noncompromising on less than top notch musical partners to improvise with. In this sense, it seems that players' skill level is an important factor in all traditions and should be taken into account. In essence, one may think of skills as a catalyst of T–L alignment. We believe that the level of skill presented by musicians is associated with the breadth and depth of their T–L spectrum. Therefore, we postulate that musicians with greater skill will present a broader T–L continuum for the various musical genres they practice.

As for *cultural nonconformity*, perhaps the most striking feature of this dimension is its disparity between being either highly strict and conformist or highly loose and nonconformist (Table 1) among the four traditions. *Western Classical* performance is strongly driven by tradition through clear unequivocal notated instructions, thus appeared as encouraging high conformity regarding cultural expectations. *Hindustani and Carnatic classical traditions* are similarly guided by cultural expectations, perhaps even more explicitly and specifically. This complies with Pudaruth's (2016) description of the complex systems Hindustani players subscribe to when performing their orally transmitted music. Therefore, though differing in many respects, we deem Western Classical and Hindustani music to share a similar level of strong sentiment over their long living traditions, which appropriately accounts for their label as "classical." In contrast, *Jazz* and *Free Jazz Improvisation* can be placed on the other extreme of the cultural nonconformity range, as one of the main characters of jazz performance lies within the players' ability to stretch the boundaries of any norm or tradition, or to completely defy them, as in the case of *Free Jazz Improvisation* (Berliner, 1994; Lewis, 2002; Niknafs, 2013; Schroeder, 2019). We wish to add one caveat, relating to the cultural expectation of Jazz audience regarding the performance's structure (i.e., including solo versus ensemble part). In this sense, although jazz playing grants musicians many degrees of freedom in several aspects of the piece performed (e.g., the melody, harmony, timbre, arrangement), most players conform with the cultural expectation of the structure of the performance, by alternating between solo and ensemble parts, leaving it almost exclusively untouched throughout this genre's lifetime.

When considering the level of *creative freedom* across all four musical genres, we note a sharp contrast between the *Western Classical* genre to all the rest. While Western Classical performance affords the least creative freedom to players, who are autonomous in only subtle musical elements such as dynamics and tempo (Thom, 2020), all other genres seem to incorporate high levels of creative freedom. We posit that *Hindustani music* and *jazz music*, all share a similar level of creativity enabled within their performance. In all three genres the players are expected to provide a constant flow of new musical materials, as the quality of the performance relies greatly on their ability to create novel music in the moment.

While players in *Hindustani* music are in fact composing their piece "in the moment," they are bound to highly strict guidelines which eventually narrow their freedom of musical choice, e.g., the fixed patterns of the Hindustani Tala (Pudaruth, 2016). *Jazz* players, on the other hand experience a greater range of independent exploration while improvising but are yet bound to a musical form

2 In effect, Western classical music presents an abundance of social conditions, and presents a diversity of situations afforded by different types of musical performances (e.g., playing in an orchestra, singing in a choir, or playing in a chamber music group). Nevertheless, we wish to stress that an underlying principle is shared by all Western classical performances today, and that is, they all establish pre-determined roles, and adherence to the (many, changing and complex) social structures determined through the musical arrangement.

3 This was specifically highlighted in personal correspondence with with Anagha Bhat regarding Hindustani music.

(i.e., the jazz standard) that serves as a basis for their improvisation. Ultimately, *Free jazz improvisors* are expected to use their creative resources in full and are expected to create in the moment the form and musical substance in the most free, surprising and novel way they can imagine (Berliner, 1994; Lewis, 2002; Niknafs, 2013; Schroeder, 2019).

Common group membership and musical interaction

Common group membership (CGM) relates to a person's sense of belonging, affiliation, rapport, and obedience to a certain social group, and is known to effect positive social behavior towards group members (in-group) and negative behavior towards non-members (out-group) (e.g., Tajfel, 1970; Branscombe and Wann, 1992). It has been suggested that group music performance entails CGM through, for example, interpersonal synchrony (Tunçgenç and Cohen, 2016; Cross et al., 2019; Bente and Novotny, 2020), the continuous temporal alignment of players according to the rhythmic structure of the musical piece, and their collective focus on a shared beat (e.g., Savage et al., 2021). While CGM may be considered as a positive driving force for prosocial behavior, it may also comprise certain negative sides, such as increased conformism or exclusion of non-group members (Rabinowitch, 2022). We argue that CGM is not fixed and can vary according to the social dynamics present within the interaction. Indeed, a looser attitude could produce a more tolerant form of CGM (TGM), which we term tolerant group membership, entailing a weaker sense of inclusion on the one hand, and high freedom and creativity on the other (Rabinowitch, 2022). Conversely, tighter social interactions may lead to more stringent CGM, entailing for example, strong social bonding and inclusion, but lower creativity and individuality. We thus conjecture that different musical styles could associate with different degrees of CGM. In particular, our analysis predicts that playing Western Classical music, for example, should give rise to stricter CGM among the players, whereas Free Jazz Improvisation should drive CGM towards the more lenient TGM. Other musical styles should have an intermediate effect. Therefore, the impact of musical performance on social interaction is music-style dependent.

Conclusion

Music is a prevalent human activity, extending from deep social roots. We have sketched how different styles and genres of music performance may have emerged from distinct social climates and practices, and have proposed a systematic method for mapping different types of music according to four major dimensions of classification, *structural sparseness*, *flexible social roles, cultural nonconformity*, and *creative freedom*. To this end we have adopted the notion of tight vs. loose adherence to social norms and practices widely used in the social sciences, and characterized each musical form in terms of tightness/looseness, deriving an overall score for each music type along this continuum. This approach enables to compare and distinguish between different musical traditions and styles and their impact on social dynamics, discerning between musical styles that are predicted to elicit tighter interactions (e.g., stricter group membership), such as Western Classical music, and those promoting looser interactions (e.g., tolerant group membership), such as Free Jazz Improvisation. Therefore, music performance occupies a broad spectrum of styles that originate from and evoke a range of fundamental social dynamics.

Further research is required in order to understand how such advantages might be deployed in varied contexts such as music, educational and therapeutic settings. For example, what would be the ideal type of music to encourage creative and independent learning and what musical style would support group work and cooperation? Building on the theoretical notions of this paper, we would hypothesize that whereas styles that are considered as looser on the musical T–L continuum may promote student creativity, other styles that are assumed tighter on the continuum, calling for stricter adherence to musical roles and arrangements, may encourage social bonding and group learning but not creativity or individuality. Several studies imply a connection between playing Western Classical music and a discrete type of social tendencies. For example, Müller et al. (2018) pointed to the prosocial effect and increased levels of in-group cohesion associated with singing in choirs (which mostly perform Western Classical music). Focusing on Western traditions, emphasized the tension between several social and organizational components underlying small musical ensembles, namely stability and change, collectivity versus individuality, and maturity versus emergence (Pennill and Dermot, 2021). Our analysis provides an underlying explanation for the social matrix embedded in such musical contexts, suggesting that playing notated and oral music embodies tighter social structures, which in turn might influence the way music groups behave and develop together.

Interestingly, as specified by Small (1998), while originating in a different ecology, nowadays, (tight) Western classical music exists mainly among privileged, liberal, and democratic societies (i.e., societies which are characterized as loose according to Gelfand et al., 2021). Looser-classified musical genres on the other hand, such as classical Indian music, are highly prevalent among more traditional and tight classified societies. Several explanations might account for this contradiction, one of them, perhaps pertaining to the evolution of music's role in society (Goehr, 1994; Davies, 2001). For example, while classical music seemed to represent the Catholic laws and traditions for many years (Taruskin, 2010), it might have become a privileged and almost individual artistic choice in the current boundless capitalistic musical market (Small, 1998). In other words, the music score remained the same but the musical performance (i.e., Small's concept of *musicking*) might represent different values and uses along its life span.

Conversely, group (Ruud, 1998; Ansdell, 2014) and dyadic (Hadar and Amir, 2021) improvisation has been described by several researchers as a liminal experience, enabling players to establish close relationships, and requiring their acknowledgment of each other's individual identities, in a way that resonate Buber's concept of I-Thou (Buber, 2000). Our study argues that the benefits derived from participating in group improvisation might subscribe to the level of looseness enabled between players, which lays the basis for players' unique and inner voices to unfold. Such processes are also highly pertinent to musical work as described in the music therapy context (Bruscia, 1998; Nordoff and Robbins, 2007; Hadar and Amir, 2021), whereby musical improvisation is utilized to create a unique social bond between client and therapist and to enable clients' individual voices to be revealed. Different conditions and methods might be at play to enable such therapeutic processes, e.g., creating a safe and predictable environment for clients (Bruscia, 1998), engaging in deep listening to clients' sounds, movements, and general expressions (Nordoff and Robbins, 2007; Hadar and Amir, 2021). We argue that a fundamental ingredient for therapeutic progress may be the level of looseness enabled between client and therapist. Moreover, we feel that further research should focus on the dialectical movement between tight and loose components in music therapy, and its significance to therapeutic outcomes in music therapy.

Ultimately, this paper aimed to dissect various social structures embedded within musical performance as reliant on the extent of tightness or looseness of specific social dimensions. We believe that further research could allow greater understanding of the possible social, emotional, cultural, and so forth effects afforded by different performance styles. While one type of performance (i.e., loose) might advance freedom of individual exploration and self-expression, participating in a different style (i.e., tight) might promote feelings of belonging and embracement within a larger group or tradition.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

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Inducing and disrupting flow during music performance

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Flow is defined as a state of total absorption in an activity, involving focused attention, deep engagement, loss of self-conscious awareness, and self-perceived temporal distortion. Musical flow has been associated with enhanced performance, but the bulk of previous research has investigated flow mechanisms using self-report methodology. Thus, little is known about the precise musical features that may induce or disrupt flow. This work aims to consider the experience of flow from a music performance perspective in order to investigate these features and introduces a method of measuring flow in real time. In Study 1, musicians reviewed a self-selected video of themselves performing, noting first, where in the performance they recalled "losing themselves" in the music, and second, where their focused state was interrupted. Thematic analysis of participant flow experiences suggests temporal, dynamic, pitch and timbral dimensions associated with the induction and disruption of flow. In Study 2, musicians were brought into the lab and recorded while performing a self-selected musical composition. Next, participants were asked to estimate the duration of their performance, and to rewatch their recordings to mark those places in which they recalled "losing themselves in the moment." We found that the proportion of performance time spent in flow significantly correlated with self-reported flow intensity, providing an intrinsic measure of flow and confirming the validity of our method to capture flow states in music performance. We then analyzed the music scores and participants' performed melodies. The results showed that stepwise motion, repeated sequence, and a lack of disjunct motion are common to flow state entry points, whereas disjunct motion and syncopation are common to flow state exit points. Overall, such initial findings suggest directions that warrant future study and, altogether, they have implications regarding utilizing flow in music performance contexts.

KEYWORDS

flow, music, performance, attention, expectation

1. Introduction

Flow is a state of total absorption in an activity—in other words, the feeling of losing yourself in the moment (Csikszentmihalyi, 1990). It is a psychological state involving effortless and focused attention, deep engagement, loss of self-conscious awareness, a sense of control over the situation, positive affect, temporal distortion (time seems to pass more quickly), and intrinsic motivation (Nakamura and Csikszentmihalyi, 2014). Flow is experienced in a wide variety of activities, including sports—often referred to as being "in the zone" (e.g., Jackson, 1996; Jackson and Csikszentmihalyi, 1999; for a review see Swann et al., 2012), music listening and performance, writing (e.g., Larson, 1988; Perry, 2009), coloring (e.g., Curry and Kasser, 2005;

Forkosh and Drake, 2017), playing video games (e.g., Cowley et al., 2008; Michailidis et al., 2018), and other such activities that involve concentration, immediate feedback, clear goals, and a match of situational challenge to personal skill.

The flow state is directly associated with well-being, particularly through its engagement of positive emotions and intrinsic motivation (Csikszentmihalyi, 1990, 2002; Delle Fave et al., 2011; Tse et al., 2020; Loepthien and Leipold, 2021). Moreover, flow by definition is an experiential form of well-being, which has been shown to positively predict declarative well-being—e.g., increased positive mood, job satisfaction, or satisfaction with life (Ilies et al., 2016; Habe et al., 2021). In addition to improving well-being and positive affect, flow may be relevant to coping with mental health challenges, including larger challenges such as the current COVID-19 pandemic (Habe et al., 2021). For instance, Csikszentmihalyi (1990) wrote that the ability to turn a stressful or hopeless situation into an enjoyable and agentic flow experience can help us cope with major life tragedies by translating a threat into an intrinsically-rewarding, goal-oriented challenge. Since flow has been found to be related to wellbeing, the purpose of the current study was to investigate the conditions that seem to support induction into as well as interruption from the flow state. As music activities cultivate flow more often than other activities (Lowis, 2002) and musical flow is understudied (Chirico et al., 2015), we chose to study the conditions for the activation and disruption of the flow state while individuals perform music.

In general, the flow literature has informed which types of musical activities involve flow; namely, composition, listening, and performance (Chirico et al., 2015). For example, previous research has provided preliminary evidence that the goal-oriented creative compositional process and a lack of disruptive thoughts fosters flow, and that negative thoughts can bring one out of the flow state. Crafting a composition through therapeutic songwriting results in high levels of flow (Mac Donald et al., 2006; Baker and Mac Donald, 2013). In fact, songwriting flow has been shown to improve clinical therapeutic outcomes for substance abuse patients (Silverman et al., 2016). Even outside of the music therapeutic context, composition creativity has been found to be positively associated with flow (e.g., Byrne et al., 2003). Additionally, another form of composition that induces flow is improvisation. A small, but growing body of work exists on flow and jazz improvisation. For example, one study by Forbes (2020) investigated improvisational jazz singers' experiences of flow in the form of anecdotal interviews, finding that (1) flow occurs when the performance is going in the way the performer desires, and is disrupted by the occurrence of negative or self-critical thoughts and that (2) flow in improvisational music is a deeply meaningful, intrinsically rewarding experience. Another study interviewed 18 jazz musicians and found that jazz flow may be induced by the presence of other group members, allowing one to "become one with the group" (Hytönen-Ng, 2013). Beyond interviews, Biasutti and Frezza (2009) found through self-report questionnaires that improvisational flow is positively correlated with musical practice and with anticipation, suggesting that practice improves the fluency necessary to experience flow. Another body of work in this vein has employed investigated improvisational flow through an interactive music composition machine system, which allows feedback during the creative process, one of the components of flow. Past work has shown that composing through this interactive system is conducive to the flow state for musicians (Nijs et al., 2012a,b).

There has been some preliminary work on flow during music listening. One such study had participants either imagine a situation where they performed a musical piece that was challenging and ambitious for them or a situation where they listened to music, finding that music listening was more highly conducive to flow than music performance (Loepthien and Leipold, 2021). Another listening study by Diaz (2013) found that a mindfulness induction allowed participants to experience higher flow, by allowing them to focus more on listening to music. Additionally, in regards to music listening, Ruth et al. (2017) found that flow is positively associated with liking for listened to radio music. However, apart from the three aforementioned studies, there has generally been very little work on flow in the realm of music listening.

The majority of the literature on flow involves music performance (e.g., Sinnamon et al., 2012), and studies on other musical activities often use performance as a reference point. However, as found by a recent review, these performance studies use varied self-report methodologies that may leave ambiguity in distinguishing the flow mechanisms from their confounds (Tan and Sin, 2021). A major finding from the performance literature is that more impediments to flow emerge in the form of the situation exceeding the performers' skill and in the form of performance anxiety caused by the fear of social judgment. As such, previous work has found a significant negative association between performance anxiety and flow (LeBlanc et al., 1997; Wrigley and Emmerson, 2013; Cohen and Bodner, 2018), and there is some evidence that interventions such as yoga can decrease performance anxiety to increase flow (Khalsa and Cope, 2006; Butzer et al., 2016). Similarly, studies of music performance students found that, since the majority of participants believed that they did not possess sufficient skill to meet the challenge of the performance, they did not find the performance absorbing or intrinsically enjoyable, two of the major conditions of flow (Fullagar et al., 2013; Wrigley and Emmerson, 2013). Interestingly, in the aforementioned study comparing music listening and performance, the authors note that the social-evaluative nature of performance may have impeded flow (Loepthien and Leipold, 2021). However, it is worth noting that the way the authors tested music performance—by inviting participants to think of performing a piece that is ambitious for them (i.e., exceeds their skill level)—already would not likely facilitate flow, since one of the main conditions of flow is a challenge that meets but does not exceed skill level. Indeed, performance context seems to affect the experience of flow vs. performance anxiety. As a further example, Cohen and Bodner (2019) investigated the contextual variables that affect flow and performance anxiety, finding that percussionist professional musicians experienced higher flow and lower performance anxiety than string player professional musicians, and that age is positively associated with flow. Finally, flow during musical performance has physiological correlates—specifically, flow was associated with decreased heart period, decreased blood pressure, and increased respiratory depth and increased heart rate variability (de Manzano et al., 2010). These results suggest that a demanding task like music performance increases activation of the sympathetic nervous system alongside deep breathing, which could be an "indicator of effortless attention and flow" (de Manzano et al., 2010, p. 306).

A recent review found that studies on flow in musical performance primarily have used self-report methods to investigate the psychological conditions of flow (Tan and Sin, 2021). However, the performance paradigms used to induce flow vary greatly. For example, in Fullagar et al.'s (2013) study, participants were asked about their flow during an examination. This led to the authors finding that flow is linked to performance anxiety. However, flow has also been found to be linked to improved performance and effortlessness (de Manzano et al., 2010). This study instead had musicians bring a piece into a non-evaluative lab context and play it multiple times. The striking difference in methodology in the field has led to mixed conclusions about the psychological nature of flow. Another point of interest about the performance literature is the bias towards dispositional flow, rather than state flow (Chirico et al., 2015). Dispositional flow refers to enduring characteristics that make flow more likely to occur, such as having an autotelic personality (Nakamura and Csikszentmihalyi, 2005). State flow, on the other hand, involves real-time external contexts and characteristics that foster flow (e.g., Bakker, 2005). Dispositional flow measures individual differences, from a psychological perspective, though it is less well equipped than state flow to understand external musical factors which may also be contributing to inducement of the flow state. These non-standardized performance paradigms and partiality to dispositional self-report methodologies not only approach flow from a solely psychological lens, but also leave ambiguity in terms of parsing the mechanisms behind musical performance flow. This in turn motivates the present approach of studying the mechanisms underlying flow from a musical analysis perspective.

While there has been some research on what types of musical activities involve flow, there is very little research on the mechanisms that cause such flow to occur. In other words, there is research on when flow occurs, but other studies have not yet empirically examined *how* it occurs. The active process of music performance presents an illustrative opportunity to investigate the flow state through participant-generated music. This methodology allows for the investigation of flow through a different methodology: musical analysis of real time flow moments. There is some previous work on investigating the mechanisms behind flow induction, particularly through the emotional role of music. For example, Marin and Bhattacharya (2013) asked pianists about the valence and arousal of emotions experienced during the flow state, finding that induced high-arousal positively- and negatively-valenced emotions are associated with the experience of flow. However, while this study does take an important look at explaining the *how* behind flow induction, it still approaches the question of flow from a solely psychological perspective, emotions. No study to our knowledge has yet investigated the intramusical aspects that induce musical emotions and thus may induce flow, which is a part of the gap that this study fills. This new disciplinary perspective provides a novel viewpoint to disambiguate mechanisms behind the state of flow.

The aim of this study was to investigate the features that induce and disrupt the flow state. To this end, we conducted two experimental studies to identify the internal and external factors affecting the activation and maintenance of flow through music performance. In Study 1, participants were qualitatively interviewed about a past flow performance experience on the factors that affect when they are in flow. In Study 2, we built upon this paradigm by recording participants' in-person performances, capturing when they went in and out of flow in real time. Study 2 compliments Study 1's qualitative approach by providing quantitative support to the conclusions found in Study 1. Overall, these studies identify musical features that are conducive and disruptive to the flow state.

2. Study 1

2.1. Materials and methods

2.1.1. Participants

Participants were recruited by sending emails to musician listservs at a large West Coast private university inviting them to participate in the study in return for a $20 Amazon gift card. To participate, all participants were asked to provide a pre-recorded performance video where they recalled being in the flow state. Submitted performance videos were recorded on average 3.5 years (SD = 1.7) prior to the study. Retrospective performances were used since Study 1 was launched during the COVID-19 pandemic, decreasing the possibility of more recent performances. Participants were eight college musicians with on average 13.3 years (SD = 5.9 years) of musical experience with different instrumental specialties, including voice, violin, viola, cello, electronics, and electric and acoustic guitar. Three of the participants were male and five were female. Performances include three solo, and five group events. Additionally, six of the performances were in front of a live audience, while two were private events. The average length of performance was 12.5 min (SD = 12.6).

Consent was obtained from all participants and research was approved by the Institutional Review Board at Stanford University.

2.1.2. Procedure

Participants answered open-ended questions through a Qualtrics survey about their performance and flow. Through the survey, participants submitted and reviewed a self-selected, pre-recorded video of themselves performing. They were asked to note where in the performance they recall "losing themselves" in the music (i.e., when they became so absorbed in the music that they stopped being consciously aware of their performance) as well as noting the timestamps where their focused state was interrupted. Participants were then invited to reflect on their performance and comment on any recollections or thoughts for the specific timestamps they provided. Additional demographic questions regarding participants' performance background and experience were collected to ensure that the participant was well-versed in the performance of their instrument, which may be a precondition to experiencing flow.

2.2. Results

The videos and responses were viewed and qualitatively coded for flow conditions at each timestamp where the performer indicated that they were brought in and out of the flow state. A thematic analytic approach of qualitatively identifying overarching flow condition themes was conducted in order to determine what factors participants identified as influencing and disrupting flow in real time. We adapted the methodology delineated by Vaismoradi et al. (2016) in this analysis. The qualitative analysis was performed by the first author, with support from the third author, both of whom have expert music theoretical and performance expertise. The three main stages of theme development in qualitative content and thematic analysis we performed are as follows: (1) Initialization, involving reading responses and highlighting recurrent meaning units, conceptual and relationship coding and looking for abstractions in participants' accounts, and writing reflective notes on observed patterns; (2) Construction, involving classifying codes by common meaning, comparing links between code patterns to delineate overarching themes, and labeling categories of code patterns; and (3) Rectification, involving cycles of correction to the themes, and relating themes to established knowledge to contextualize the findings in the broader literature. This qualitative analytic approach allowed for the attainment of rich data that suggest both avenues for future research as well as a starting basis for understanding the mechanisms behind reaching and maintaining the flow state. The conditions found to induce flow and the conditions found to disrupt flow will be reported and connected to the existing literature. Flow inductions and disruptions will be grouped by (1) musical conditions and (2) performance conditions.

2.2.1. Flow inductions

Participant reports indicate that conditions conducive to flow include (1) crescendo and decrescendo dynamics, (2) temporal distortion/agogics, (3) memorization, (4) improvisation, (5) a lack of anxiety and mistakes, and (6) performers' emotional connection to the section. Figure 1 depicts the different themes identified in the data. The left column shows that these themes fell into two categories: (1) Features of the music that bring attention to the present moment (swelling dynamics, rubato/performance agogics), and (2) Factors that reduce potential for external or performance disruptions (memorization and improvisation, a lack of anxiety or mistakes, emotional connection to the music). Each of these themes will be discussed in turn in relation to the current literature. See Supplementary material for thematic analysis.

2.2.1.1. Musical factors that induce flow

There were two musical factors found to induce flow: Dynamics, and Performance agogics.

Dynamics were a common theme in inducing flow, specifically moments of a musical piece that "swell" (crescendo and then decrescendo, going from forte to piano). For example, one participant noted that their "intensified flow moments … rel [y] on a severe dynamic drop from crescendo to piano." The existing literature has not examined dynamics specifically in terms of flow, but it has pointed to a relationship between dynamics and emotion, of which is a component of flow. Kamenetsky et al. (1997) found that variations in dynamics resulted in increased perceived emotional expressiveness. Additionally, Gabrielsson and Juslin (1996) found that happy and sad/tender musical expressions involve rapid or slowly increasing volume respectively, as seen in the crescendos (swells) noted by this study's participants. Such "swelling" dynamics may induce flow, since they can elicit the positive emotion characteristic of flow.

Another identified theme was agogics—places where time and stress are used as emphasis for particular notes. For example, one participant wrote that they "tend to get much more 'elastic'" with their playing when in flow, referencing their use of agogics. Like dynamics, performance agogics have not been studied in terms of flow. However, Rosenblum (1994) conveys how rubato is associated with emotional expressivity. Therefore, it may be that emotional expressivity through rubato is related to the positive mood characteristic of flow.

2.2.1.2. Performance factors that induce flow

There were four performance factors found to induce flow: Memorization, Improvisation, Having no anxiety about mistakes or technical spots, and one's Favorite part of piece/emotional connection to section.

Memorization was found to increase the likelihood of experiencing flow. As an example, one participant wrote that they "try to learn [their] music by heart and let it become instinctual," since doing so helps them with "nerve management" and giving "a moving, heartfelt, and present performance." Previous studies have found that lower heart rate variability during working memory-and attention-demanding tasks such as performance can indicate lower mental effort, which in turn relates to the effortless and focused attention of flow (Bruya, 2010; de Manzano

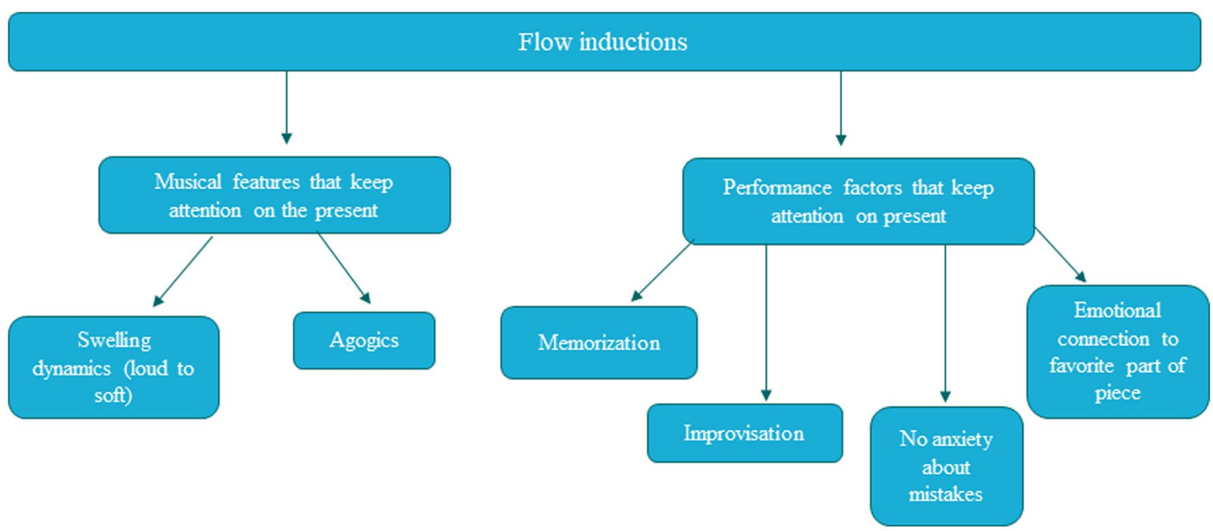

FIGURE 1
Thematic analysis of factors conducive to flow for participants.

et al., 2010; Keller et al., 2011) Therefore, reducing the demand on memory in performance may be a mechanism by which memorization increases the likelihood of reaching flow. Additionally, increased practice reduces later performance anxiety (Norton et al., 1978). Thus, the high amount of practice required to memorize a piece may also increase comfort and decrease the likelihood of flow-disrupting mistakes.

Participants also identified improvisation as a factor that induced their flow. In fact, one participant who performed in a group with a dancer said, "I lost myself when my improvised music became somehow one with the dancer." Some jazz literature discusses improvisatory flow. Mistakes disrupt flow, but improvisation has the special performance capacity of being "able to re-frame mistakes as further fodder for improvisation" (Forbes, 2020, p. 798). In other words, improvisation, as found in the present study, may lessen the impact of mistakes on attention, thus facilitating flow.

Another factor that induced flow was a lack of performance anxiety about mistakes. For instance, one participant wrote, "I did not worry about technique or about producing a mistake … [t] he audience disappeared and it felt as if I were singing through my cello." Previous literature indicates that flow is more likely to occur when the performance "goes well," that is, goes in the way the performer desired (Forbes, 2020). Additionally, the same study found that mistakes disrupt attention and flow, and thus the lack of these mistakes in a performance going as desired is conducive to flow. Thus, the theme of a lack of mistakes or anxiety detected in this study fits well with the existing literature.

Finally, emotional expressivity was identified as key to flow. One participant, for example, indicated that their flow "seems to correspond with [their] bias (favorite part of the piece)." Accordingly, previous research has found that performing one's favorite musical style is more conducive to flow regardless of what that favorite style is (Marin and Bhattacharya, 2013). Thus, the theme that a section being a performer's favorite makes it more conducive to flow reflects an extension of the previous literature.

2.2.2. Flow disruptions

Participants reported several factors that disrupt flow: (1) Sudden melodic, harmonic, and dynamic changes, (2) intonation/frequency abnormalities, (3) anxiety about physical or technical aspects of performance, (4) mistakes, and (5) feeling out-of-sync with group members. Figure 2 shows the different themes identified in the data. The left column again shows that these themes fell into two categories: (1) Violation of musical expectations (melodic/harmonic/timbre/dynamic changes in the music), and (2) Violation of performance expectations (intonation issues and feeling out-of-sync with group members, mistakes, and anxiety). Each of these themes will be discussed in relation to the current literature. See Supplementary material for thematic analysis.

2.2.2.1. Musical factors that disrupt flow

There were two musical factors found to disrupt flow: Sudden melodic, harmonic, and dynamic changes, and Intonation and being out of tune.

Any surprising melodic, harmonic, and dynamic moments in the music disrupted flow. For example, one participant noted that the moment that took them out of flow was an "abrupt transition from a dimming note to a clash of roaring chords." While the relationship between flow and melody, harmony, and dynamics has not been directly studied, previous research has indicated a relationship between dynamics, melody, harmony, and attention, of which is a significant factor of the focused flow state. Dynamics are one of the most salient factors that attract attention when listening to music (Macleod et al., 2009), and nonmusicians and musicians are sensitive to dynamics and melody in music (Geringer and Madsen, 1995) as well as harmonic expectations (Loui and Wessel, 2007). Therefore, since dynamics, melody, and harmonic changes seem to attract our attention, unexpected changes in these musical features may draw attention away from the focused state of flow.

Intonation was another factor that was found to disrupt flow. As an example, one person indicated that it was a "slight error in intonation" that brought them "back into awareness." Previous research has not studied the relationship between intonation and flow specifically, though work on modes of listening has found that intonation is one of the factors that caught listeners' attention when listening to orchestral performances with focus (Macleod et al., 2009).

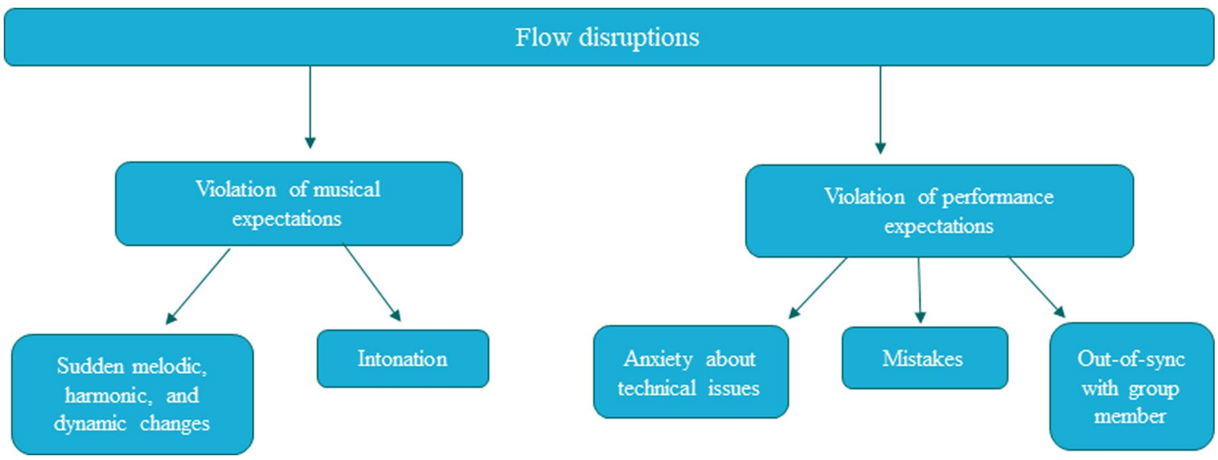

FIGURE 2
Thematic analysis of factors disruptive to flow for participants.

Thus, it may make sense that mistakes in intonation, as an attention-drawing mechanism, could bring someone out of the flow state.

2.2.2.2. Performance factors that disrupt flow

Having anxiety about upcoming technical or physical aspects disrupted flow. For instance, one participant wrote, "What brought me out of flow was probably my own fear of a difficult part coming up… I came back to reality because I had to convince myself that I could get through it." Previous studies have found that anxiety over musical accuracy disrupts flow (LeBlanc et al., 1997; Fullagar et al., 2013; Wrigley and Emmerson, 2013). In accordance with this literature, the present study found that anxiety over future technical areas disrupts attention on the present moment and thus disrupts flow.

Making mistakes while performing also was found to draw attention away from flow. One person alluded to this by saying they "flubbed a note" that "forced [them] back into the performance context," thus disrupting their flow. As aforementioned, mistakes can catch attention and disrupt flow (Forbes, 2020). Therefore, the theme of mistakes disrupting flow aligns with previous work on the dynamics of musical flow.

Disruptions to group dynamics were also found to disrupt the flow state. For example, one participant wrote, "I completely forgot the structure of the piece and was just thrown off when the vocalist entered and just continued soloing instead of moving back into the harmony." In terms of the literature, group dynamics in flow experiences is a relatively new field of study, though a pilot study by Hart and Di Blasi (2013) found that the combined flow results from getting into the "group groove." Furthermore, a single mistake by one performer can knock the group out of its "groove," (Hart and Di Blasi, 2013). Therefore, it may be possible that one performer feels the group groove while others do not. Interestingly, group flow is distinct from individual flow, where group members may or may not be experiencing flow at the same time (Nakamura and Csikszentmihalyi, 2005). Thus, in the case of ensemble performances, disruptions to synchronicity, as found in the present study, may impede flow.

2.3. Discussion

Study 1 investigated real-time flow during music performance by having performers retroactively report where in the video of their performance they went in and out of flow. This allowed for the identification of the factors that affect entering and maintaining the flow state. These factors are associated with previous findings in the literature and suggest a number of situations that warrant future study.

It may be that music in line with canonical expectations does not break the performer's concentration and attention, allowing for the intense focus characteristic of flow. Previous literature has found that music in line with listener temporal expectations enables selective attention (Nobre and van Ede, 2018). In this same vein, our study found that musical features that are in line with expectations are conducive to the flow state, suggesting that the mechanism by which these features modulate flow is through attention. Furthermore, our study found that the activation of the emotional component of flow by musical factors such as dynamics and rubato is conducive to flow. As such, musically-induced emotions during a performance may be conducive to flow experience. This result supports Marin and Bhattacharya's (2013) finding that self-reported high-arousal emotions are positively associated with the flow state. As such, future research should investigate the affective arousal that the musical features of flow (e.g., dynamics) invoke to understand the affective component of flow from a music feature-analytic perspective. As Marin and Bhattacharya (2013) also found that individual difference variables such as emotional intelligence are associated with flow, it would be interesting for future research to investigate how trait individual differences interact with specific musical features in terms of inducing the affective component of flow. Additionally, future research should investigate if these affective characteristics of music induce flow in additional domains beyond performance, such as music listening. There is no work to our knowledge that identifies dynamics and rubato, both musical features, as aspects conducive to flow. However, previous literature does support that such features modulate attention (Macleod et al., 2009). Thus, the musical features identified in this study may modulate attentional aspects of flow. Lastly, factors that decreased the likelihood of attentional distractions in the form of mistakes (i.e., improvisation and memorization) also made flow more likely to occur. This result supports the literature's previous findings that flow occurs when a performance "goes well"— in other words, the performance transpires as the performer expects (Forbes, 2020).

In a similar vein, it may be that anything that violates canonical performance or musical expectations (e.g., intonation errors, melodic, harmonic, and dynamic surprises) draws the performer's attention away from the moment and results in them leaving the flow state. Previous work on violation of expectations indicates that violations of expectations create emotions in music, which may in turn disrupt the emotional component of flow. For instance, Meyer (1956) proposed that musical emotions are formed on the basis of fulfilled or suspended musical expectations, in other words, that the confirmation and violation of musical expectations produces emotions in the listener. Along with the aforementioned findings that the violation of expectations has been shown to attract attention (Janata, 1995; Loui and Wessel, 2007), new or unexpected harmonies lead to specific psychophysiological reactions such as shivers (Sloboda, 1991). Thus, it may be that the violation of expectations can disrupt flow.

Limitations include that this study involved only eight college musician participants, and thus may not be generalizable to other larger contexts, such as non-college musicians or nonmusicians. Further research beyond the anecdotal evidence provided by these eight participants will thus be necessary for generalizability. However, this pilot study was a necessary step to identify flow factors before the paradigm could be applied more generally to a larger population. Additionally, since six of the performances were in front of live audiences, the pressure of performance anxiety may be a confounding factor to our results, since performance anxiety may decrease with higher familiarity and rehearsal with the piece (Sinico et al., 2012) and with higher flow (Marin and Bhattacharya, 2013). However, performance anxiety may still be present regardless of performance expertise as measured in hours of practice (Brugués, 2011), and thus could affect all participants. We note that in this study, the same themes occurred across participants, regardless of musical expertise and performing in front of an audience. One additional limitation is that there was large variance between the length of the submitted recordings (SD = 12.6 min). While we acknowledge that the variation in performance length is a potential confound of this study, we note that our goal was to elicit flow instances in a naturalistic ecologically valid way, which explains why we see this variability. Future work will investigate temporal dynamics as an influence on flow. A further limitation is that the recordings were created on average 3.5 years (SD = 1.7) prior to the study—years had elapsed between the performance and the study, introducing the possibility of participant error in recalling their thoughts and feelings during the performance retrospectively. However, we note that participants reported that their memories of their flow experiences were strong, and that they remembered accurately when they were in flow. For instance, one participant wrote, "In these moments I only thought about expressing to my fullest." Furthermore, as flow is associated with strong positive emotions (e.g., Croom, 2014; Alexander et al., 2021), and strong emotions are associated with better memory and recall (e.g., Goldstein, 1992; Cahill et al., 1995; Tyng et al., 2017), it may not be surprising that musicians can recall in great detail a past flow experience years later. However, while retrospective recall is a limitation of Study 1, Study 2 addresses this possibility by asking participants to recall when they were in flow directly after performing. Another limitation is that this first study only employed qualitative self-reported interviews, rather than a quantitative data-driven approach. Study 2 will expand on Study 1's paradigm by investigating flow through an in-person real-time quantitative investigation.

3. Study 2

3.1. Materials and methods

3.1.1. Participants

Participants were a sample of 25 undergraduate classical musicians who completed the study in return for £30 in cash. Five participants were excluded from the analysis due to either not experiencing flow (1 participant), or failing to provide complete data (4 participants), leaving a final total of 20 participants. Participant mean age was 20.05 years (SD = 1.23 years). In the total sample, 70% were female musicians, and 30% were male. The total instrumental distribution was 40% woodwinds, 25% brass, 15% voice, 10% strings, and 10% keyboard, including flute, oboe, clarinet, alto saxophone, French horn, flugelhorn, trombone, cello, violin, and piano. Participants had been playing their instrument for an average of 11.25 years (SD = 2.31).

Consent was obtained from all participants and research was approved by the Institutional Review Board at Stanford University.

3.1.2. Procedure

Participants were asked to bring a musical composition that they felt comfortable playing to an in-person session. They first read an unrelated article as a distractor task, and then they performed the piece they brought. The distractor task was included in order to reduce subjects' conscious consideration about whether or not they were in flow while performing. As flow involves focusing attention on the task at hand, bringing attention instead to meta-awareness of whether or not one is in flow could interrupt the flow state. Participants' performances were recorded on video. After performing, participants filled out a Qualtrics survey including a distractor task (reading comprehension questions), the Flow State Scale Short Form (FSS), and an item asking participants to estimate the duration of their performance. Participants then re-watched their performance video and reported all of the places (timestamps and measure numbers) where they recall "losing themselves in the moment" during their performance. Participants then completed demographic questions and submitted a PDF or picture of the score that they played from.

3.1.3. Measures

3.1.3.1. Flow

We used the Flow State Scale Short Form (FSS, Jackson and Marsh, 1996) to operationalize self-reported flow. Participants were asked to fill out the FSS in relation to how they felt while performing. The FSS is a 10-item scale composed of two subscales—one that measures Absorption (4 items; e.g. "I do not notice time passing"), and one that measures performance Fluency (6 items; e.g. "My thoughts/activities run fluidly and smoothly"). Responses to the items are given on a discrete 7-point Likert scale, ranging from 1 = "Not at all" to 7 = "Very much." The Cronbach's alpha for the FSS was $\alpha = 0.87$, which indicates acceptable reliability (Taber, 2017). The scale is scored by taking the mean of all 10 items to get the total state flow, leading to a continuous score. The mean FSS score across all participants is 4.74 (SD = 0.99). Absorption and Fluency subscores were calculated by taking the mean of the subscale items. The Absorption subscale score had a mean of 4.3 (SD = 0.99) across all participants and an alpha of $\alpha = 0.56$, indicating low reliability. The Fluency subscale score had a mean of 5.03 (SD = 1.20) across all participants and an alpha of $\alpha = 0.91$, indicating high reliability.

3.1.3.2. Time distortion

Time distortion is one aspect of flow (Nakamura and Csikszentmihalyi, 2014). In this study, we measured time distortion by asking the participant to estimate how long they spent performing, and we calculated the difference between participants' time estimate and the length of the recording (how long they actually spent performing).

3.1.3.3. Flow duration

We operationalized flow duration as the proportion of time spent in flow, calculated by dividing the total time spent performing by the time spent in flow (the sum of all of the durations of the participant reported timestamps). A proportion of the total performance time was used instead of a flat value since the reported flow time durations varied greatly (range: 5 to 175 s, mean: 46.9 s).

3.1.3.4. Distribution of pitch intervals

One of the most straightforward ways to examine melodies is by looking at the distribution of pitch intervals (the sequence of two adjacent notes in a melody), which summarizes the frequencies of interval categories in a given set of melodies (Vos and Troost, 1989; Thompson, 2013). Thus, we examined the distribution of pitch intervals in three conditions: the measures that participants indicated being lost in the moment (flow condition), the 4 measures preceding the flow condition (before condition), and the 4 measures following the flow condition (after condition) formed each of 3 conditions for within-excerpt comparison (see Figure 3 for an example). These conditions were each transcribed as score files from the participant-submitted scores through MuseScore 3.6.2, after which they were exported into midi files. The midi files were converted into.csv files using the Python library py_midicsv (Wedde, 2023).

Melodies were represented using MIDI notation, which maps each frequency to a positive integer number (e.g., a middle C4 in

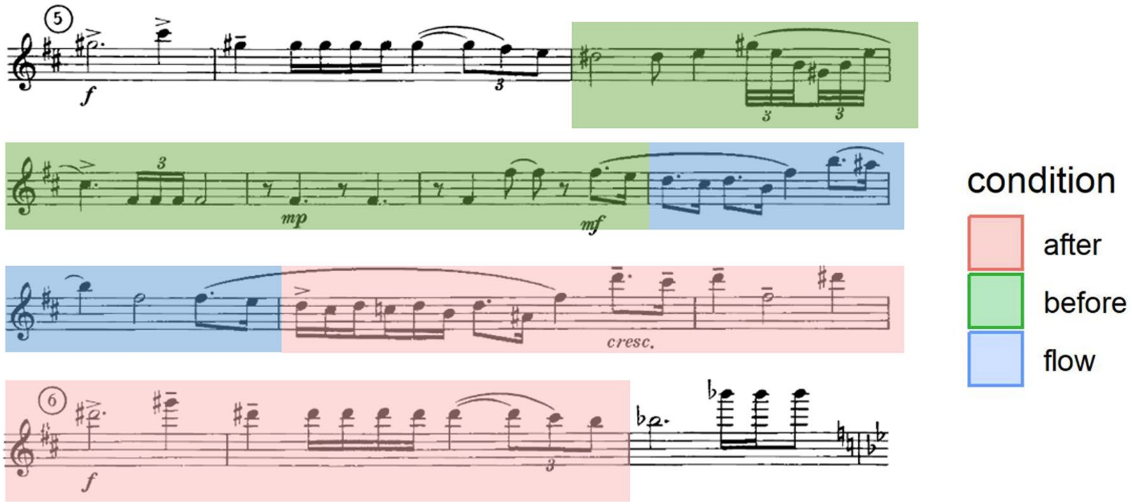

FIGURE 3
Condition annotated excerpt, from Prokofiev Flute Sonata, mvt 1.

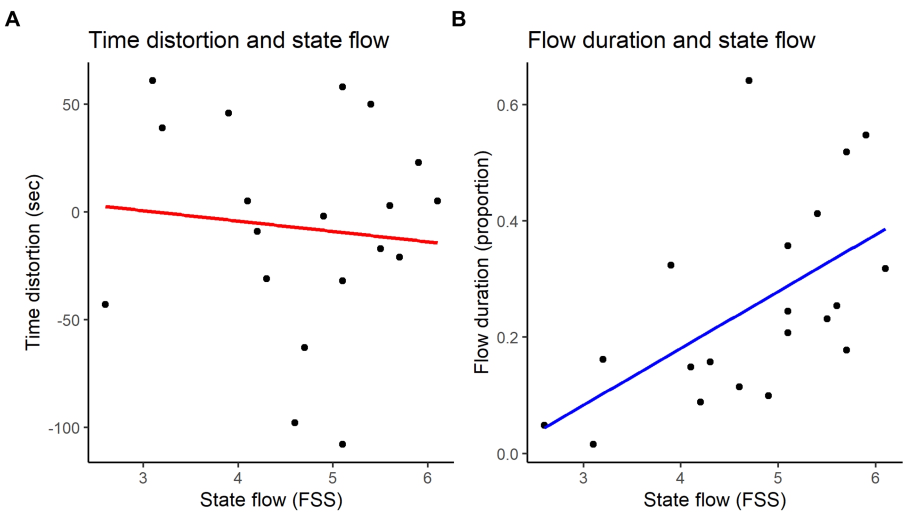

FIGURE 4
(A) State flow is not associated with time distortion (r=−0.100, *p*=0.67); **(B)** State flow is positively associated with the proportion of time spent in flow (r=0.562, *p*<0.01).

a piano keyboard is mapped to the MIDI note number 60). Using MIDI, we can represent melodies using absolute pitch representation (the sequence of MIDI note values that define a melody, e.g., [64, 66, 67, 63, 64]). However, most people represent melodies using relative pitch representation instead (Dowling, 1978), where pitches are expressed relative to each other rather than in absolute terms. Thus, we represented using the sequence of pitch intervals (e.g., [2, 1, −4, 1]). Pitch intervals in each condition were calculated by subtracting each MIDI note value from the preceding one in the sequence of notes making up each melody.

For pianists, only the right hand was transcribed as a melody. Melody flow excerpts reported by participants were excluded if there were not 4 measures on either side of the excerpt that could serve as controls (i.e., if the flow measures overlapped with the before or after of the subsequent or preceding flow excerpt, or if the flow excerpt occurred at the beginning or end of the piece).

3.2. Results and discussion

3.2.1. Flow associations

To study the relationship between self-reported flow intensity and the temporal dimension of flow, we performed correlation analyses using the stats package in R (R Core Team, 2013). The results of flow associations (duration and time distortion) are shown in Figure 4. We found that self-reported flow state (FSS) and time distortion were not significantly associated [r (18) = −0.100, $p = 0.67$]. However, we found that self-reported flow state (FSS) was significantly associated with the proportion of time spent in flow [r

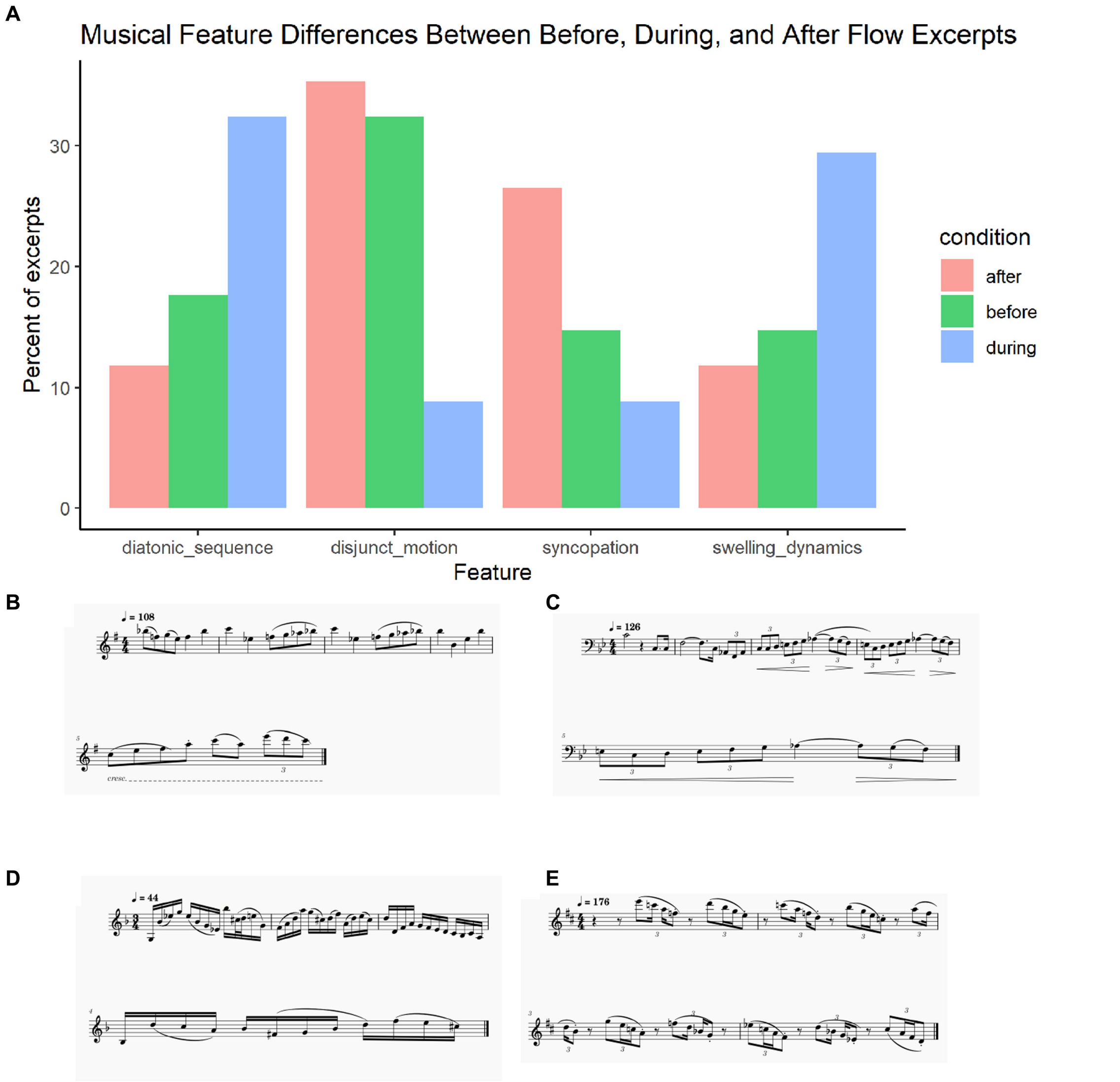

FIGURE 5
(A) Musical feature differences between before, during, and after flow excerpts; **(B)** Repeated sequence during flow, excerpt from Sonatine pour Flûte et Piano by Claude Arrieu; **(C)** Swelling dynamics during flow, excerpt from Concertino for Trombone by Ferdinand David; **(D)** Disjunct motion after flow, excerpt from Concertino for Flugelhorn and Piano, mvt 2 by William Himes; **(E)** Syncopated rhythms after flow, excerpt from Recorda Me by Joe Henderson.

(18) = 0.562, $p < 0.01$]. We then explored further correlations with the FSS subscales (e.g., Engeser and Rheinberg, 2008; Laakasuo et al., 2022) and found that this effect was primarily driven by fluency [r (18) = 0.569, $p = 0.009$]; the subscale absorption was non-significant [r (18) = 0.368, $p = 0.110$]. This finding suggests that the degree, or intensity, of flow in the moment, particularly performance fluency, is associated with the duration of the flow experience. This is consistent with Study 1, which shows that technically challenging parts of the performance disrupt the focus of the flow state, while no anxiety about making mistakes (i.e., performance fluency) facilitates flow. Additionally, the literature points to proficiency in performance facilitating the flow state more so than absorption (e.g., Stupacher, 2019; Spahn et al., 2021); hence, fluency's prominence in this performance study fits with previous findings as well. This finding additionally confirms that the duration of flow is a valid measure of intrinsic flow experience.

3.2.2. Score analysis

Two music theory experts (the first and third authors) analyzed the scores for the before, during, and after conditions to identify qualitative differences in the music features that are conducive to (during) and disruptive to (after) flow, as compared to a control (before). Results were discussed and confirmed as above (see Figure 5A for a summary of feature prevalence across conditions).

3.2.2.1. Flow inducement

The flow state featured a different pattern of repeated melodic sequence (i.e., the repetition of a passage or motif, often at a higher or lower level of pitch), mainly diatonic sequences, compared to the after condition and before condition. See example in Figure 5B.

Melodic sequence in the literature has long been thought of as something that is in line with musical expectations (e.g., Narmour, 2000). Therefore, it could be that melodic sequence confirms canonical

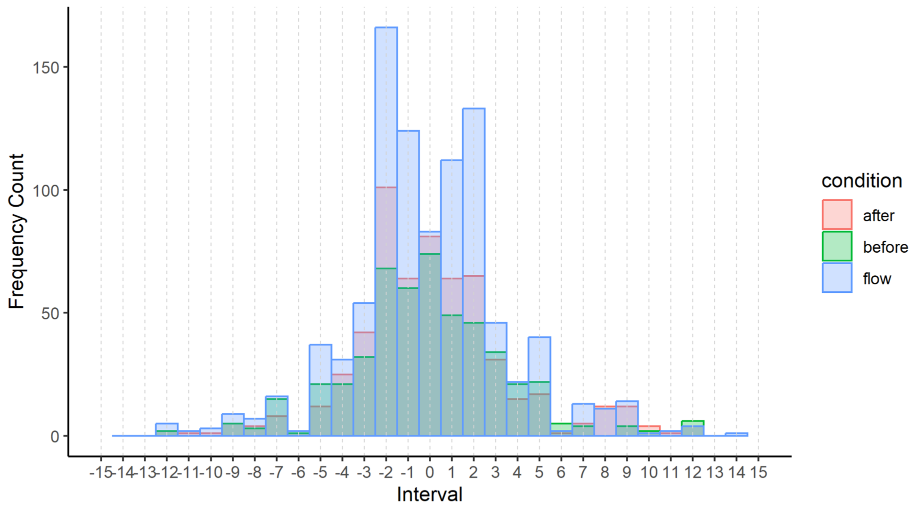

FIGURE 6
Distribution of pitch intervals across conditions.

expectations and does not break the performer's concentration, allowing for the intense focus characteristic of flow, as Study 1 found.

The flow state is also characterized by the presence of dynamic swells with hairpin crescendo decrescendo patterns. This supports the finding from Study 1's thematic analysis that swelling dynamics conduce flow. See example in Figure 5C.

3.2.2.2. Flow disruption

Additionally, flow was characterized by limited salient disjunct motion (i.e., large interval skips) relative to the before condition and the after condition, which was characterized by more frequent disjunct motion. This makes sense in the context of the finding that large unexpected jumps in pitch catch our attention as measured through event-related brain potentials (ERPs), pulling our attention away from the moment (Stefanics et al., 2009). See example in Figure 5D.

The period after flow also featured more syncopated rhythms than the flow state and the before condition. This finding is contextualized by the literature which has found syncopation to be a way of creating tension (Gomez et al., 2005), which may attract attention away from flow. Supporting this, syncopation, as compared to synchrony, takes more effortful attentional processing, activating additional cortical and subcortical regions of the brain (Mayville et al., 2002). See example in Figure 5E.

3.2.3. Melodic features analysis

Since melodic features were described in the qualitative thematic analysis in Study 1, and melodic distinctions (e.g., lack of disjunct motion) were found to characterize the flow condition relative to after and before flow, we performed melodic features analysis on the excerpts, comparing the flow condition to the before and after conditions as controls.

As is visible in Figure 6, there is a higher tendency of smaller pitch intervals (< 3 semitones) in the flow condition compared to both before and after conditions. We therefore performed statistical significance tests in R to identify differences in the proportion of small intervals (< 3) across conditions. Since an ANOVA test assumes that the data are normally distributed and assumes homogeneity of variance, and our data were not normally distributed (Shapiro–Wilk test on the ANOVA residuals was significant, $W = 0.773$, $p < 0.001$) and did not pass homogeneity of variance (Levene test was significant, $F = 3.23$ $p = 0.04$), we used a non-parametric Kruskal-Wallis rank sum test, finding that there was a significant difference between conditions ($p = 0.035$). However, the Kruskal-Wallis test alone does not tell us which groups are different from each other. Therefore, we used a pairwise Wilcox test, finding that flow is significantly different from before flow ($p = 0.019$) and after flow ($p = 0.040$), and before and after flow are not significantly different from each other ($p = 0.654$).

The results revealed that there is a significantly higher proportion of small pitch intervals in the flow condition compared to before and after flow. This indicates a higher degree of stepwise motion in the flow state. This finding provides quantitative support for the finding from the score analysis that flow is less characterized by disjunct motion/interval skips as opposed to the after and before conditions.

In the literature, stepwise motion is widely found to be one of our main melodic expectations when listening to Western music (Cenkerova and Parncutt, 2015). In keeping with traditional musical expectations, computer algorithms that mimic Western composition even use melodic rules such that the generated melody must progress in stepwise motion or, if it jumps, it must continue the stepwise motion from the point where it jumped (e.g., Rader, 1974).

Therefore, stepwise motion confirms our musical expectations, and it follows that breaks in stepwise motion (i.e., disjunct motion) violate our expectations. As such, the finding that the after condition included less stepwise motion indicates that it uses more surprising intervals than the flow condition. Surprising larger intervals and larger melodic jumps have been found to draw attention (Schröger, 1996) and violate expectations (Cuddy and Lunney, 1995). Thus, this melodic analysis result is supported by the literature and additionally provides quantitative support to Study 1's finding that surprising musical features that violate expectations draw attention and disrupt the flow state.

3.2.4. Discussion

This study is the first to identify musical correlates to the inducement and disruption of the flow state. Study 2 built upon Study 1 by supporting the qualitative themes with musical analysis of the scores and of the melodic features. Specifically, Study 2 found that flow inducement often has a pattern of repeated melodic sequences and swelling dynamics, both of which confirm musical expectations and may draw attention to the emotion of the moment, allowing for the intense focus of the flow state. Flow disruption patterns were found to include syncopated rhythms and disjunct motion, both of which take attention and effortful processing, thus disrupting the focus of the flow state. The melodic features analysis results support the conclusions from Study 1 and the score analysis, finding that the flow state is characterized by stepwise motion, which conforms to musical expectations and thus is conducive to flow. This stepwise motion differs from the disjunct motion that characterizes the measures following flow, and it may be that this forms a surprising change in the melody, akin to the theme expressed by participants in Study 1 that surprising changes in the melody disrupted their flow. All of these results point to a main mechanism of flow: that flow is induced when musical expectations are followed, and disrupted when musical expectations are violated, drawing attention away from being in the moment.

It is interesting to note that the duration of flow is positively associated with flow state. This indicates that the duration of flow has to do with the experienced intensity of state flow. Interestingly, multiple participants in Study 1 indicated a period of more "intense flow" compared to other flow states. For example, one participant wrote that in comparison to "general flow," "intensified flow moments are especially musically juicy." Accordingly, this novel flow duration metric may be interesting to consider in further study on flow intensity.

Limitations of this study include that there were a limited number of excerpts and participants, meaning that more research is needed on a larger corpus of excerpts to confirm these musical features' generalizability beyond this sample. We see potential in future studies to find ways to extend this pattern, for example, by conducting a broadly scalable listening experiment to access a larger sample beyond performing musicians. Additionally, future research should investigate musical features of flow through different avenues, such as music composition.

4. General discussion

The present study considered flow during music performance to investigate the musical feature correlates of flow state entry points and exit points. Putting the two studies together, we found that flow inducement involves swelling dynamics, and performance agogics (e.g., rubato) as well as repeated melodic sequences. These features confirm musical expectations and may draw attention to the emotion of the moment, allowing for the intense focus of the flow state. Flow disruption patterns were found to include sudden melodic, harmonic, and dynamic changes, syncopated rhythms, and disjunct motion, which violate expectations and command attention and effortful processing, thus disrupting the focus of the flow state.

Altogether, Study 1 and Study 2 suggest a number of musical-feature situations that warrant future study in the flow literature, as well as propose a mechanism for how musical features affect the state of flow: through musical expectations' effect on our attention and focus. This flow mechanism could also apply to other flow activities such as sports (e.g., Jackson and Csikszentmihalyi, 1999), or playing video games (e.g., Cowley et al., 2008). Auditory expectations in general have evolutionary roots, allowing organisms to identify and evaluate noisy or ambiguous stimuli for danger (see Pearce and Wiggins, 2012). Given the nature of auditory expectations as an evolutionarily-important skill, this expectation-attention flow mechanism may be particularly interesting to study with respect to activities with a strong auditory component like music or sports. However, the broader framework of expectation-attention may apply to other situations (e.g., writing, coloring) as another component related to the challenge-skill balance of flow. It may be, for instance, that we have expectations of meeting the challenge-skill balance during performance, and when those expectations are violated, we break out of the flow state. Future research can investigate this hypothesis further.

Previous studies on musical flow primarily employ self-report methodology (Moneta, 2012), and, accordingly, there is little research on a music-driven explanation of flow—this study is the first, to our knowledge, that investigates flow from a musical feature-analytic perspective rather than a solely psychological perspective (i.e., using music as a medium to study flow more generally rather than as a source of flow). This study therefore is also the first to look into why music is one of the activities that induces flow most frequently (Lowis, 2002).

Flow has been studied using interviews, questionnaires, and experience-sampling methods, and while the latter allows for the attainment of a large corpus of flow moments, it necessarily interrupts the flow experience, a notorious problem in the flow literature (Nakamura and Csikszentmihalyi, 2009). The present studies address this limitation by introducing a method of measuring real-time flow: recording a performance and viewing it immediately afterwards affords a measure of when flow occurred during the moment without interrupting the flow state as it occurs. This is also an important strength of our study given that much of flow research is performed through self-report questionnaires asking participants to recall a distant time or imagine a hypothetical experience (Moneta, 2012). This study presents a new methodological paradigm for investigating musical flow that complements self-report inventories. Accordingly, another strength of the present studies is that, together, they provide a dual and complementary qualitative (Study 1) and quantitative (Study 2) approach, providing methodologically rich data for the novel study of musical features in flow. Additionally, we present a novel method of measuring the duration of flow: quantifying the proportion of time spent in flow. This is, importantly, a more intrinsic measure, thus less subject to potential self-report biases. This measure could be used in future studies on flow, even beyond music performance. For instance, flow duration could be measured in a flow listening study to identify which songs induce flow for more of their relative runtime.

Given that we measured state flow in the present study, future studies could also include a trait flow measure such as the Flow Proneness Questionnaire (SFPQ; Ullén et al., 2012), in order to investigate how the duration of state flow during a specific music performance associates with the trait-level flow experiences during musical activities (Butkovic et al., 2015). It may additionally prove interesting to explore how state flow maps onto trait flow in future work on musical flow.

One limitation of this study is that we did not operationalize the differences between regular and intense flow, a distinction alluded to by multiple participants in Study 1. This is an open question reflected in the literature as well, reported by qualitative interviews as the difference between shallow and deep flow (Moneta, 2010). Future research can investigate this difference further in how it relates to flow intensity, as measured by a participant's FSS score. This study found that spending a higher proportion of time in flow is related to higher FSS, or higher reported flow intensity. This novel measure of flow could be used in future research to investigate the qualitative difference between shallow and deep flow more quantitatively.

Another limitation of this study is that it only investigates flow from the performance perspective. As Chirico et al. (2015) note in their review, music performance may be less conducive to flow than other modes of music engagement (i.e., composition and listening), due to its association with performance anxiety (e.g., Fullagar et al., 2013; Cohen and Bodner, 2018). Therefore, one important next step for future research is to investigate the musical features of flow through other forms of music engagement, such as listening. Music listening also allows the study of musical features of flow to expand beyond the study of musicians (as in the present studies) to the general population.

The present study paves the way for future directions in flow research from the music-analytic perspective. For example, future studies can employ a similar method of analyzing further musical features (e.g., frequency and amplitude of recordings themselves) of self-reported flow through music information retrieval, on a larger sample of participants. Future work also should investigate the direct relationship between musical features that induce and disrupt flow and affect—for instance by asking the participant to report both affect and flow while rewatching their performance or listening to a song recording. Additionally, future work should explore other cultural domains and traditions of music beyond the realm of Western classical music. It will be interesting and imperative to investigate if these musical features of flow are culture-specific or universal aspects of human musical experience.

Overall, this work has important implications for music performance research. Through a novel music-analytic perspective of performance flow, we identified musical features that induce the flow state and musical features that disrupt it. This paradigm paves a new pathway for research into the underlying mechanisms of flow, as well as how they interact with other features of performance, such as attention and affect. Additionally, the findings of this study have practical performance implications. For example, flow inducement features could be implemented in practical performance situations by choosing pieces for performance that involve these features or by adding them in as practical interpretations (e.g., adding dynamic and rubato expression), in order to increase the likelihood of attaining the flow state during performance, and decrease the likelihood of disrupting it. A possible further extension of this work is in music composition: Utilizing these features in composition could potentially create more flow-inducing pieces for classical or film music, or even for the pop music industry. Additionally, listening to performances and recordings involving these musical features could potentially help nonmusicians tap into flow. Future research can investigate these potential implications in detail. In essence, maintaining the flow state through paying attention to musical inducement features and minimizing flow disruption features may better allow us to tap into the positive emotions and intrinsic motivation characteristic of flow, which may, in turn, act as an avenue through which music engagement can improve wellbeing.

Data availability statement

The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found below: https://github.com/jzielk/Inducing-and-disrupting-flow.

Ethics statement

The studies involving human participants were reviewed and approved by the Institutional Review Board, Stanford University. The ethics committee waived the requirement of written informed consent for participation.

Author contributions

JZ carried out the experiment. JZ carried out the analyses with support from MA-T and JB. JZ wrote the manuscript. MA-T helped supervise the project. JZ and JB conceived the original idea. JB supervised the project. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Supplementary material

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The effect of bio-electro-magnetic-energy-regulation therapy on sleep duration and sleep quality among elite players in Norwegian women's football

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The current study investigated if physical loads peak on game days and if Bio-Electro-Magnetic-Energy-Regulation (BEMER) therapy is affecting sleep duration and sleep quality on nights related to game nights among elite players in Norwegian women's elite football. The sample included 21 female football players from an elite top series club with a mean age of ~24 years (± 2.8). Sleep was measured every day over a period of 273 consecutive days with a Somnofy sleep monitor based on ultra-wideband (IR-UWB) pulse radar and Doppler technology. The current study was conducted as a quasi-experiment, where each player was their own control based on a control period that lasted for 3 months, and an experimental period that lasted for 5 months. Accordantly, the time each player spent with BEMER therapy was used as a control variable. Multivariate analyses of variance using FFMANOVA and univariate ANOVA with False Discovery Rate adjusted *p*-values show that physical performance (total distance, distance per minute, sprint meters >22.5 kmh, accelerations and decelerations) significantly peak on game day compared with ordinary training days and days related to game days. The results also show that sleep quantity and quality are significantly reduced on game night, which indicate disturbed sleep caused by the peak in physical load. Most sleep variables significantly increased in the experiment period, where BEMER therapy was used, compared to the control period before the introduction of BEMER therapy. Further, the analyses show that players who spent BEMER therapy >440 h had the most positive effects on their sleep, and that these effects were significantly compared to the players who used BEMER therapy <440 h. The findings are discussed based on the function of sleep and the different sleep stages have on recovery.

KEYWORDS

sleep, elite football, recovery, physical load, BEMER therapy

1. Introduction

Elite women's football (soccer) is an open loop sport that involves demanding physical actions as well as high mental loads (Nédélec et al., 2012; Jordet et al., 2020; Baptista et al., 2022). The physical demands in men's and women's elite football involve high occurrences of high-intensity actions, such as accelerations and decelerations, rapid change of direction, jumps, high-intensity runs and sprints, and direct contacts with opposing players (Datson, 2016; Marqués-Jiménez et al., 2017; UEFA, 2021; Winther et al., 2021). Further, the mental demands in football involve the players' ability to perceive the constantly shifting environment on the field, quickly decide which action that is favorable in the play-counter play, and quickly execute the decisions made to try to outplay the opponent team (Williams, 2000). Thus, focused attention, shifting attention, the recognition of effective decisions stored in episodic memory (learned actions in similar situations), and making rapid decisions based on these perceptual-cognitive processes, are key mental processes in elite football. Such physical and mental efforts might lead to disturbances in the players' physiology and neural processes (Nédélec et al., 2013).

Since elite women's football has developed to exhibit more powerful and faster physical movements- (accelerations, decelerations, high-intensity runs, sprinting, jumps) and quicker and more rapid decisions from the football players, football training sessions must facilitate the development of such demands (Díaz-García et al., 2023). Taken together, the high physical-and mental loads in elite women's football, especially during game-specific training sessions and football games, are demanding. The physical effort may lead to muscle fiber micro ruptures and muscular fatigue (Peake et al., 2017), and the excessive mental effort may lead to perceptual-cognitive overload (Jordet et al., 2020; Díaz-García et al., 2023). It is important to emphasize that there are substantial differences in high-intensity actions between playing positions in women's elite football, with central defenders exhibiting lower relative distance and the fewest high-intensity activity bouts in distance and duration compared with all other outfield positions (Datson, 2016; Winther et al., 2021). Additionally, within-player sprint variability between official games can be more than 32% without being considered abnormal (Baptista et al., 2022). Nevertheless, the players train according to the various game demands in the different positions. Female football players are therefore exposed to a constant struggle to optimize the balance between the extensive load they are exposed to, and the recovery needed to keep fresh without reducing fitness (Fullagar et al., 2015; Moen et al., 2021).

Research shows that competition days in different sports affect subsequent sleep, since competitions are associated with reduced sleep quality and more sleep disturbances caused by the high physical loads in competitions (Fullagar et al., 2015; Knufinke et al., 2018; Biggins et al., 2020). Recent research has also observed increase in physical game-play performances of elite senior female players and that these physical and mental efforts peak significantly during football games, and that football games leads to acute fatigue that reduces physical performance ability over the following hours and days [Ispirlidis et al., 2008; Fédération Internationale de Football Association (FIFA), 2019; Lathlean et al., 2019; Winther et al., 2021]. Thus, to maintain and further develop the elite football players' performance, they need optimal recovery to compensate for the physical and mental load (Bird, 2013; Smith et al., 2018). Studies show that sleep is disturbed on the nights close to game nights and game days in football are also found to reduce sleep quantity and quality (Fullagar et al., 2016; Roberts et al., 2019; Moen et al., 2021; Silva et al., 2022). Even though evening football games are found to have a negative effect on sleep (Sargent and Roach, 2016; Lastella et al., 2018; Nédélec et al., 2019), studies also claim that the game itself affect sleep more than the starting hour of the game (Lalor et al., 2018). Carriço et al. (2018) revealed a significant reduction of 65 min in sleep duration following female elite football games at both daytime and evening, compared to ordinary training days, where sleep duration averaged 6 h and 36 min. However, in general, there is a scarcity of data on female elite football players and few studies have investigated how sleep and the different sleep stages are affected by football games (Moen et al., 2021).

The strenuous demands of football games and game-relevant training sessions, encompassing physical and mental exertion, give rise to significant physical and mental disruptions, requiring a considerable amount of time for recovery (de Hoyo et al., 2016; Scott et al., 2020). The physiological disturbances, such as training and game induced muscle fiber micro ruptures and muscular fatigue, have a notable increase the first 24 h after a game, peak between 24 and 48 h, and then subside (Ascensão et al., 2008; Magalhães et al., 2010). The football players usually need from 72 to 96 h to restore metabolic homeostasis (Ispirlidis et al., 2008). The ability to gain optimal recovery in elite football is therefore of crucial importance to prevent the possibility of performance decrement (Andersson et al., 2008; Carling et al., 2012). Consequently, players who experience faster recovery will have a significant advantage by achieving quicker readiness for both training sessions and football games (Terrados et al., 2011).

The homeostasis and circadian rhythm are two internal biological processes that work together and provide the opportunity for important recovery processes to occur. The homeostasis process keeps track of the player's need for recovery based on the physiological stress of different loads, and together with the circadian rhythm it regulates the players' need for sleep. Sleep is the state where physiological processes necessary for recovery occurs and elite football players need to obtain both adequate quantity and quality of sleep to achieve optimal recovery (Venter, 2012; Nédélec et al., 2015; Moen et al., 2021). Sleep contributes to homeostatic control of energy conservation, and optimal functioning of the glymphatic, immune, metabolic, and endocrine systems (Bonnar et al., 2018). Physiological growth, repair, and neuromuscular performance are affected during sleep as well as brain homeostasis and neural plasticity, processing of emotional inputs and emotional regulation (Hrozanova, 2021). Thus, sleep is important for the restoration of the players' physiology and their cognitive and behavioral performance, as well as their learning and memory capacity. Importantly, each sleep stage has a distinct complementary role in the overall human body recovery process (Vyazovskiy and Delogu, 2014). A recent study found that the night following football games were associated with reduced time in bed, total sleep time, time in all three sleep stages (light, deep, and REM), longer sleep onset latency and increased respiration rate in non-REM sleep (Moen et al., 2021). The study also found that players' increase in perceived fatigue was associated with increased time in bed and deep sleep, and increased REM sleep was linked to a subsequently decreased in perceived fatigue (Moen et al., 2021). Thus, both the total amount of sleep football players gains and the distributed amount of time in the different sleep stages seem to be important in the recovery process to complete homeostasis. However, research claims that football players do not necessarily obtain enough sleep to become optimally recovered, especially after football games (Fullagar et al., 2015, 2016; Moen et al., 2021). Paradoxically, it is found that sleep among female elite football players is disturbed at the night after playing football games, and that this occurs at the same time as the need for recovery is increased (Moen et al., 2021). Thus, the disturbed sleep is claimed to be a result from the extraordinary loads associated with the football games.

Therefore, tools and methods that can monitor and influence functional recovery for elite football players are of high interest for players and coaching staff (Nédélec et al., 2012, 2013). Interestingly, research indicates that the use of Pulsed Electromagnetic Field (PEMF) therapy has the potential to influence human recovery through impacting tissue regeneration such as exercise-induced muscle damage (Basset, 1993; Nédélec et al., 2012, 2013; Ross et al., 2019). A recent study also claims that an increase in blood flow improves performance recovery between bouts of high-intensity exercise, and that PEMF might be an effective tool to achieve this (Borne et al., 2017). A physical vascular therapy based on PEMF that uses Bio-Electro-Magnetic-Energy-Regulation (BEMER) is found to have positive effects on several areas that are related to functional recovery (Bohn, 2013; Bohn et al., 2013). Therefore, BEMER therapy is considered to be a promising tool in therapeutic settings (Bohn, 2013). The use of PEMF therapy is mainly found to affect the blood flow in capillaries and the smallest blood vessels (microcirculation) in healthy muscles (Klopp, 2017). The heart needs help for the blood to flow through the capillaries (arterioles and venules) and capillaries are therefore equipped with a pump mechanism, where the tissue in the blood vessel walls contracts and extracts (relax) alternately to positively influence the blood flow (Intaglietta, 1990). When the body is exposed to stress this mechanism might be hampered (Pal et al., 1988). When the body is exposed to the weak pulsed electromagnetic fields produced by BEMER it is found to affect the rhythmical contraction–extraction mechanism in the blood vessel walls, and blood flow is increased (Bohn et al., 2013). This mechanism is defined as vasomotion. Due to an increased microcirculation PEMF and BEMER therapy is found to reduce pain (Benedetti et al., 2020), lower stress (Alzayed and Alsaadi, 2020), increased energy (Haase et al., 2011), and decreases inflammation and increases speed of regenerating homeostasis (Ross et al., 2019). Interestingly, BEMER therapy is also found to stimulate increase in quantity and quality of sleep (Bohn et al., 2013).

It is suggested that BEMER therapy might be beneficial in sports (BEMER Group, 2021), however scientific evidence is still missing (Lockie, 2021). Several studies claim that sleep is disturbed after football games and the nights close to game nights (Moen et al., 2021). Therefore, implementing a recovery tool that promotes the body to attain a normal sleep state following such demanding efforts would be effective in enhancing the overall recovery process. A recent study suggests that future studies should investigate the use of recovery strategies for improvements in sleep after football games, and that objective measurements should be used to detect workload, to investigate if the physical loads actually peak on game days compared to ordinary training days (Moen et al., 2021). The aim of the current study is to investigate objectively if physical loads peak on game days, and investigate whether BEMER therapy is affecting sleep duration and sleep quality among elite players in Norwegian women's football? Since research has found that sleep is disturbed after games at the same time as the need for recovery has increased, the current study will focus on the days related to football games. The following hypothesis were developed:

> *H1*: The physical loads in women's elite football peak at game day.
>
> *H2*: BEMER therapy is affecting the elite women's football player's sleep duration and sleep quality on game nights and the nights following game days.

2. Methods

2.1. Participants

Participants were recruited from a Norwegian female top level team in football. All players from the A team (25 players) together with their coaching staff were invited to an information meeting regarding the current research project. The aim of the research project was explained in detail, together with a description of responsibilities for the different tasks in the study, logistics during the project period, and the data collection process. The football players who decided to participate in the study signed a consent form approved by the local Regional Committee for Medical and Health Research Ethics (REC) in Central Norway (project ID 2017/2072/REK midt). Twenty-three football players returned signed forms and were enrolled in the study. However, one of the players decided to withdraw from the study after a month of data collection and one person used BEMER only 47 h for the whole experimental period and these two players were therefore omitted from the study. Thus, twenty-one football players (mean age 23.68 ± 2.8, range 20–29 years) participated in the current study. It was important to invite players from the same team to control the content of training sessions and games for the participants, and additional participants were therefore not available.

2.2. Instruments

The data collection lasted from the 1st of February 2022 until the 31st of October 2022 and covered both the pre-season and the complete official game season for the team. The relevant measurements for the current study are a measurement that detect objective sleep and a measurement that detect objective physical loads.

2.2.1. Sleep

The Somnofy sleep monitor (version 0.7, VitalThings AS, Norway) is a novel, fully unobtrusive tool for sleep assessment, utilizing an impulse radio ultra-wideband (IR-UWB) pulse radar and Doppler technology. Somnofy is certified according to the Federal Communication Commission (FCC) and "Conformité Européene" (CE). The IR-UWB radar emits radio wave pulses in the electromagnetic spectrum, which can pass through soft materials (e.g., clothes or duvets), but are reflected by denser materials (e.g., a human body). As the pulses are reflected, they are returned and received by the IR-UWB radar again. Then, time-of-flight is used to analyze the time it takes to cover the distance between the radar and the object (the person), and then back to the radar. The movement of the sleeping person and their respiration rate are derived from the IR-UWB radar by utilizing the Doppler effect and Fast Fourier Transform, allowing the Somnofy to monitor the movement and respiration of the individual in bed with high precision. The raw movement and respiration data are processed by a sleep algorithm, which uses machine learning to calculate relevant sleep variables. Recently, a full validation of Somnofy against manually scored Polysomnography (PSG) found that Somnofy is an adequate measure of sleep and wake, as well as sleep stages, in a healthy adult population (Toften et al., 2020). Sleep studies in athletes, investigating the associations between sleep variables, sleep stages and physical and mental loads, have shown the Somnofy to be appropriate for use in athletic populations (Hrozanova et al., 2018, 2020; Moen et al., 2020). Table 1 shows the sleep variables that were obtained from the Somnofy sleep monitor in the current study.

2.2.2. Physical load–GPS tracking

To quantify movement patterns and physical demands the football players were equipped with the FIFA-approved STATSports APEX (Statsports, Northern Ireland) system. During both training and games, each football player wore a GPS tracker on their upper back in a tight-fitted vest. To minimize inter-device errors, each player used the same GPS unit during the entire data collection period. After each training session and game, the recorded data from the units was retrieved and uploaded to the club's laptop *via* the manufacturer software (STATSports Sonra 2.1.4). The complete dataset was exported to the researchers after the data collection period was finished. The raw data from each unit contains the id of the football player, in addition to time, latitude, longitude, Doppler-derived speed (m/s), heart rate (bpm), horizontal accuracy (Hacc), horizontal dilution of precision (Hdop), quality of signal, and instantaneous acceleration impulse, all captured at 10 Hz, while Micro-Electro-Mechanical-System data was captured at 100 Hz. The validity and levels of accuracy (bias <5%) of this tracking system have been previously presented (Beato et al., 2018). The variables that were collected for the purpose of the current study were the total sprint distance (meter) at higher speed than 22.5 km/h (SSM–High Intensity Sprint), total running/walking distance (TDI–Total Distance Meter), the number of accelerations higher than 2.26 m/s^{-2} (ACC–Accelerations), the number of decelerations higher than 2.26 m/s^{-2} (DEC–Decelerations), the amount of running/walking distance per minute (DPM), and the player's maximal sprint speed (km/h^{-1}) during training sessions and official games (PMS–Player's Maximal Speed).

TABLE 1 Sleep variables derived from the SOMNOFY® sleep monitor.

Sleep variable	Unit	Description
Sleep onset (SON)	hh:mm	Time of day of sleep start (first onset of the night)
Sleep offset (SOF)	hh:mm	Time of day of wake-up (last wake-up of the night)
Time in bed (TIB)	h	The period between bedtime and get-up-time, including sleep and awake
Sleep onset latency (SOL)	h	The time it takes for the participant to fall asleep from when they intend to sleep
Total sleep time (TST)	h	Total sleep time from sleep onset to time at wake-up
Light sleep (LSL)	h/%*	Total amount of time in the light stages of sleep
Deep sleep (DSL)	h/%*	Total amount of time in deep sleep
Rapid eye movement sleep (REM)	h/%*	Total amount of time in REM sleep
Wake after sleep onset (WSO)	h	Times awake after sleep onset and before final awakening
Sleep efficiency (SEF)	%	The percentage of time from SON to SOF spent asleep
Respiration rate (RPR)	N	The number of respiratory ventilations in 1 min in non-REM sleep

*Percentage of sleep stage in relation to total sleep time.

2.2.3. BEMER therapy device

BEMER stands for Bio-Electro-Magnetic-Energy-Regulation and the device uses a pulsed electromagnetic field (PEMF) to deliver a patented bio-rhythmically defined therapeutic signal. The BEMER Essential-Set was delivered to each of the football players in the current study, and the set contains the BEMER Box Professional control unit, where the football players administrate the different therapy programs, the BEMER Body applicator for full-body application, and the BEMER Pad applicator for local body application. The BEMER Box Professional control unit registers the time therapy programs were used by the players. At the end of the study, each football player's BEMER Box Professional control unit was analyzed to register the total amount of hours each football player used the BEMER therapy (BMT–BEMER Time).

2.3. Procedure

Once all participating football players returned the signed consent forms, the necessary equipment for sleep monitoring was delivered, along with instructions for correct use. The football players were instructed on the correct placement of the sleep monitor and the importance of correct settings for optimal functionality. The data collection entailed day-to-day monitoring of the football players' sleep detected by the Somnofy sleep monitoring device and physical loads collected by the GPS STATSports APEX tracking system. The researchers had access to a real-time overview of participants' compliance with the study and monitored the progress closely throughout the whole data collection to address and solve any technical issues in relation to the sleep monitoring systems and GPS STATSports APEX tracking system.

The 273 data collection days of the current study were divided into four periods: Experimental period 1 (Exp1): the control period before the introduction of BEMER therapy lasted from the 1st of February until the 30th of April (89 days), Experimental period 2 (Exp2): introduction period for BEMER therapy from the 1st of May until the 31st of May (31 days), Experimental period 3 from the 1st of June until the 30th of September (Exp3): a period where the players were familiarized with using BEMER therapy under a period with a normal training week and games in the week ends (122 days), and thereafter Experimental period 4 from the 1st of October until the 31st of October (Exp4): a period using BEMER therapy in an extraordinal hard congested fixture period due to qualification to Champions League, play offs in the Norwegian national cup and official games in the series (31 days). Figure 1 shows the different periods in the current study.

2.3.1. The BEMER protocol

The BEMER set was delivered to each football player after the 3 months control period (Exp1) was over (1st of May). The football players were instructed to use the BEMER base program 8 min in the morning and 8 min in the evening every day (BEMER Group, 2020). The base program has 10 different intensities, and the football players were instructed to start with intensity 1 the first week and increase by one on the intensity scale for each week. At intensity 6 the players were instructed to go back to intensity 3 and increase for each week until they reached intensity 6. This base protocol was followed throughout the intervention period. The players were also instructed to use the BEMER therapy program after high intensity training sessions and football games. The BEMER therapy program has 3 levels, where level 1 lasts for 12 min, level 2 for 16 min and level 3 for 20 min. The first two weeks the players were instructed to use BEMER therapy program level 2, and the next weeks level 3. After 8 weeks the players were instructed to use the BEMER Special mode program during sleep. The players placed the BEMER Body applicator for full-body application mattress under their sleeping mattress, and the BEMER Special mode program allows the football players to set their weakening time on the BEMER Box Professional control unit, and the BEMER therapy will start 2 h before the players wake up. They were instructed to use this program once a week after 8 weeks with the base program, and increase with one session the second week, and use it for up to three times each week throughout the intervention period.

2.4. Statistical analyses

Initially, IBM SPSS (version 27.0) was used to conduct demographic and descriptive statistical analyses, which are presented as mean ± standard deviation (S.D.). Extreme outliers of sleep data, defined as epoc counts of sleep sessions that were below 3 h (1,000 s) and sleep sessions where time in no presence are higher than 3,000 s were deleted. Also, to avoid that movements in the room were detected as sleep data, sleep sessions between 12.00 after midnight and 20.00 before midnight were deleted.

Within each experimental period (Exp1, Exp2, Exp3 and Exp4) the days/nights were classified as different types of days/nights: days/nights that were not close to a game and were ordinary training days where classified as training day/night (TN), night before game (NBG), game day/night (GN), game day/night plus 1 (GN1) or game day/night plus 2 (GN2) (Table 2 and Figures 2, 3). Each night is related to the day the need for sleep is developed. Thus, the day the football game is performed equals GN.

On some rare occasions there were two successive games and two games with only one day in between, which resulted in a combination of the night classes presented in Table 2. These rare cases were omitted from the data as they were not balanced between the experimental periods. The different players used BEMER therapy in various degree. The real time they used BEMER therapy was collected from the BEMER devices after data collection termination and incorporated in

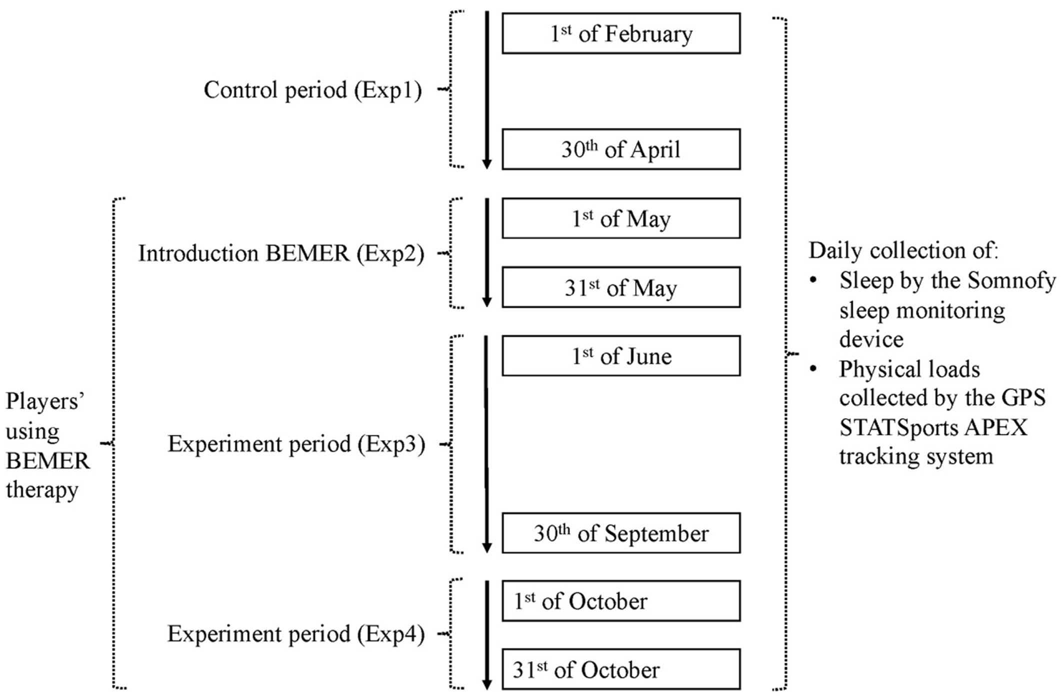

FIGURE 1
The different periods of data collection during the study.

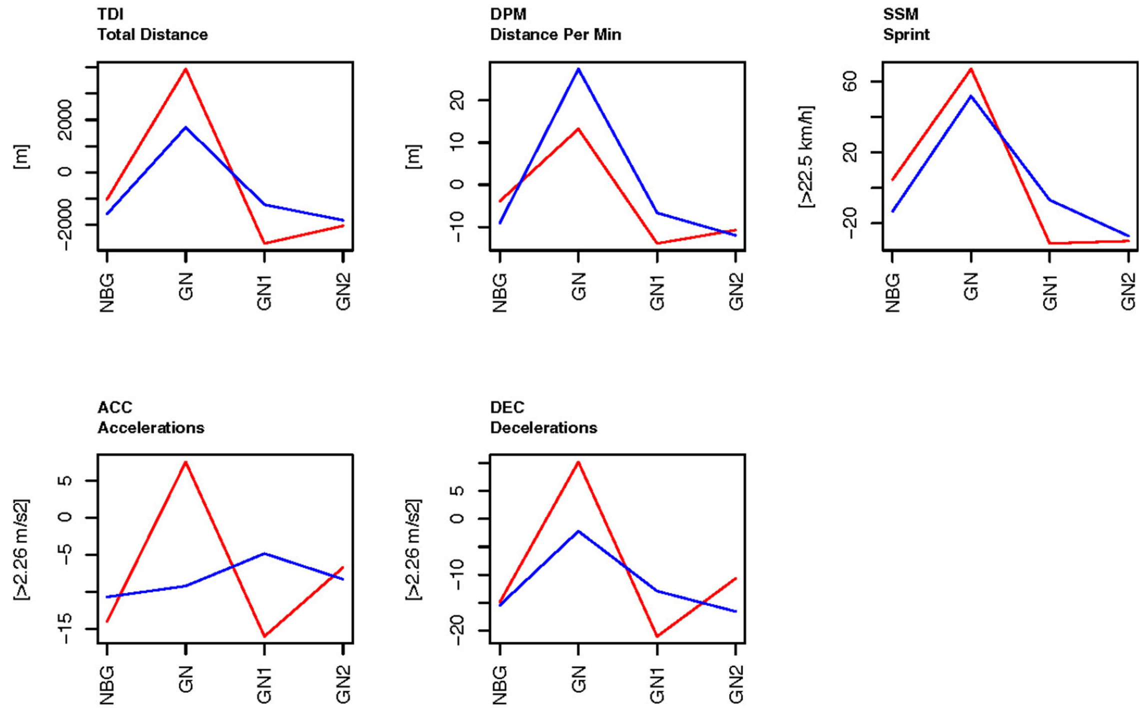

FIGURE 2
The physical load GPS-tracking on the days related to football games during the control period Exp1, before BEMER (red), and experimental period Exp3, the BEMER test period (blue). The data display each type of nights as a difference to the training nights (TN) for each person within the same experimental period. The baseline (0 on the *y*-axis) is means of the ordinary training days that were not close to a game (TN), as calculated for each person within each experimental period. TDI, total distance; DPM, distance per minute; SSM, sprint distance; ACC, Accelerations; DEC, Decelerations; NBG, night before game; GN, game night; GN1, night after GN; and GN2, night after GN1.

TABLE 2 Classification of days related to the players' participation in football games.

TN	Nights after ordinary training sessions and not close to a football game: Training Nights
NBG	The night before a football game
GN	The night following the football game: Game night
GN1	The night 1day following game night: Game night +1
GN2	The night 2 days following the game night: Game night +2

the statistical analysis by dividing the individuals into two groups: group 1 (B1) used BEMER more than 150 h and less than 440 h during the experimental period, and group 2 (B2) used BEMER more than 440 h. The football players were then classified by a variable B-level, based on if they had used BEMER below 440 h ($N = 6$) or more than 440 h ($N = 15$).

For each group of variables (physical load data and sleep data), days without observations were omitted. This resulted in 1928 observations for physical data and 3,883 observations of sleep data. For each football player within each experimental period, the means of general training days was used as baselines, and the observed values of nights close to football games (NBG, GN, GN1 and GN2) were considered as a difference to the players' mean values of TN. Experimental period 2 (Exp2) was the introduction period of BEMER therapy and was omitted from these analyzes. Furthermore, because of significant data loss in Exp4, occasions of successive games with or without only one day between and less days in Exp4 compared with Exp1 and Exp3, data from Exp4 was omitted from the further analyzes.

These data were analyzed as three-ways factorial design by univariate analysis of variance ANOVA with False Discovery Rate adjusted *p*-values (Moen et al., 2005) and by multivariate analysis of variance using FFMANOVA (Langsrud, 2003, 2005). The three design variables in the analyses of variance were:

(1) Type: NBG, GN GN1, or GN2
(2) Exp: Control period Exp1 or experimental period Exp3
(3) B-level: 150–440 h or above 440 h total BEMER time

Each of these three factors and all two-ways interaction between them were used as design variables in the analysis of variance. The analysis was performed in R version 4.2.1 using the ffmanova R package[1] (Langsrud et al., 2007). FFMANOVA gives a validation of all parameters simultaneously by performing Principal Component Analysis (PCA), where the first and most important PC's are validated toward the PC's reflecting noise in the data. Separate analyses were performed for physical activity and for sleep observations using the design variables Type, Exp and B-level observed as a difference to means of the training nights within each player in Exp1.

1 https://cran.r-project.org/package=ffmanova

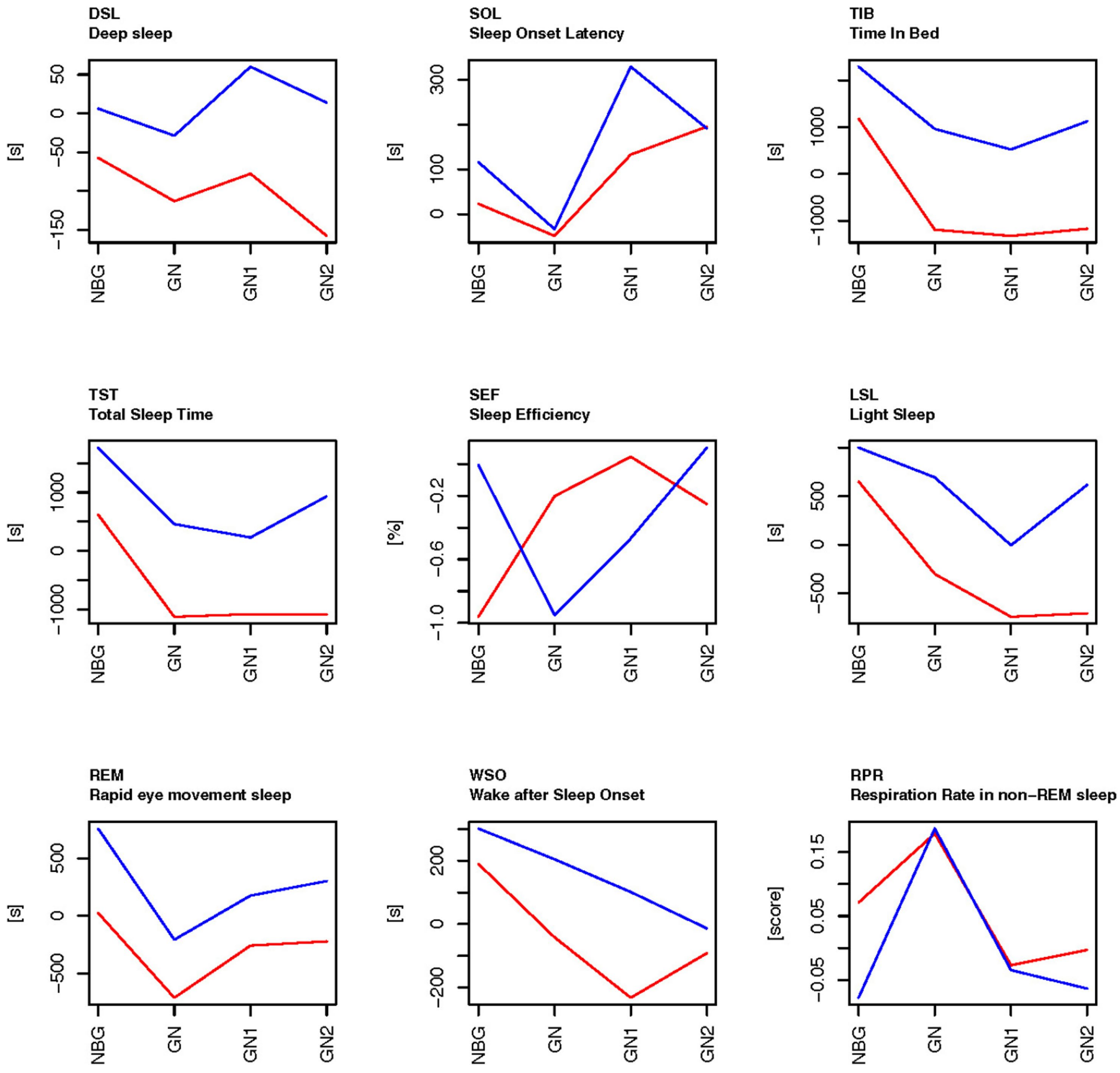

FIGURE 3
The sleep data on the days related to football games during the control period (Exp1-red) and experimental period (Exp3-blue), compared to the baseline scores on general training nights. The baseline (0 on the *y*-axis) is means of ordinary training days that were not close to a game (TN), as calculated for each person within each experimental period. NBG, night before game; GN, game night; GN1, night after GN; and GN2, night after GN1.

3. Results

The current study had a total potential of collecting 6,006 data points including sleep and physical performance data using GPS tracking over the 273 days. For the objective sleep data, 4,746 or 79%, of the potential 6,006 data points were collected and available for analyses. Missing data was a result of occasional disengagement of the football players with the sleep monitoring systems, technical issues with connecting the Somnofy units to Wi-Fi (especially at some hotels), travels where the football players forgot their sleep monitoring devices at home, and one of the football players was transferred to another club in July. Of the 6,006 potential data points of physical performance data, 2,497 or 41,6%, were collected. Data was lost due to training sessions where the GPS tracking vest was not appropriate to use (example strength training), and to the players' occasional forgetfulness. Overall, a total of 406 observations from training and official football games were investigated for the 273 consecutive days, there were 339 occurrences where the football players played full time games (45 min x 2), 42 played one half or more (+ 45 min) and 80 played less than 30 min. Descriptive statistics (mean ± STD) of the studied sleep variables during the entire period of data collection including all football players, and at game nights are shown in Table 3.

For the physical load data there were 389 datapoints in the control period Exp1 and 468 datapoints in the experimental period Exp3. For the sleep data there were 674 datapoints within control period Exp1 and 797 datapoints for the experimental period Exp3.

The studied physical load variables collected by the GPS STATSports APEX tracking system showed that the mean locomotor distance of the players during an average training session was 4,315 meters (±1863), they sprinted (speed above 22.5 km/h) a mean distance of 26 meters (±47), and their mean registered maximal speed was 23.3 km/h (± 3.7). During football games the mean distance for the football players that participated in the game was 9,313 meters (±4,743), they sprinted a mean distance of 127 meters (±107), and

TABLE 3 Descriptive statistics for the objective sleep patterns, based on the total period of 4,746 nights of data in 21 females football players, and the night after completing full football games (252 nights), respectively.

Sleep variable	Mean (± STD)	Mean (± STD) game nights
SON	24:00 (± 00:58)	00:10 (± 00:59)
SOF	08:37 (± 01:06)	08:44 (± 01:05)
TIB	09:33 (± 01:21)	09:29 (± 01:20)
SOL	00:42 (± 00:30)	00:39 (± 00:28)
TST	08:02 (±01:11)	07:58 (± 01:14)
LSL	04:46 (59%) (±00:52)	04:53 (± 00:57)
DSL	01:19 (17%) (±00:22)	01:19 (± 00:23)
REM	01:57 (24%) (±00:33)	01:45 (± 00:31)
WSO	00:34 (±00:32)	00:34 (± 00:31)
SEF	84.4 (±7.7)	84.1 (± 7.9)
RPR	15.4 (±1.9)	15.9 (± 2.3)

STD, standard deviation; SON, sleep onset; SOF, sleep offset; TIB, time in bed; SOL, sleep onset latency; TST, total sleep time; LSL, light sleep; DSL, deep sleep; REM, rapid eye movement; WSO, wake after sleep onset; SEF, sleep efficiency; RPR, non-rapid eye movement respiration per minute.

TABLE 4 Multivariate and Univariate ANOVA using FFMANOVA for validation of changes in Physical load–GPS tracking variables on days close to football games (Type), the experimental periods (Exp), and the BEMER group (B-level) based on time spent on usage (across all variables and within each variable).

MANOVA across all variables			ANOVA within each variable				
Variable	DF	*p*-value	TDI	DPM	SSM	ACC	DEC
Type	1	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**
Exp	1	**0.000**	**0.001**	**0.000**	**0.070**	**0.098**	**0.018**
B-level	3	**0.046**	0.186	0.831	0.154	0.324	0.300
Exp*Type	1	**0.000**	**0.000**	**0.000**	**0.011**	**0.000**	**0.000**
B-level*Exp	3	0.900	0.971	0.971	0.971	0.971	0.461
B-level*Type	3	**0.065**	**0.003**	0.747	0.138	0.138	**0.004**
Residuals	844						

DF, degrees of freedom; TDI, total distance; DPM, distance per minute; SSM, sprint distance; ACC, Accelerations; DEC, Decelerations; Type, days that was not close to a game (TN); day before game (NBG), gameday (GN), gameday + 1 (GN1) or gameday + 2 (GN2), B-level = (BEMER level) is on two levels: (1) < 440 h (2) > 440 h.
Significant differences are in bold.

their mean registered maximal speed was 26.8 km/h (± 2.2). The football players' mean of BEMER therapy use was 595.7 h (±252.9) during the experiment periods Exp2, Exp3 and Exp4.

For all physical variables there were significant main effects of type of day/night (Type), significant main effects of experimental period (Exp), and significant interaction between these factors (Table 4). Among the physical variables, distance per minute (DPM) is the only variable that is not influenced by the time the football players actually participated in the games or in the training sessions, but the relative locomotor distance of the players during the time they participated in the games or training sessions. Figure 2 shows that during a football game (GN), the DPM was higher than during normal training days (the baseline), both in the control period (Exp1) and in the experimental period (Exp3) (reflected by positive values for DPM at GN in Figure 2). Compared with the days before and after the game (NBG, GN1 and GN in Figure 2) there was a peak at the game day (GN) both for the experimental period (Exp3) and for the control period (Exp1), but a higher value for the experimental period (Exp3). For the days close to a game, the distance per minute were shorter than the means during normal training days (the baseline), which resulted in negative values in Figure 2. All other physical variables, except acceleration in the experiment period (Exp3), also peaked at the game day. At GN these variables were higher in the control period (Exp1) than in the experimental period (Exp3). However, these values were not controlled to be the relative locomotor effort players participated in the games or in training sessions.

For the sleep variables there were significant main effects of type of days/nights (Type), and significant main effects of experimental period (Exp) for most sleep variables (Table 5). There were no significant interaction effects between these two factors. The sleep variables time in bed (TIB), total sleep time (TST) and light sleep (LSL) were all higher in the experimental period (Exp3) than in the control period (Exp1) at all types of days/nights: the game nights and the nights close to a game (Figure 3). In the control period Exp1, deep sleep (DSL), time in bed (TIB), total sleep time (TST), light sleep (LSL) and REM-sleep (REM) were below the baseline on game nights (GN) and the two nights following game nights (GN1 and GN2). There were also significant effects of type of days/nights with a drop from the night before a game (NBG) to the game nights (GN), both in the experimental period (Exp3) and in the control period (Exp1). The time in deep sleep (DSL) also showed a tendency of higher values in the experimental period (Exp3) than for the control period (Exp1) but did not reach statistical significance (Table 5).

The amount of REM sleep was significantly higher in the experimental period (Exp3) than the control period (Exp1), and significantly higher on the night before game compared to their baseline scores within the experimental periods, whereas the amount of REM sleep droped to their baseline level on game night (GN) and increased on GN1 and GN2. In experimental period (Exp3), but not in the control period (Exp1), REM was above the baseline the day after the game, and the day thereafter. The result was similar in the control period (Exp1), but then the REM sleep levels are lower than their baseline scores. Wake after sleep onset (WSO) was above baseline the night before game and has a linear trend toward baseline level on GN2 in the experimental period (Exp3), whereas it was below baseline levels in the control period (Exp1) on GN and the two following nights. The respiration rate in non-REM sleep increased significantly on GN compared to the players' baselines scores in both the control period and the experimental period.

There are interacting effects between the BEMER therapy group variable (B-level: the amount of time the players used BEMER therapy) and the scores over the experimental period for most of the sleep variables (Table 5). For sleep variables with significant interaction effects between B-level and Exp, Figure 4 shows the results of means for the players that used BEMER >440 h and those that used BEMER <440 h.

Figure 4 shows that the players who had the most extensive exposure to BEMER therapy (>440 h) had significantly lower sleep onset latency (SOL) than the players who had fewer hours of BEMER therapy (<440 h), and that the value decreased from Exp1 to Exp2 and Exp3. In experimental period Exp3, the total sleep time (TST), sleep

TABLE 5 Multivariate and Univariate ANOVA using FFMANOVA for validation of changes in sleep variables on nights close to football games (Type), the experimental periods (Exp), and the BEMER group (B-level) based on time spent on usage (across all variables and within each variable).

MANOVA across all variables			ANOVA within each variable								
Variable	DF	*p*-value	SOL	TIB	TST	SEF	LSL	REM	DSL	WSO	RPR
Type	1	**0.000**	0.169	**0.000**	**0.000**	0.718	**0.000**	**0.000**	0.719	0.321	**0.000**
Exp	1	**0.000**	0.627	0.000	0.000	0.633	**0.000**	**0.000**	**0.090**	0.199	0.403
B-level	3	0.213	0.805	0.310	0.805	0.310	0.758	0.310	0.310	0.299	0.758
Exp*Type	1	0.714	0.915	0.391	0.527	0.527	0.379	0.883	0.915	0.883	0.527
B-level*Exp	3	**0.000**	**0.003**	0.597	**0.001**	**0.000**	**0.011**	**0.026**	**0.079**	**0.003**	0.373
B-level*Type	3	0.659	0.840	0.840	0.840	0.881	0.840	0.840	0.840	0.816	0.840
Residuals	1.457										

DF, degrees of freedom; SOL, sleep onset latency; TIB, time in bed; TST, total sleep time; SEF, sleep efficiency; LSL, light sleep; REM, rapid eye movement; DSL, deep sleep; WSO, wake after sleep onset; RPR, non-rapid eye movement respiration per minute; Type, nights that was not close to a game (TN), night before game (NBG), game night (GN), game night + 1 (GN1) or game night + 2 (GN2), B-level = (BEMER level) is on two levels: (1) < 440 h (2) > 440 h. Significant differences are in bold.

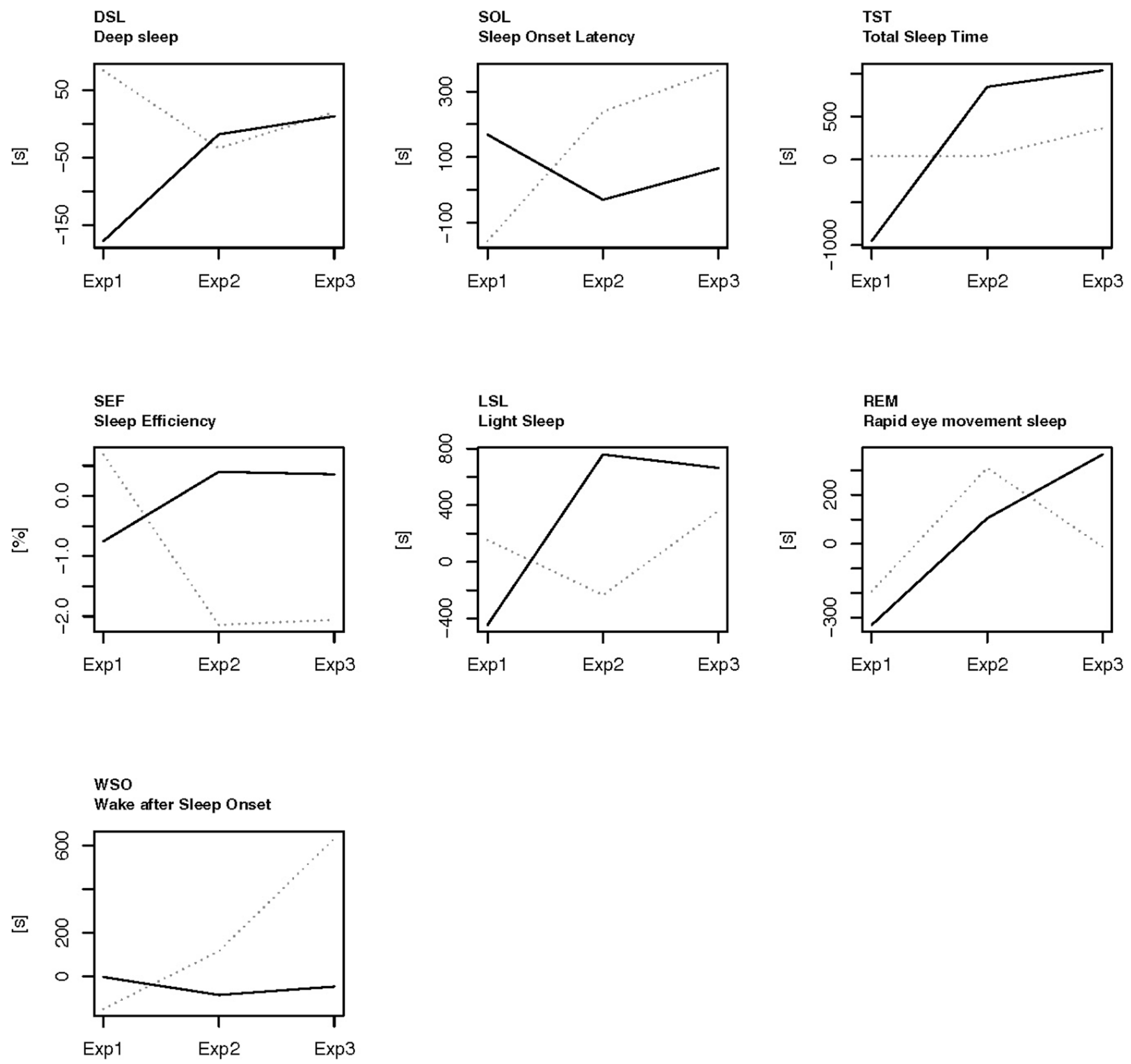

FIGURE 4
The sleep data detected in the different experimental periods for the players who used BEMER more than 440 h (marked line) and the players who used BEMER less than 440 h (dotted line). The baseline (0 on the *y*-axis) is means of the days of ordinary training days that were not close to a game (TN), as calculated for each person within each experimental period. Exp1, the control period; Exp2, introduction period for BEMER; Exp3, familiarized with the use of BEMER and using the BEMER; Marked line, players who used BEMER more than 440 h; Dotted line, players who used BEMER therapy less than 440 h.

efficiency (SEF), and the amount of REM sleep are all significantly higher than in the group of players who spent less time on BEMER therapy. Wake after sleep onset (WSO) time was significantly lower for the group who spent a higher amount of time on BEMER therapy. The players who had the highest amount of time with BEMER therapy increased their deep sleep (DSL) significantly from Exp1 to Exp2 and Exp3.

Figure 5 displays the results of the players that used BEMER >440 h (B2) on sleep variables prior to-and post football games in the control-and experimental period.

Figure 5 also shows that the pattern for the sleep variables TST, LSL, REM, and DSL share the same pattern as in Figure 3, where both groups are included in the analyses, whereas the sleep variable sleep onset latency (SOL) was significantly lower on game night in the experimental period (Exp3) for the players who used BEMER therapy more than 440 h than for those who used BEMER therapy less, and sleep efficiency (SEF) was above or close to the baseline levels on nights close to game nights in the experimental period (Exp3), but below the base line in the control period (Exp1).

4. Discussion

The aim of the current study was to investigate objectively if physical loads peak on game days, and whether Bio-Electro-Magnetic-Energy-Regulation (BEMER) therapy is affecting sleep duration and sleep quality among elite players in Norwegian women's elite football. To the authors knowledge there are currently no studies that document possible effects of BEMER therapy on sleep in elite sports. The first hypothesis of the current study predicted that the physical demands in women's elite football peak at football games. The prediction was confirmed whereas all collected physical variables significantly

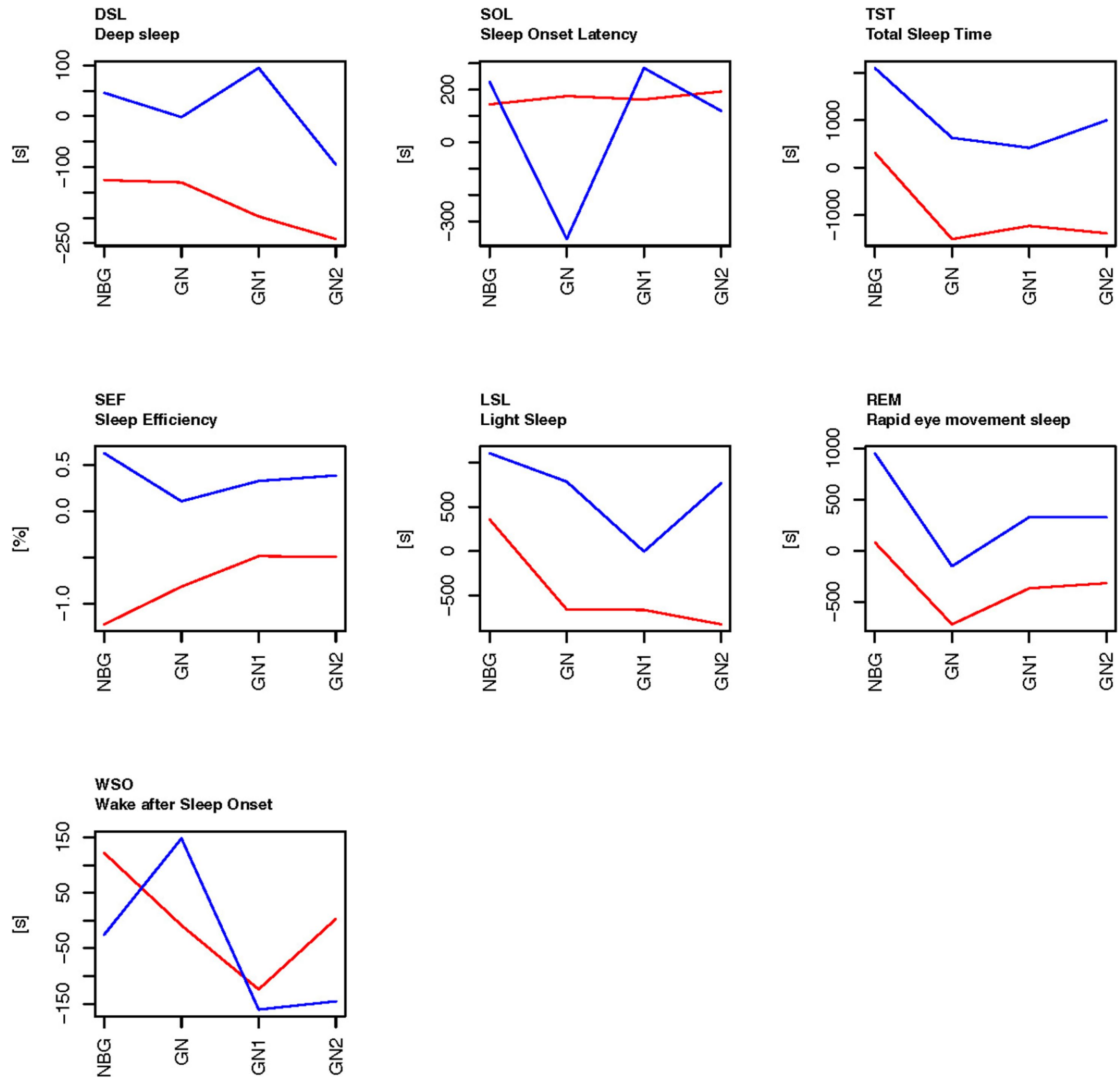

FIGURE 5
The sleep data on the days related to football games during the control period (Exp1-red) and experimental period (Exp3-blue), compared to the baseline scores on general training nights for the players who used BEMER therapy more than 440 h. The baseline (0 on the *y*-axis) is means of the days of ordinary training days that were not close to a game (TN), as calculated for each person within each experimental period. NBG, night before game; GN, game night; GN1, night after GN; GN2, night after GN1.

increased on game days compared to general training days. The second hypothesis predicted that BEMER therapy affected the elite women's football player's sleep duration and sleep quality on game nights and the nights following game days. The second hypothesis was also confirmed whereas the football players' sleep duration and sleep quality significantly increased in the experiment period compared to the control period on game nights and the nights following game days.

4.1. Physical loads peak on game days in women's football

As predicted in the hypothesis the results in the current study show that the physical loads tracked by the GPS tracking system (STATSports APEX) were significantly higher on game days compared to the statistical means of general training days, the day before game, the day after the game and two days after the game. Total running/walking distance, distance per minute, sprint meters above 22.5 km/h, and the number of decelerations peak on game days in both the control-and the experimental period. The number of accelerations peak on game days in the control period, but not in the experimental period. Accordingly, research claims that the mental loads on match days are significantly higher than normal training days, since both the cognitive-perceptual demands rises, as well as the emotional arousals associated with football games (Ispirlidis et al., 2008; Winther et al., 2021). Thus, both the physical-and mental loads peak on game days compared to all other training days, and thus the need for recovery becomes more important. The significant increase in respiration rate in non-REM sleep on game night compared to their baselines scores in both the control period and the experimental period, is also associated with stress from increased loads (Moen et al., 2021). However, the current study shows that both sleep quantity (total sleep time) and sleep quality (the time distributed in the different sleep stages and time awake after sleep onset) are reduced on game days, especially in the control period. This result is in line with earlier research that claims that sleep is disturbed on game nights because of a significantly peak in physical and mental loads (Fullagar et al., 2016; Lalor et al., 2018; Roberts et al., 2019; Moen et al., 2021). Improved sleep quantity and quality on game nights, and the nights following game nights, will therefore reflect a potential positive environment for more comprehensive recovery after such a significant increase in loads.

4.2. Improved recovery equals changes in sleep quantity and quality

The results from the current study show that total sleep time has significantly increased after the introduction of BEMER therapy compared to the control period on game nights (Table 5 and Figure 3). Time in bed has also increased significantly, and the significant increase in time in bed and total sleep time also applies to the nights before games, game nights, game nights +1 and + 2. Interestingly, total sleep time is significantly lower on game nights and game nights +1 and 2 than the players' normal sleep status (Figure 3) in the control period, and above the players' normal sleep status after the introduction of BEMER therapy. The decreased total sleep time that is detected in the control period on game nights can be explained by the physical and mental disturbances caused by the increased loads associated with the football games (Lalor et al., 2018; Moen et al., 2021). The significant increase in respiration in non-REM sleep on game nights strengthen this explanation, since raised respiration often is caused by an increase in physiological or psychological stress (Figure 3). The increased total sleep time after the introduction of BEMER therapy indicate that the players' sleep is not interrupted in the same degree in the experimental period. Thus, the increased total sleep time is associated with the raised need for recovery caused by the peak in load associated with the football games, and that the players achieve their needs for recovery after games to a larger degree after the introduction of BEMER therapy. However, the patterns of the players' sleep associated to football games (TIB, TST, LSL, REM, DSL) show that all sleep variables raise either the night after the game (game night +1), or the following night (game night +2), which indicate that the players' still need to catch up their sleep to be in total balance after the loads associated with the game (Ispirlidis et al., 2008). Research claims that players need about 3 to 4 nights to restore metabolic homeostasis (Ispirlidis et al., 2008). The results in the current study also show that the players who used BEMER therapy more than 440 h significantly improved their total sleep in the experimental periods (Figure 4), and significantly more than the players who used BEMER therapy less (Table 5). Interestingly, their time spent in bed was not significantly different. Thus, the findings from the present study provides evidence to support the assertion that the introduction of BEMER therapy leads to a significant improvement in sleep quantity.

4.2.1. Sleep quality

The attributes that often are used to define sleep quality are sleep efficiency, sleep onset latency, total sleep time, and wake after sleep onset (Nelson et al., 2022). Importantly, sleep quality must be related to the players' acquired need for recovery, and sleep quality is also claimed to be impaired when there is reduction in deep sleep and REM sleep, in combination with increased time in light sleep (Berry, 2012). The results in the current study show that total sleep time, light sleep, REM sleep, and deep sleep are significantly reduced on game nights in the control period, and that all these variables are significantly higher after the introduction of BEMER therapy on game nights and all nights related to game nights. Total sleep time naturally affects the time spent in the different sleep stages, whereas longer total sleep time necessarily associates with longer durations in sleep stages, and longer total sleep time equals increased recovery. Each of the sleep stages fulfills a distinct role to the overall function of sleep, and at the same time the sleep stages have complimentary roles (Vyazovskiy and Delogu, 2014). However, sleep stage distribution in elite athletes is not yet fully understood (Moen et al., 2021).

In light sleep the brain waves, respiration and heart rate slows down, and the muscles become more relaxed compared to wakefulness (Singh and Stephen, 2022). These slow down activities help the physical restoration of the players. The development of motor skills is also associated to light sleep, and the brain processes and consolidates information by transferring information from short-term to long-term memory (Nishida and Walker, 2007). The light sleep stage also helps to restore the brain's cognitive processes. A football game is both physical-and cognitive demanding, and an increase in light sleep might therefore improve recovery, especially when both deep-and REM-sleep increase at the same time.

An increase in REM sleep after football games will help the players to regulate their emotions, consolidate experienced episodes in the game related to the play–counter play interactions, and recover from muscular damage caused by physical efforts in the game (Vgontzas et al., 1997; Peever and Fuller, 2017). The hypothalamic–pituitary–adrenal (HPA) axis is found to be activated in REM sleep and modulates the stress response system by stimulating the adrenal release of cortisol (Chrousos et al., 2016). Football games at elite level often result in potential muscle fiber micro ruptures which lead to inflammatory processes (Nédélec et al., 2013), and cortisol is found to reduce such inflammations (Braun and Marks, 2015). Interestingly, a recent study among female football players at international level, shows that increases in REM sleep were associated with subsequently decreased perceived fatigue the next day (Moen et al., 2021). Thus, loads associated with football games seem to increase the need for higher amounts of REM sleep to be fully recovered.

An increase in deep sleep after football games will help the players to obtain physical restoration, since deep sleep helps our bodies to repair, regenerate and restore from the extraordinary loads associated with football games (Nédélec et al., 2015). The endocrine system increases the secretion of growth hormones in deep sleep, which allows the muscles to regenerate and grow (Åkerstedt and Nilsson, 2003; Halson, 2014). Other hormones also increase during deep sleep, such as hormones that regulates the stress response and melatonin, which helps to reduce stress and promote relaxation. Therefore, deep sleep has an especially vital function for physical recovery (Doherty et al., 2021). Deep sleep also regulates learning, where information from the day (e.g., from the game) are transferred from short-term to long-term memory, which is important in football that is a dynamic sport where decisions must be made in the moment based on information that is recalled from episodic memory. Therefore, deep sleep is needed for football players to be fully recovered from games (Knufinke et al., 2018), and that the combination of REM-sleep and deep sleep seem essential in the recovery process after extraordinary loads.

However, the results also show that sleep onset latency is higher in the experiment period on the night after the night after game (game night +1), and that sleep efficiency is lower on game night, and that wake after sleep onset is higher on all nights related to game night in the experiment period compared to the control period (Table 5 and Figure 3). Taken together, the results are a bit contradictive to claim that sleep quality is improved after the introduction of BEMER therapy. On the one side, sleep variables that are used to consider sleep quality such as total sleep time, light sleep, deep sleep, and REM sleep have increased after the introduction of BEMER therapy. On the other side, sleep variables such as sleep onset latency and wake after sleep onset have increased, which is negative, and sleep efficiency is reduced on game night. However, when BEMER time is included in the analyses as a control, the results show that sleep onset latency is significantly lower, and that total sleep time, sleep efficiency, light sleep, and REM sleep are higher in the group of players who spent BEMER therapy more than 440 h in the experimental period (Figure 4). The results also show that deep sleep is significantly increased among the players who spent more than 440 h compared to the group that spent BEMER therapy less, and that the group with less use had an increase in wakening's after sleep onset. The results further show that that in the group of players that spent BEMER therapy more than 440 h, sleep onset latency was significantly reduced on game nights in the experiment period, and that total sleep time, sleep efficiency, light sleep, REM sleep and deep sleep are significantly increased in the experiment period on game nights and nights associated to game nights (Figure 5). It is also worth noting that all sleep variables were reduced significantly below the players' baselines on ordinary training days on game night in the control period, whereas the sleep variables are close to or above their baselines on game nights in the experimental period (Figures 3, 5). Thus, in total, the results in the current study indicate that sleep quality is significantly improved after the introduction of BEMER therapy.

4.3. Conclusion, limitations, and strengths

Earlier studies claim that elite football players obtain suboptimal recovery on game nights because of the extraordinary loads caused by the game (Moen et al., 2021), and that sleep loss have a negative impact on exercise performance (Craven et al., 2022). The current study also shows that the players' total sleep time and their distributed time in light-, deep-and REM-sleep drop on game night, while the objective measured loads peak on game night. Interestingly, the players obtain significantly more total sleep time and distributed time in light-, deep-, and REM-sleep after the introduction of BEMER therapy. BEMER therapy therefore seems to be an efficient recovery tool since the state of sleep represents the best natural enhancer for recovery (Bonnar et al., 2018). However, some limitations should be kept in mind when interpreting the current results. First, what sleep need football players have after completing extraordinary loads on game nights, and what distribution between the different sleep stages that are optimal, are not fully understood. The results should therefore be interpreted with caution. Second, the study would have benefitted from a larger sample size and a control group. The relatively low number of participants may have influenced the power of the conducted statistical analyses and is therefore a limitation in the current study. Third, the loss of all potential sleep data may also have influenced the results. Fourth, the players might have been influenced by seasonal effects such as different stress levels throughout the pre-season and season, to different training-related physiological levels throughout the pre-season and season, and to seasonal differences in hours of daylight. The current study has several strengths as well. First, the participants in the current study are female football players in a Norwegian top series club. Second, the data collection lasted for 9 months, which resulted in many data points for each player. Third, the intervention was designed with a control period for each player, and the analyses controlled for the actual time players used BEMER therapy. The analyses and results that included BEMER therapy time strengthen the design in the current study.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving humans were approved by Research Ethics (REC) in Central Norway (project ID 2017/2072/REK midt). The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

Author contributions

FM, SAP, and AK contributed to the conception and design of the study. EM, FM, and KL performed the statistical analysis. FM wrote the first draft of the manuscript. FM, MV, KG, AK, and MR organized the logistics during the experiment, and FM, MV, KG, MR, and SAP organized the database. EM wrote sections of the manuscript. FM and SAP contributed to the main revision of the manuscript. FM, SAP, and EM contributed to the final manuscript revision. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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Physiological synchrony and shared flow state in Javanese gamelan: positively associated while improvising, but not for traditional performance

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The experience of shared flow refers to the optimal balance between challenge and ability for a given task, resulting from interpersonal action in a group situation. The performance of Javanese gamelan is an ideal setting to investigate shared flow, due to the requirement that all performers on varying instrumental parts work harmoniously, allowing for shared flow and its native equivalent, *ngeli*. To minimise the disruption of flow, while still measuring it continuously, one way to assess a person's state is by measuring physiological responses of the sympathetic (i.e., fight-or-flight) system, namely heart rate and skin conductance. Flow has been related to physiological signatures, and shared actions in music-making have been related to synchronised physiology. However, to our knowledge, no study yet has directly investigated the links between shared physiology and shared flow. Therefore, this study aimed to assess the associations between flow states, physiological synchrony, and Javanese gamelan playing. Subsequently, we tested for differences between advanced and beginner groups playing traditional gamelan pieces and improvising. Firstly, a factor analysis revealed a two-factor solution of Awareness and Absorption for self-reported shared flow. Next, using inter-subject correlation to assess synchrony and circular shuffling to infer significance, we found a greater proportion of significance in traditional playing compared to improvised playing for the experienced group, and the opposite for the beginner group. Lastly, linear mixed models revealed largely positive associations between synchronised physiology and shared flow during improvised playing, and negative associations during traditional playing, regardless of experience levels. This study demonstrates methodological possibilities for the quantitative study of shared flow in music-making contexts, and potential differences in shared flow experience in improvised and traditional, or prescribed, playing.

KEYWORDS

flow state, gamelan, synchrony, coupling, skin conductance, heart rate

1. Introduction

The underlying mechanics of musicians performing together are somewhat mysterious. In gaining insights into this phenomenon, a growing body of empirical research has shed light on the behaviours, interactions, and coordination strategies of ensemble musicians (Gugnowska et al., 2022; Khalil et al., 2022; Kohler et al., 2022; Delius and Müller, 2023). One mechanism which could aid collaborative musical contexts is the experience of shared flow, though this has been seldom explored (Cochrane, 2017; Harmat et al., 2021; Tay et al., 2021). Shared flow refers to flow as a result of interpersonal action in a group situation (Pels et al., 2018).

1.1. Flow and shared flow

To date, flow states have most frequently been investigated in individuals and are defined primarily as a balance between challenge and skills for a given task and moderate mental effort among other facets (Nakamura and Csikszentmihalyi, 2014).

Initial conceptions of shared flow stemmed from Csikszentmihalyi's conception of individual flow (Csikszentmihalyi and Larson, 1987; Csikszentmihalyi and Csikszentmihalyi, 1988). This later inspired Sawyer's work on group flow and group creativity (Sawyer, 2006), who argued that group flow goes beyond the sum of independent flow experiences. For some researchers, shared flow or group flow is often seen as an extension of individual flow state, where it typically arises through and contributes to synchronous or coordinated action (Gloor et al., 2013; Walker, 2021), or challenging cooperative activity (Magyaródi et al., 2022). However, recently it has been argued that different forms of shared flow exist and vary according to the level of self-other overlap, or the level of interconnectedness and closeness between one individual and another. Hackert et al. (2022) describe fundamental differences between what they call 'shared interactive flow' and 'group flow', whereby the degree of self-other overlap can be thought of as a spectrum that may vary between these two flow states; higher overlap is the latter, while less overlap is the former. Both shared interactive flow and group flow may occur in alternation, due to the dynamic and changeable nature of group flow (Pels and Kleinert, 2022). Shared interactive flow is focused on the shared task, although is experienced on an individual level within an interactive social context of moderate self-other overlap. In group flow, however, the focus is both on the task and the group due to the continuous and synchronous social interaction being a requirement, and self-other overlap is at its fullest. Just as group flow involves a greater merging of self and other, so too does moving in synchrony (Hu et al., 2022), or coordinating with one another in a musical group (Liebermann-Jordanidis et al., 2021). Self-other overlap is typically measured *via* the visual scale of Inclusion of Self in Other scale (Aron et al., 1992), however, we simply interpret this here as the hypothetical level of connectedness present among a group.

Musical situations are one paradigm where the dynamism of flow states can be experienced and studied in a multitude of ways, as music is often played in an ensemble where there is a coordinated group goal to perform music (see reviews, Tan and Sin, 2021; Tay et al., 2021). Situations in which the actions of one influence another as a series of causes and effects, for example, improvisation, are seen as most favourable for group flow to arise. Additionally, an individual's performance may change over time. The musical material may vary in the level of challenge it presents, and so too might the individual's capacity to meet such challenge. It is often exemplified through performance in improvising jazz groups, whereby actions of individuals are highly interrelated across the group, and the resulting flow is therefore above any one player due to the social, dynamic and collaborative context in which it arises (Hackert et al., 2022). In such contexts, individual flow experiences are difficult to disentangle from group flow experiences, due to the social context being the catalyst for flow. This article adopts the understanding that there may be distinctions between shared interactive flow and group flow (Hackert et al., 2022) between playing contexts, for instance between improvised and prescribed playing, which may also depend on the level of musical experience. Consequently, these terms are used in relation to their relevant contexts. Shared flow is used as a more general, overarching term.

1.2. Relevance of flow state to gamelan

Shared interactive flow and group flow are likely mechanisms to aid music ensemble performances. While there are plenty of different kinds of ensembles that could be examined, the current study focused on an ensemble type that affords greater opportunities for flow states, namely Javanese gamelan. Javanese gamelan requires that all individual instruments work harmoniously, allowing for the potential occurrences of shared interactive flow or group flow, and the native equivalent, *ngeli*, meaning to float together (Tan et al., 2020). Underpinning the egalitarian ethos of gamelan is interlocking synchrony of structural instruments and repetitive cyclical patterns, whereby governance is distributed throughout the ensemble in an algorithmic sense, and individual and combined outcomes are reciprocally predicted and monitored (Matthews, 2018). As opposed to the case of a Western orchestra, where the first violin or conductor may act as lead roles, gamelan is non-hierarchical in that all instruments are of equal significance (Sorrell, 1990).

Most types of gamelan cross-regionally share the same fundamental basis: a core melody, punctuation of the melody, and drumming patterns (Loth, 2016). Although there are some differences between gamelan practises specific to different regions, its conceptual basis of meaning and structure varies minimally (Loth, 2014). In traditional pieces or *gendhing*, the core melody, or *balungan* line, consists of groups of 4 beats, known as *gatra*, which is typically taught aurally or through prescribed written notation (Sorrell, 1990). A *gendhing* incorporates cycles of series of *gatra* in which melodic parts play the continuous *balungan* line, and other structural instruments play interlocking beats punctuating the structure (Pickvance, 2005). Generally, a drummer typically leads the group from the start to the end of pieces, signalling changes in tempo and section (Macdonald et al., 1999). The structural instruments are not as technically demanding as the drums, melodic or solo instruments, yet these parts are equally important in their role of signalling subdivisions of the structure for the rest of the players. The end of each cycle is marked by a gong, which also acts as a signifier to return to the start. This cyclical, and inevitably, repetitive nature of gamelan allows for effortless memorisation and full absorption for individuals in the activity (Diamond, 1979), and in turn, shared flow state.

Although gamelan has these general structures as described above, we look at two overall styles of gamelan: playing from a traditional piece and improvisation. Within traditional pieces, structural and temporal changes require individuals to think beyond their individual roles. For instance, how a change in drumming pattern might trigger rhythmic subdivisions for certain instruments, and how a change in register for those same instruments might trigger a change of section and melodic material for the entire ensemble. Such structures and ensemble dynamics may allow for the potential rise and fall of flow through the fluctuations in shared attention. Therefore, in the context of traditional gamelan, the actions of one influence another, spreading throughout the ensemble. Where traditional pieces are often written down, players may focus primarily on their individual roles, and intermittently be forced into an awareness of the changeable interactive setting. This may subsequently facilitate shared interactive flow, as this is related to individual flow experience of flow in an interactive setting, whereby individuals are focused on their tasks, or individual parts and their interaction with others (Hackert et al., 2022). Improvised playing, on the other hand, involves a great degree of self-other merging and shared awareness, and therefore lends itself more to group flow due to the entire focus being on the shared task as a result of the social interaction. Findings from Liebermann-Jordanidis et al. (2021) may support this, as they found interpersonal coordination to be facilitated by simultaneous self-other segregation and integration, allowing for performers to adapt to and anticipate the actions and timings of others. Improvisations are not so typical in traditional gamelan ensembles. However, there are exceptions for instruments requiring a greater level of skill, where elaborations around the melody tend to have a degree of improvisatory character (Perlman, 2004). Furthermore, gamelan lends itself well to group improvisation. Indeed, improvisationis a prevalent technique in both gamelan-based music therapy and community music groups in the United Kingdom, as the instruments are tuned to scales that allow for harmonies which form a cohesive sound with ease (Loth, 2014, pp. 113–114).

Depending on individual ability and level of group training, which is seen to be paramount to fostering group flow experiences (Salanova et al., 2014; Pels et al., 2018), a highly skilled gamelan group may reach group flow in playing a traditional piece, so long as all individuals were extremely familiar with their individual parts, which may not be the case with beginner groups. This is also supported by an assertion by (Sawyer, 2015) that group flow is more likely to occur when all agents are equally involved in the creative process, and consequently, group flow may be unachievable if players do not have comparable skills.

1.3. Measurement of flow

1.3.1. Self-reports

Many studies on shared flow centre on qualitative investigation through means of phenomenology or grounded theory (Hart and Di Blasi, 2015; Hill et al., 2018) or retrospective pre-validated scales. In measuring flow quantitatively, the Flow State Scale or Flow State Scale-2 (Jackson and Marsh, 1996; Jackson and Eklund, 2002), for instance, have been used to assess the presumed level of shared flow by equivocating the individual's experience to that of the group (Keeler et al., 2015; Gaggioli et al., 2017). Alternatively, scales designed to measure the shared flow experience rather than the individual could be adopted and validated in musical contexts, according to Tay et al. (2021). One suggestion is the group task absorption scale by Salanova et al. (2014). However, the Shared Flow Scale by Zumeta et al. (2016) might be a better tool. Although this tool does not align with the theory of Hackert et al. (2022) nor does it differentiate between the potential experiences of shared interactive flow and group flow, it yields greater promise. First, it is based on the flow items posited by Jackson and Marsh (1996) and replaces individual pronouns with plural. Second, it was validated in the context of a drumming march.

A self-report measure may not be enough to disentangle shared interactive flow from group flow. However, one potential way of viewing the differentiation is by considering Hackert et al. (2022) assertion that group flow may be measurable from a third-party observation or objective measure, even when not evident from an individual perspective. A continuous and undisruptive measure may therefore be employed alongside the Shared Flow Scale, such as physiological measures.

1.3.2. Physiological indicators of flow state

Flow states have been said to co-activate both branches of the autonomic nervous system; the sympathetic branch, linked to the fight-or-flight response, and the parasympathetic branch, linked to rest and digestion (Tozman et al., 2015).

Much of the work on physiological indicators of flow state has primarily assessed Heart Rate Variability (HRV) which has been associated with domains of flow linked to concentration or balanced challenge and skill. This has been observed through a linear relationship with parasympathetic activation (Peifer et al., 2014; Tozman et al., 2015; Bian et al., 2016; Thissen et al., 2021), and moderate sympathetic activation (de Manzano et al., 2010; Peifer et al., 2014). Taken together, these findings form a varied understanding of how cardiovascular activity might be related to flow, but generally, it is agreed that it is indicative of co-regulation of sympathetic and parasympathetic activity (Ullén et al., 2010; Tian et al., 2017; Thissen et al., 2021), potentially in the form of an inverted-u-shape (Peifer et al., 2014; Bian et al., 2016). Such studies indicate the substantial potential of HRV to measure potential flow experience. However, the necessity to calculate such variance over at least 5 minutes (Task Force of the European Society of Cardiology the North American Society of Pacing Electrophysiology, 1996) does not allow for the ability to observe momentary changes in parasympathetic and sympathetic activation. While HR changes as indicators of flow activity may be confounded by physical exertion (Jaque et al., 2020), there still seems to be potential to relate heart rate (HR) changes to changes in flow experience in the context of music performance (Horwitz et al., 2021; Jha et al., 2022). Ultimately this is due to the potential for sympathetic and parasympathetic activity to increase or decrease HR, respectively (Pérez et al., 2021).

In addition to cardiovascular activity, skin conductance (SC), is also prevalent in studies on physiological responses and flow state due to it being indicative of arousal in the sympathetic nervous system (Bian et al., 2016), and flow requiring a moderate level of arousal between boredom and stress (Csikszentmihalyi and LeFevre, 1989; Peifer et al., 2014). Supporting this notion, Tian et al. (2017) found moderate levels of SC as being related to flow experience compared to that of stressful states. SC changes have also been linked to mental effort associated with planning and execution in piano improvisation

(Dean and Bailes, 2015), which could, in turn, suggest an important role for SC in the study of flow in dynamic music performance.

While the outlined studies show relationships between individual flow states, we move to consider how shared flow experiences may be reflected by shared physiological patterns. One study that attempted to assess the relationship between these variables in chamber musicians was conducted by Horwitz et al. (2021), however, no significant relationship between synchronised flow experiences and overall HR means was observed. As shared flow experiences often encompass synchronised movements (Gloor et al., 2013), and self-other overlap are related more specifically to group flow (Hackert et al., 2022), it is relevant to also consider physiological parameters related to these facets specifically.

Self-other overlap, crucial to the presence of shared interactive flow and group flow, is related to social bonding, perspective-taking, cooperation and coordination (Galinsky et al., 2005), all of which have been related to coupling of physiological measures (Vanutelli et al., 2017; Gordon et al., 2020; Tomashin et al., 2022). Physiological coupling of both SC and cardiac activity in dyadic interactions or groups has been noted in numerous contexts, typically *via* methods of inter-subject correlation (ISC) of time-series data. HR has been found to synchronise in response to shared cognitive processing of video stimulus (Madsen and Parra, 2022), and audio narratives (Pérez et al., 2021), but also in response to co-ordinated action in group drumming (Gordon et al., 2020) and togetherness in improvised movement (Noy et al., 2015). Tomashin et al. (2022) found that physiological synchrony could predict group cohesion, resulting from both levels of coordination in drumming and a group decision-making task. Coupling of both SC and RR has been found to occur across audiences of live concerts (Czepiel et al., 2021), and in group decision-making tasks (Gordon et al., 2021). Furthermore, HRV has been found to synchronise across individuals (Ruiz-Blais et al., 2020; Lange et al., 2022). Nonetheless, to our knowledge, there has yet to be any study of ISC of physiological continuous signals in music performance contexts, nor has there been any insight into how shared flow might be reflected in shared physiology.

1.4. Aims

The synchronised, interlocking, repetitive, and egalitarian aspects of gamelan described yield an optimal opportunity to disentangle shared interactive flow and group flow. Self-reported measures in flow research are often used to assess an individual's perceived shared flow experience, but in group flow, this is more likely to be assessed from an objective measure (Hackert et al., 2022). We assess this through a combination of self-reports on flow and physiological measures. Here, the assumption is that a greater sense of collectivism or cohesion would lend itself to greater physiological togetherness (Gordon et al., 2020; Tomashin et al., 2022) and in turn potential group flow. Given the outlined research gap in clarifying the distinctions between shared interactive flow and group flow, and measuring physiology in group performance contexts, we predict potential associations between group flow (rather than shared interactive flow) and physiological coupling. Ultimately, this is due to an optimum paradigm for group flow being when individuals are working together on a task involving great interactivity and interdependence, resulting in the highest level of interpersonal connectedness.

Since coordinated action, such as in musical ensembles, is associated with synchronised physiological responses (Ruiz-Blais et al., 2020; Hoehl et al., 2021), we were interested in whether such an effect emerges more in a setting facilitating group flow (improvised playing) than in shared interactive flow (traditional playing). There is a need to extend our understanding of physiological synchrony through quantitative naturalistic experimental designs (Chabin et al., 2020; Tervaniemi, 2023), and the outlined literature indicates links between physiological mechanisms and flow states. While the one hand, individual flow has been related to physiological signatures (de Manzano et al., 2010; Thissen et al., 2021), and on the other, shared actions are related to synchronised physiology, to our knowledge, no study yet has directly investigated these links between shared physiology with shared interactive flow and group flow. As Pels et al. (2018) recommended, studies should investigate conditions under which group flow may occur. Consequently, this study aimed to test whether there are associations between synchrony of physiological measures, individual and shared flow states; in addition, whether traditional or improvised playing as well as the level of experience with playing gamelan have any influence on these potential associations.

The following research questions will therefore be considered:

> *RQ 1* Is the Shared Flow Scale in gamelan playing valid and reliable in its proposed factor structure?
>
> *RQ 2* Is there a difference in significantly correlated windows of physiological synchrony between participants when playing traditional gamelan music compared to improvising as a group, and does this differ between levels of expertise?
>
> *RQ 3* How does self-reported shared flow relate to average physiological synchrony in traditional and improvised playing?

2. Materials and methods

2.1. Participants

Participants with varying experience of playing gamelan were invited for one of three recording sessions. The first recording session consisted of participants with prior experience of gamelan playing recruited from the current members and tutors of Gamelan Sekar Petak, a gamelan group based at the University of York, United Kingdom ($N = 13$, age $M = 29.6$, $SD = 10.2$, 61.5% female). The second and third recording sessions consisted of participants with no, or very minimal, prior experience of playing gamelan ($N = 16$, age $M = 24.75$, $SD = 5.58$, 62.5% female) and were students recruited from the University of York (mostly from the music department). This latter group was divided into two equal-sized groups for two recording sessions. For both groups, players' instrumental parts encompassed different instrumental groups: structural instruments of *gongs* and *kempuls* (shared by one player in the beginner group and played by two players in the advanced group); *kethuk* and *kenongs* (similarly shared by one player in the beginner group, and played by two players in the advanced group); *bonang barung* and *bonang panerus* parts; and metallophone *balungan* instruments of *sarons, slenthem and demung.*

The advanced group included: *kempyang,* played alongside the *kethuk* by the same player; an added *peking*, a slightly more elaborating *balungan* instrument; *kendhang* and *ciblon,* a set of drums playing intricate patterns that use a variety of techniques; and *gender*, a complex metallophone playing elaborate patterns weaving around the *balungan* line with both hands.

2.2. Procedure

Both experience groups played two pieces: one traditional gamelan piece from central Java that was selected to suit their collective ability and were asked to improvise a piece as a group spontaneously. The advanced group played *Ladrang Pangkur Pelog Pathet Barung* (12 min and 56 s), which had been rehearsed for several months in preparation for a concert and a dance performance. The beginner groups were taught the principles of gamelan playing and learnt their traditional piece the same morning under the guidance of a tutor, which was *Lancaran Baita Kandas Pelog Pathet Nem* (5 min and 5 s for the first beginner session, and 5 min and 51 s in the second beginner session due to an additional repetition of the opening cycle). *Baita Kandas* was largely learnt aurally due to the unfamiliarity of gamelan notation for beginners, while many players of *Pangkur* relied on the notation to varying degrees. Little instruction was given on how to navigate improvisations; players were simply asked to leave space for others, not feel pressured to play constantly and be mutually responsive to one another. Before the session, and after playing both the traditional and improvised pieces, participants completed questionnaires (detailed below), while physiological measures were taken throughout the performances. The entire sessions were video recorded. The recording sessions, including the set-up of devices, lasted around 90 min each. Due to measurement error, physiological data from two participants for each group was removed completely (total $N = 25$, experienced $N = 11$, beginners $N = 14$).

2.3. Measures

2.3.1. Self-report measures of flow state

As the study was exploratory, and to our knowledge the first of its kind, a wide variety of pre- and post-experiment measures were taken. Several of these measures encompassed items relating to the nine dimensions of flow state theorised by Csikszentmihalyi (2000):

1. Balance between the challenges of and the related individual skills for a given task.
2. Clear goals for the task.
3. Unambiguous, ongoing feedback on the progress of task accomplishment.
4. Concentration on the task at hand.
5. Merging of action and awareness.
6. Loss of self-consciousness.
7. A sense of control.
8. Transformation of time.
9. An autotelic experience.

Although we used the Dispositional Flow Scale (DFS-2), and the CORE Flow State Scale (Martin and Jackson, 2008), this paper just focuses on the experience of shared flow, using the Shared Flow Scale (SFS), a 27-item 5-point likert scale (Zumeta et al., 2016). This scale is based on a Spanish version of the original DFS (Jackson and Marsh, 1996) and an adaptation (Calvo et al., 2008), in line with the nine dimensions of flow outlined above. It assesses the experience of flow after participation in an activity, and rather than assessing the individual experience as the DFS-2 does, it instead assessed shared flow by replacing singular personal pronouns of 'I' with 'we'. Due to the exploratory and multi-faceted interests of our study, several other measures were also attained, including the Goldsmiths-Musical Sophistication Index (GOLD-MSI Müllensiefen et al., 2014), the Positive and Negative Affective Schedule (PANAS) (Watson et al., 1988), the Perceived Emotional Synchrony Scale (PESS) (Wlodarczyk et al., 2020), and the Warwick-Edinburgh Mental Wellbeing Scale (WEMWBS) (Tennant et al., 2007). However, as this paper and associated research questions are focused solely on the intersections of shared flow and physiological synchrony we do not include these in our analyses here.

2.3.2. Physiological measures

Skin conductance (SC) and electrocardiogram (ECG) measures were recorded using Shimmer Sensors, where measurement areas for sensor electrodes were prepared using 70% alcohol swabs. ECG was measured *via* a four-lead configuration from the chest. From these measures, heart rate (HR) and skin conductance (SC) were extracted to reflect an individual's physiological arousal. SC was measured *via* the inside of the right foot, which is a comparable anatomical recording site to that of the typical hand configuration (Sanchez-Comas et al., 2021; Hossain et al., 2022). This method was also selected due to having greater ecological validity, as it allows for the participant to play gamelan freely with both hands and because players traditionally remove outer footwear regardless as a way of showing respect to the instruments.

2.4. Data analysis

2.4.1. Physiological pre-processing

Physiological data, recorded at 256 Hz, were pre-processed using custom-made scripts for MATLAB. ECG data were pre-processed using a Butterworth bandpass filter with 0.2 and 12 Hz cutoff points, and 4th order zero-phase filtering. We extracted the ECG from the standard lead II configuration (Golland et al., 2015; Gordon et al., 2021). Following this, inter-beat intervals (IBIs) were calculated from the peaks of the ECG. Continuous HR was then calculated from the IBIs using the 'interp1' MATLAB (with the 'nearest' method specified) and lowpass filtered at 0.05 Hz. Only HR values between 40 and 140 beats per minute, typically associated with healthy resting HR for adults, were used in subsequent analyses. This step was taken to ensure the exclusion of any inaccurate data resulting from measurement error ($N = 3$). SC data were pre-processed using Butterworth lowpass filtering with a 0.5 Hz cutoff point and any further signals observed to be inaccurate were discarded ($N = 7$) The whole SC signal was used in all analyses. This resulted in $N = 9$ SC and $N = 10$ HR remaining signals for the advanced group, and $N = 9$ SC and $N = 12$ HR remaining signals for both beginner groups combined.

2.4.2. ISC of physiological signals and statistical significance

Both HR and SC signals were segmented into musically meaningful bins per bar, or *gatra* in Javanese terminology. A *gatra* typically encompasses a set of four notes for the *balungan* or melody line, which forms a part of a whole cycle, often in multiples of four or eight punctuated by structural instruments, and repeated.[1] Gamelan music is usually analysed in terms of these four-note *gatra* (Pickvance, 2005), and in this context, a *gatra* ranged from three to a maximum of 7 seconds in length depending on the tempo of the section. For the improvisation, the signals were segmented into bins of equivalent duration to that of the traditional pieces, of around 3 seconds. Physiological synchrony was obtained from instantaneous SC and HR signals with inter-subject correlation (ISC) analyses. We calculated Pearson's r values between all possible dyads within groups, within windows of 8 *gatra* overlapping by 4, which was decided on due to the gamelan cycles in the pieces selected working largely in structures of 8 *gatra* which are repeated. The ISC procedure follows that of Pérez et al. (2021) and was calculated using their provided MATLAB scripts. Fisher's z transformation was applied to each dyadic ISC for each segment, before calculating the mean for each set of dyadic combinations per subject. Following this, the inverse Fisher's z transformation was applied.

Statistical significance of ISC was assessed by comparing ISC calculated with original, time-locked data with control data that was computed using circularly shifted segment shuffling. This yielded a control ISC for each dyad, repeated for each group for both HR and SC. The filtered continuous signal for each subject and section was circularly shifted by a random amount 10,000 times, producing control signals for each subject and section. The same ISC procedure was followed as above. Significance was determined by calculating the proportion of control ISCs above the threshold of the actual ISC for each subject, in both traditional and improvisational pieces.

For RQ1, we conducted a confirmatory factor analysis of the original Shared Flow Scale (Zumeta et al., 2016), followed by an exploratory factor analysis and confirmatory factor analysis to assess whether there was a more appropriate solution for the observed data. For RQ2, we observed points of significance across all pieces visually, before conducting Fisher's exact tests to determine whether the proportion of significant ISCs differed between traditional and improvised playing, and between experience groups. Lastly, for RQ3, overall ISC-SC and ISC-HR variables were calculated by averaging all ISC across sections, to produce a global ISC average across the piece per participant, ISC-SC_{mean} and ISC-HR_{mean}. This was calculated for traditional and improvised pieces separately. Linear mixed models these for each participant to analyse potential relationships between physiological synchrony and self-report shared flow factors.

1 In *balangun mlaku* style refers to a *gatra* with density of four notes, however *balangun nibani* style refers to a half-density *gatra* of two notes interspersed with rests, as described by Pickvance (2005, pp. 30-31). The pieces played in this study featured both styles, and so for the analysis, two *nibani* style *gatra* were equivocated with one *mlaku* style *gatra*, which were comparable in duration.

3. Results

3.1. Is the shared flow scale in gamelan playing valid and reliable in its proposed factor structure?

Confirmatory factor analysis was conducted for all 27 items of the Shared Flow Scale (Zumeta et al., 2016) across the 29 participants, to test whether the original model of nine dimensions was a reasonable fit for the observed data. This original model was not admissible, as the covariance matrix of latent variables was not positive definite.

Therefore, we wanted to see whether there was another more appropriate solution for the data. Exploratory Factor Analysis (EFA) was then conducted using parallel analysis based on factor analysis, a maximum likelihood estimation method, and oblimin rotation. This resulted in a two-factor solution. Confirmatory factor analysis (CFA) was repeated on the model provided by the EFA, using the highest loading items and a maximum likelihood restricted estimation. This confirmed a two-factor solution of 11 items with a reasonable fit for the observed data, given the small sample size, X^2 (43, N = 29) = 58.790, CFI = 0.906, TLI = 0.880, robust RMSEA = 0.102, SRMR = 0.095. Cronbach's α for this solution was given at 0.854 and 0.835, demonstrating very good internal consistency for each factor. This model is outlined in Figure 1, and parameter estimates are given in Table 1. Labels of *Awareness* and *Absorption* were given to each of the factors, to reflect items that encompassed elements of flow holding a great deal of awareness, in comparison to those that were absorbing and automatic. Average variance extracted (AVE) = 0.581 for *Awareness*, and AVE = 0.536 for *Absorption*, while the covariance between the factors was 0.612. For further analysis, composite scores for each of these factors were taken.

Data from two participants were removed for all subsequent analyses due to anomalous extreme values that could not be accommodated in further model specifications.

3.2. Is there a difference in significantly correlated windows of physiological synchrony between participants when playing traditional gamelan music compared to improvising as a group, and does this differ between levels of expertise?

To test for significant ISC of instantaneous SC and HR signals, pairwise ISCs for each participant were computed across 8 *gatra* sections for traditional pieces and an equivalent section in length of 24 s for improvised pieces, before averaging across pairs to produce one ISC-SC and one ISC-HR value per participant and section. These values were then compared to values resulting from randomly shuffled signals. Figure 2 displays these ISC values across each of the playing sessions, whereby statistically significant values are denoted *via* coloured dots. This shows that sections yielding significant ISCs are observed to some degree across both playing conditions and for both SC and HR, albeit more so for ISC-HR than for ISC-SC.

Fisher's exact tests were used to assess differences in the proportion of significant to non-significant values between the two levels of experience, with both beginner recording sessions combined,

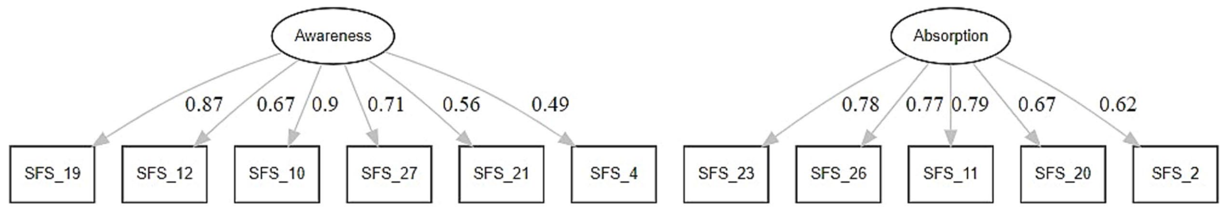

FIGURE 1
Factor loading plot showing standardised estimates of the two factors labelled *Awareness* and *Absorption*.

TABLE 1 Confirmatory factor loadings for SFS factors.

Factor		Item	Estimate	Std. Err	z-value	*p*
Awareness	SFS_19	"We felt we were competent enough to meet the high demands of the situation."	0.867	0.209	3.504	<0.001
	SFS_12	"We knew clearly what we wanted to do."	0.668	0.080	5.240	<0.001
	SFS_10	"Our abilities matched the high challenge of the situation."	0.904	0.205	3.544	<0.001
	SFS_27	"The group experience left us with a good impression, a good taste."	0.708	0.211	2.421	0.015
	SFS_21	"We knew what we wanted to achieve."	0.559	0.086	3.602	<0.001
	SFS_4	"It was really clear to us that we were doing well."	0.494	0.082	3.175	0.001
Absorption	SFS_23	"We felt totally absorbed by what we were doing."	0.776	0.195	2.934	0.003
	SFS_26	"We felt like time stopped while we were performing."	0.766	0.158	5.155	<0.001
	SFS_11	"We felt that things were happening automatically."	0.785	0.126	4.226	<0.001
	SFS_20	"We performed automatically."	0.669	0.244	2.326	0.020
	SFS_2	"We were doing things spontaneously and automatically."	0.616	0.127	3.216	0.001

N = 29.

and between playing conditions. Significance here was determined by measuring the proportion of synchrony values calculated from the original data compared to control data attained through circular shuffling, using FDR of 0.05.

For ISC-SC in traditional playing, there was a significant difference in the proportion of significant ISC-SCs between beginner and advanced experience groups ($p < 0.001$), a greater proportion of significant ISC-SC occurred for the advanced group than the beginner group in traditional playing. No significant difference in experience groups was found for improvised playing. We then split the data to isolate experience groups and account for differences between playing conditions within them. For beginner players, we found a significant difference in the proportion of significance between improvised and traditional playing ($p = 0.015$). Here, the proportion of significant ISC-SC seemed to be greater in improvised playing than in traditional playing for the beginner group. For the advanced group, a non-significant trend level difference between traditional and improvised playing was found for the advanced group ($p = 0.078$), whereby contrary to the beginner group, the proportion of significant ISC-SCs may have been slightly greater in traditional playing than in improvised playing. These results indicate that the proportion of significant ISC-SC values was greater overall for advanced players, at least in traditional playing, and that the proportion of significant ISC-SC between playing conditions when isolating beginner and advanced groups seemed to be opposing. Figure 3 displays these proportions of significance for ISC-SC graphically.

For ISC-HR, we found a significant difference between the beginner and advanced experience groups and the proportion of significance in traditional playing ($p = 0.006$) and in improvised playing ($p = 0.026$). Within these, beginners yielded a greater proportion of ISCs across both playing conditions. We then split the data to account for differences between playing conditions for each experience group separately. Overall, the proportion of significant ISC-HRs was significantly greater in improvised playing than in traditional playing for both the advanced group ($p = 0.03$) and beginners ($p = 0.009$). These results suggest that the proportion of significant ISC-HR values was greater overall for beginners, and overall for improvised playing. Figure 4 displays these proportions of significance for ISC-HR. Average significant ISCs were also compared between groups and playing conditions to assess differences in values (see Supplementary material).

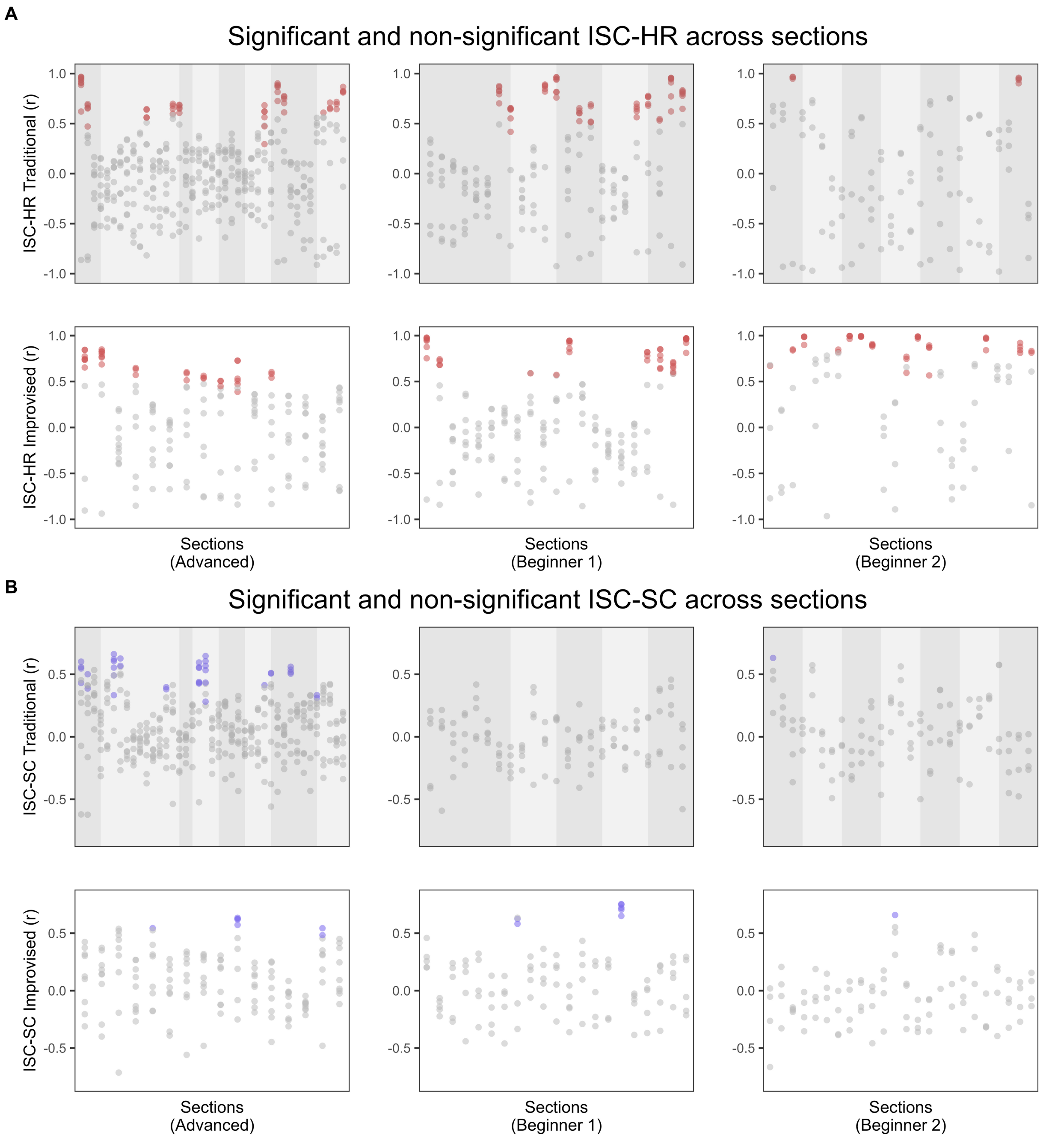

FIGURE 2
(A) ISC-HR and **(B)** ISC-SC computed for each participant and each section across traditional and improvised gamelan playing. Significance is denoted via coloured dots, using FDR of 0.05. Shaded regions indicate changes in musical material (i.e., where the section changes or more elaborating material is added) or tempo changes.

3.3. How does self-reported shared flow relate to average physiological synchrony in traditional and improvised playing?

For the following analyses, all significant and non-significant ISC values were averaged across all sections, providing overall measures of average physiological synchrony denoted by ISC-HR$_{mean}$ and ISC-SC$_{mean}$. Two separate linear mixed models were fitted for ISC-HR$_{mean}$ and ISC-SC$_{mean}$. For each of these, we investigated the fixed effects of playing conditions (improvised vs. traditional) and the shared flow factors, identified in response to the first research question of *Absorption* and *Awareness*. A random effect was only assigned experience level, as subject-level variance was negligible, and therefore did not warrant an additional subject-level random effect to explain the observed variance. Results for each indicated that the optimally fitting models involved an interaction between a shared flow factor and the playing condition.

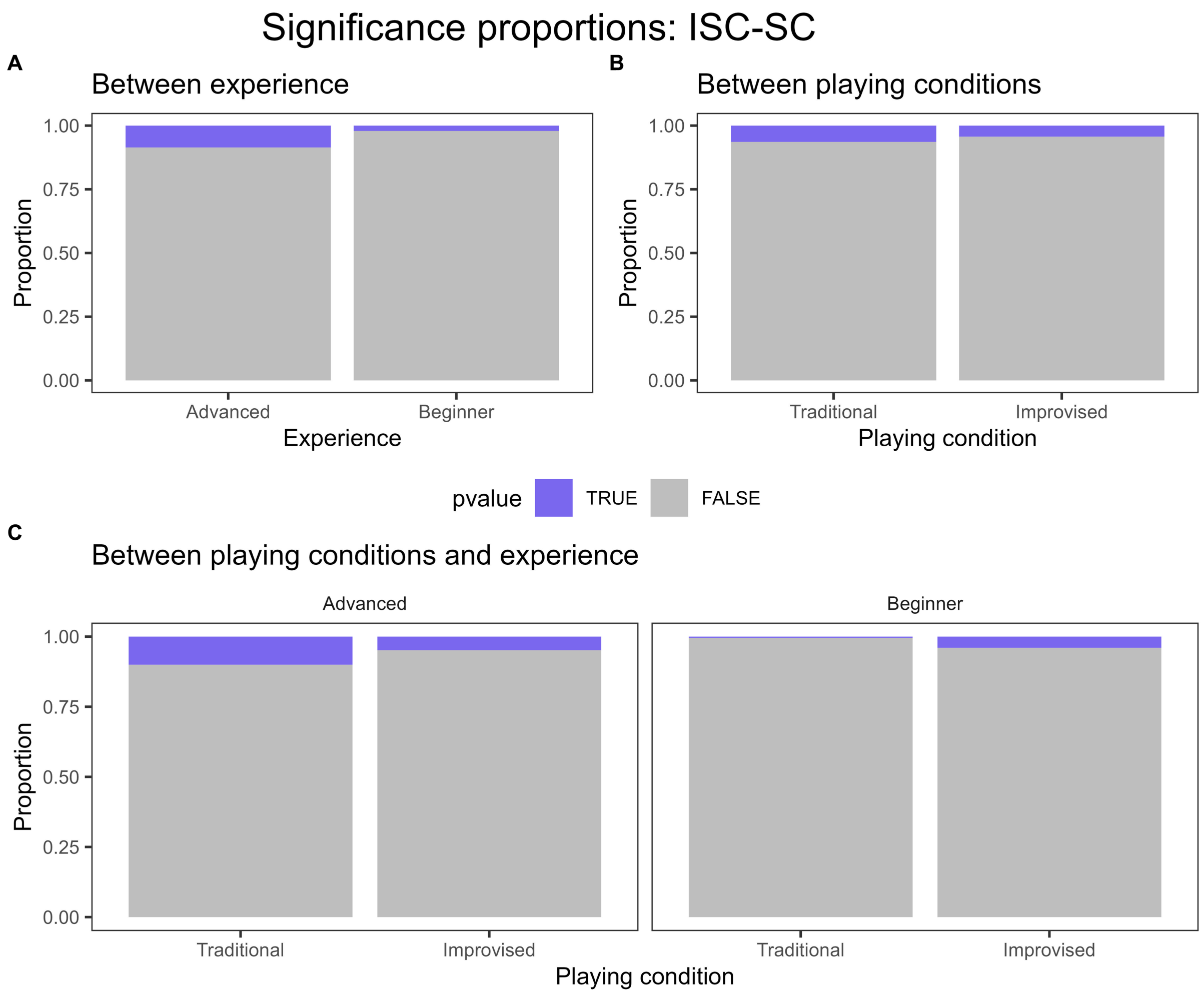

FIGURE 3
Proportion of significance for ISC-SC displayed in coloured regions for **(A)** between experience levels across both playing conditions, **(B)** between playing conditions across both experience groups, and **(C)** between both playing conditions and experience groups. Significance determined using FDR of 0.05.

3.3.1. Dependent variable ISC-HR$_{mean}$

For the first mixed model comparisons, detailed model comparisons are listed in Table 2, while full fixed effects results for these most optimally fitting models are provided in Table 3. An interaction model revealed that ISC-HR$_{mean}$ may be significantly predicted by shared *Absorption* as an overall fixed effect in improvised playing, though ISC-HR$_{mean}$ may decrease with *Absorption* specifically within traditional playing. An interaction model with shared *Awareness* demonstrated a trend-level fit above that of the condition model, and the findings of this were similar to that of shared *Absorption*. ISC-HR$_{mean}$ may be predicted by an overall fixed effect of shared *Awareness* in improvised playing, while ISC-HR$_{mean}$ seems to decrease with shared *Awareness* for traditional playing. Graphical figures are provided in Figure 5. These graphical figures suggest that contrary to the traditional playing condition, there may be a positive association between ISC-HR$_{mean}$ and both shared *Absorption* and *Awareness* for improvised playing.

3.3.2. Dependent variable ISC-SC$_{mean}$

For the second mixed model comparisons, a comparable pattern emerged. Detailed model comparisons are listed in Table 4, while full fixed effects results for this model are provided in Table 5. An interaction model indicated that ISC-SC$_{mean}$ may be predicted by an overall fixed effect of shared *Awareness* in improvised playing, while ISC-SC$_{mean}$ decreases with *Awareness* on a trend level in traditional playing, in the most optimally fitting model. Figures illustrating these predictions between factors of playing condition, shared flow factors, and ISCs are provided in Figure 6. Graphical visualisation shows that while the relationship between shared *Awareness* ISC-SC$_{mean}$ may be negligible in traditional playing, it seems to be positively associated in the context of improvised playing. Although the ISC-SC$_{mean}$ interaction model with shared *Absorption* did not show any significant improvement in the model fit, the related figure is still included for the sake of consistency.

4. Discussion

In furthering our knowledge of mechanisms of joint music-making, this exploratory study is the first of its kind to investigate the experience of shared flow and physiological correlates in the context of Javanese gamelan. The primary aims were to explore aspects of shared flow (RQ1)

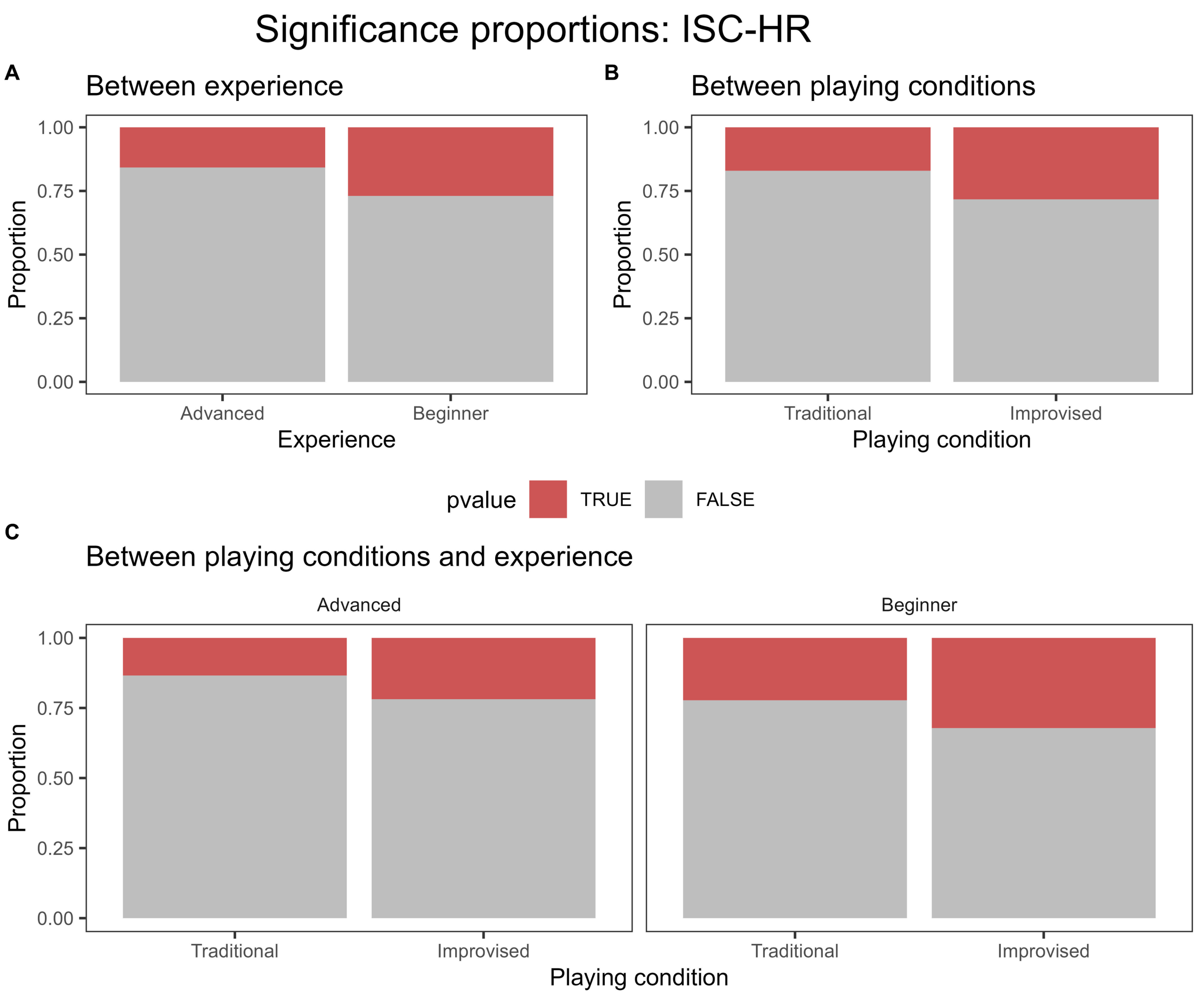

FIGURE 4
Proportion of significance for ISC-HR displayed in coloured regions for **(A)** between experience levels across both playing conditions, **(B)** between playing conditions across both experience groups, and **(C)** between both playing conditions and experience groups. Significance determined using FDR of 0.05.

TABLE 2 Dependent variable: ISC- HR_{mean}; independent variables: condition (traditional, improvised), shared flow factors (*Absorption*, *Awareness*).

Model	AIC	BIC	Marginal R^2	Conditional R^2	Improvement in model fit	
					$X^2(1)$	p
ISC- HR_{mean} Null Model	0.8	6.0		0.136		
ISC- HR_{mean} ~ Condition	−2.2	4.7	0.099	0.239	4.9991	0.02536
ISC- HR_{mean} ~ Condition + *Awareness*	−0.7	8.0	0.108	0.253	0.5083	0.4759
ISC- HR_{mean} ~ Condition × Awareness	**−3.5**	**6.9**	**0.190**	**0.339**	**5.3242**	**0.0698°**
ISC- HR_{mean} ~ Condition + *Absorption*	−0.4	8.3	0.103	0.233	0.1569	0.0692°
ISC- HR_{mean} ~ Condition × Absorption	−4.4	6.0	0.207	0.342	6.1872	0.0453°

Linear mixed effects model between ISC-HR_{mean} values and shared flow factors. Condition is given as a fixed effect, and experience group as a random effect. Bold text indicates the most optimally fitting model. Null model: HR ~ 1 + (1|experience). As compared to HR ~ Condition. $X^2(1)$ increases to $X^2(2)$ for two fixed effects, and $X^2(3)$ in interaction models; HR: $N = 21$.

and synchronised physiological parameters of heart rate (HR) and skin conductance (SC) *via* inter-subject correlation (ISC) (RQ2) while participants played Javanese gamelan pieces. We assessed whether there might be any differences in significant mean ISCs between the experience levels of the players and between improvised or traditional pieces. Finally, we assessed the extent that the physiological synchrony was related to self-reported flow (RQ3). Shared flow has scarcely been studied in group music contexts. Where it has, potential physiological patterns underlying the experiences have not been measured. Additionally, gamelan has had little attention from psychologists and presents an opportunity to study such effects in a highly ecologically valid setting, where cyclicality and egalitarianism meet in instrumental form. Our findings revealed a complex picture of the differences in ISC-HR and ISC-SC underlying traditional playing and improvised playing between experience groups. Shared flow factors and ISCs were positively associated with each other for improvised playing, and negatively for traditional playing.

TABLE 3 Fixed effects results for the most optimally fitting interaction models with ISC-HR_{mean} as a dependent variable.

Dependent	Estimate	Std. Error	*df*	*t*	*p*
ISC-HR_{mean} ~Condition × Awareness+(1|experience)					
(Intercept)	0.191	0.078	2.870	2.441	0.096†
Condition (traditional)	−0.109	0.062	39.993	−1.758	0.087†
Awareness	0.125	0.058	40.023	2.140	0.039*
Condition (traditional):Awareness	−0.186	0.082	39.993	−2.262	0.030*
ISC-HR_{mean} ~Condition × Absorption+(1|experience)					
(Intercept)	0.202	0.075	2.784	2.707	0.080†
Condition (traditional)	−0.120	0.060	39.946	−2.010	0.051†
Absorption	0.110	0.053	40.424	2.073	0.045*
Condition (traditional):Absorption	−0.190	0.074	39.946	−2.551	0.015*

†Denotes non-significant trend at $p \leq 0.10$, *denotes significance at $p < 0.05$. $N = 21$.

In addressing our first research question, we used the Shared Flow Scale (Zumeta et al., 2016) to explore aspects of shared flow. The SFS was initially selected for two reasons. First, the scale had previously been used in a comparable context of a drumming march at a festival. Second, shared flow has been identified as parallel to a Javanese concept of *ngeli* specifically in a gamelan ensemble. However, in its original form, our confirmatory factor analysis of the Shared Flow Scale (Zumeta et al., 2016) did not yield an admissible model. This could have been due to the situation. Shared flow experiences in situations of music-making might be fundamentally different to the classic nine-factor conceptualisation shared with Csikszentmihalyi's (2000) flow. For that reason, it may be difficult to capture such an experience using similar scales. Instead, our solution encompassed factors that we labelled as *Awareness* and *Absorption*, reflecting both the absorbing and challenging nature of gamelan playing. We see these factors as potentially comparable to the need for simultaneous self-other integration and separation in group music performance, highlighted by Liebermann-Jordanidis et al. (2021). However, the SFS does not clearly distinguish between potential antecedents and outcomes of shared flow, and where antecedents may be equivalent across both shared interactive flow and group flow, the outcomes may differ (Hackert et al., 2022). Future work involving self-reports on shared flow experiences may therefore wish to explicitly differentiate between antecedents and outcomes through the use of separate scales or groups of items.

Our findings regarding the potential differences in both the proportion of significant ISCs and the overall value of significant ISCs were mixed. We found a greater proportion of significant ISC-SC for advanced players compared to beginner players, while the opposite was true for ISC-HR. When splitting the data by experience, the proportion of significant ISC-HR seemed to be greater for improvised playing than traditional across both experience groups, while for

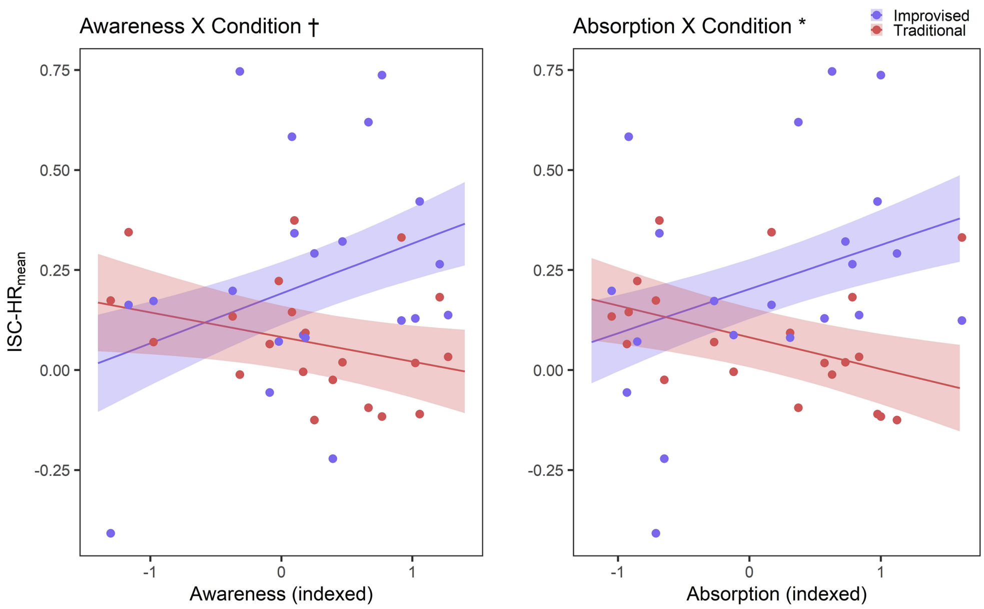

FIGURE 5
Results for RQ3. Graphical depiction of predictions of ISC-HR_{mean} by shared flow factors interacting with music condition. Shaded areas represent standard error. Predictions for ISC-HR_{mean} in improvised playing are represented in blue, while traditional playing is represented in red. † Denotes trend-level model fit improvement at $p \leq 0.10$, *denotes significant model fit improvement at $p < 0.05$.

TABLE 4 Dependent variable: ISC-SC_{mean}; independent variables: condition (traditional, improvised), shared flow factors (*Absorption*, *Awareness*).

Model	AIC	BIC	Marginal R^2	Conditional R^2	Improvement in Model Fit	
					$X^2(1)$	p
ISC-SC_{mean} Null Model	−66.8	−62.2		0.201		
ISC-SC_{mean} ~ Condition	−64.8	−58.7	0.002	0.203	0.0639	0.800
ISC-SC_{mean} ~ Condition + Awareness	−65.5	−57.9	0.065	0.254	2.7614	0.251^
ISC-SC_{mean} ~ Condition × Awareness	**−67.0**	**−57.8**	**0.139**	**0.332**	**6.2524**	**0.100^**
ISC-SC_{mean} ~ Condition + Absorption	−62.8	−55.2	0.002	0.207	0.0766	0.962^
ISC-SC_{mean} ~ Condition × Absorption	−65.1	−56.0	0.098	0.309	4.3746	0.224^

Linear mixed effects model between mean ISC values and shared flow factors. Condition is given as a fixed effect, and experience group as a random effect. Bold text indicates the most optimally fitting model. Null model: SC ~ 1+ (1|experience). ^As compared to SC Null Model. $X^2(1)$ increases to $X^2(2)$ for two fixed effects, and $X^2(3)$ in interaction models; SC: $N = 17$.

TABLE 5 Fixed effects results for the most optimally fitting interaction model with ISC-SC_{mean} as a dependent variable.

Dependent	Estimate	Std. Error	*df*	*t*	*p*
ISC-SC_{mean} ~ Condition × Awareness + (1|experience)					
(Intercept)	0.042	0.033	2.954	1.264	0.297
Condition (traditional)	0.011	0.026	31.995	0.424	0.674
Awareness	0.065	0.025	32.028	2.605	0.014*
Condition (traditional):Awareness	−0.068	0.035	31.995	−1.921	0.064†

†Denotes non-significant trend at $p \leq 0.10$, *denotes significance at $p < 0.05$. $N = 17$.

ISC-SC, the difference in the proportion of significance between the two playing conditions was opposing for each experience group, at least on a non-significant trend level. Potentially this could indicate differences in required effort associated with levels of expertise and resultant physiological parameters. Furthermore, beginners were taught their parts aurally, while many of the advanced players still relied on written notation. This distinction may have also accounted for these inconsistencies between measures.

HR indicates activity of both the sympathetic and parasympathetic branches of the autonomic nervous system, while SC is an indicator of sympathetic activity alone. Accordingly, the differences in findings between experience levels and playing conditions are not necessarily surprising. Levels of attention may not affect parasympathetic activity (Pérez et al., 2021), while the degree of challenge and associated effort facilitating flow experience might (Thissen et al., 2021). Further to this, sympathetic activation as an indicator of arousal appears to form an inverted U-shape relationship with flow (Peifer et al., 2014; Tozman et al., 2015). For that reason, it seems plausible that a greater proportion of significant ISC-HR was present for beginner players who may have felt more of a fluctuating shared sense of challenge overall. Nevertheless, when observing the differences between playing conditions for each experience group separately, improvised playing yielded a greater proportion of significant ISC-HR for both groups. This perhaps instead relates to improvisation leading to greater levels of togetherness, enhanced engagement, and enjoyment (Noy et al., 2015), which may also be supported by a greater proportion of significant ISC-SC in improvised playing compared to traditional playing for beginners. Meanwhile, the finding of a greater proportion of significant coupling in traditional playing for advanced players may be attributed to heightened arousal levels, in that their piece involved more temporal and structural changes than the beginner piece. These findings must be taken with great caution, however, as the number of significant data points for ISC-SC was far fewer than for ISC-HR, and the sample is small overall. As such, we acknowledge these findings are limited in their power and form merely a starting point in a novel area of research. There is a necessity to further disentangle the roles of shared sympathetic and parasympathetic activity in relation to shared flow experiences in differing contexts. Future studies with greater power may therefore find it worthwhile to explore such effects of expertise and playing style further.

Crucially, through the use of linear mixed effects models, we found that overall physiological synchrony underlying flow seems to be fundamentally different between improvised and traditional playing. The shared flow factors seemed to negatively predict mean ISCs in traditional playing, and positively predict mean ISCs in improvised playing, on at least a trend level. These findings support the notion that ISC might not only occur in situations involving joint listening settings (Czepiel et al., 2021; Dauer et al., 2021; Pérez et al., 2021), but also in joint music performance settings. Extending knowledge of how more successfully coordinated action may result in greater physiological coupling on some level, even for non-experts or those with a low level of in-group familiarity (Gordon et al., 2020; Ruiz-Blais et al., 2020), our results demonstrate a novel contribution of shared flow experiences. Tightly coordinated actions are necessary for the successful performance of music, which in turn is often found to involve some degree of shared flow experience (Cochrane, 2017; Tay et al., 2021; Magyaródi et al., 2022).

Contrary to a previous finding that did not find a relationship between shared flow and overall mean HR (Horwitz et al., 2021), we observed a relationship between mean physiological coupling and shared flow. As this relationship seems to differ between improvised and prescribed playing conditions, there seem to be differences between physiological behaviours underlying shared interactive flow

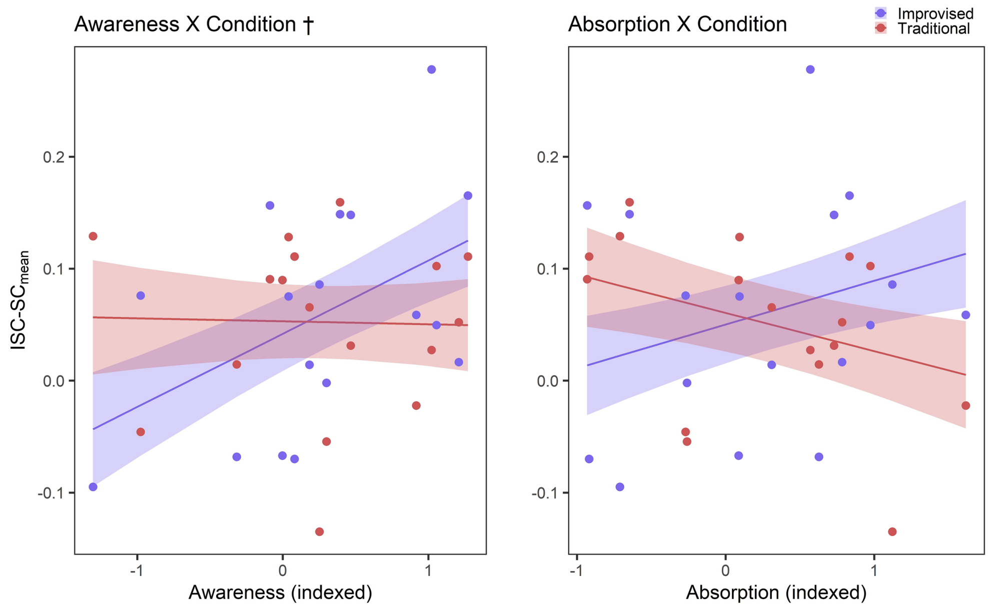

FIGURE 6
Results for RQ3. Graphical depiction of predictions of ISC-SC$_{mean}$ by shared flow factors interacting with music condition. Shaded areas represent standard error. Predictions for ISC-SC$_{mean}$ in improvised playing are represented in blue, while traditional playing is represented in red. † Denotes trend-level model fit improvement at $p \leq 0.10$.

and group flow. This finding may support the potential for improvised playing and associated flow to result in greater physiological connectedness. As Hackert et al. (2022) theorise, group flow arises from a context in which it relies on the interactivity of the ensemble. Shared interactive flow experiences are rather experienced on the individual level, as the occurrence of flow is not solely dependent on interactivity. The differences between these might be evident in the differences between traditional and improvised gamelan playing. In the former, many participants in the advanced ensemble were playing from notated music, especially the less experienced advanced players. Similarly, although the beginners were taught aurally initially, there was not enough time in the workshop dedicated to ensuring all players were aware of the inner workings of all parts with fluency. The resultant piece may have therefore been played successfully without much awareness towards the group, aside from the occasional tempo change or section change. For improvised playing, on the other hand, interactivity is fundamental to group improvisation, regardless of experience levels. Experience level was incorporated as a random effect in the linear mixed models due to mixed and minimal differences in the proportion of significant physiological synchrony between experience groups, and we did not acknowledge differences in learning style (i.e., from notation or memory) in our questionnaire. As such, these ideas are merely speculative, and we encourage future studies to explore the potential influence of learning style on the relationship between shared interactive flow, group flow, and underlying physiological synchrony.

5. Limitations

We emphasise here that almost all players in these ensembles were Western university students. The results may have looked quite different for more experienced gamelan players, especially those residing in Java who rehearse in more traditional ways. Something integral to the practise of gamelan is the focus on the group as a whole, rather than individual's role within it. This notion may be difficult for Western players to fully resonate with, and therefore their engagement with traditional playing may still come from their Western ensemble experiences. Our advanced group, Gamelan Sekar Petak, is comprised of players who have been learning gamelan for many years, with some having studied in Java, alongside students who may have only been learning gamelan for less than a year at the university. Further to this, Gamelan Sekar Petak does not typically improvise in their rehearsals. It would, therefore, be fruitful to replicate the study with more experienced groups, groups in which members are comparably experienced, and/or groups that are more accustomed to improvisation. We anticipate that for groups with comparable traditional playing expertise to that of Gamelan Sekar Petak, and perhaps more experience with improvisation, similar results may arise. However, for more experienced gamelan groups, with comparably little improvisation experience, group flow experiences may be positively associated with physiological synchrony in the context of traditional playing. Subsequently, the degree to which our results are generalisable is unclear.

Our most prominent limitation is the small sample size of the study and unequal group sizes. In gamelan, the number of players is restricted due to the number of instruments, and thus the only way of increasing this sample is by studying the experience of multiple groups or multiple sessions with each group. The consequences of our sample comprising only two groups of varying experience levels, and recorded over three experimental sessions, may have had implications for every stage of the analysis. The beginner players were separated into two experimental sessions, also due to the number of instruments available, and the experience of these beginners may have been different between groups. The familiarity between group members was also not considered. Aside from differences in the experience of gamelan between the advanced group and the beginner group, they also differed in the amount of time in which they have been playing together and have known one another. Some beginner players may have known one another due to how they were recruited, but this was not accounted for in the data.

To tailor the potential for flow experiences to arise and improve the potential compatibility between participants' skills and level of potential challenge, different pieces were selected for the beginner group and the advance group. The beginners' piece was particularly repetitive and featured a short amount of musical material with only one melodic variant, and few tempo changes. This allowed players to learn the piece from memory in a short amount of time. To suit the ability of the advanced players, their piece was lengthier, with more variations to the structure and tempo and additional, more complex instruments. The differences in instrumentation, style, structure, and form of these pieces could have led to quite different flow experiences between groups. Furthermore, although the advanced players' piece had been rehearsed for several months beforehand, many players were still reliant on the notation, while some had been familiar with the piece for years. Discrepancies in the learning style (i.e., aurally or written) were therefore present on both inter-and intragroup levels. Overall, a limitation of any quasi-experimental study design is that not all inter-individual differences, including and beyond those described, can be accounted for and controlled for. Future work may wish to improve experimental control, however as this is the first exploratory study in this area, its naturalistic study design necessitated compromises.

With regards to physiological measurement, SC sensors attached *via* the foot seemingly have not been used in an experiment of this kind before. Similar sensors monitoring SC attached to the hand were used to monitor shared physiological responses in response to a stimulus, rather than active activity, such as listening or group decision-making tasks (Czepiel et al., 2021; Dauer et al., 2021; Gordon et al., 2021). Furthermore, participants' body hair was not removed to minimise discomfort and invasiveness as much as possible, and as a result, the preparation of the area for recording ECG was not at an optimum. To that end, much of the loss of data and suitable signals may be associated with participants' continual movement and changing of sitting position, resulting in poor contact between the electrodes and the skin or disconnected leads.

Lastly, in an effort to improve ecological validity and reduce disturbance to the natural playing environment, questionnaires were only completed before and after the entire playing session, meaning any flow experience that differed between improvisation and traditional playing cannot be discerned. Further to this, the questionnaire was completed following the improvised session for both groups, and the experience of that may have been at the forefront of participants' minds when responding to the SFS which asked for the overall experience of both traditional and improvised playing.

6. Conclusion

This study is the first to our knowledge that demonstrates the potential for shared flow experiences to be reflected by physiological synchrony and contributes to the sparse research into physiology in joint music-making. Importantly, in diversifying our understanding of music performance not just in Western music making, we explore ensemble performance in Javanese gamelan.

Within our study, two groups of differing levels of experience played traditional gamelan pieces and improvised as a group, while physiological parameters of SC and HR were continuously measured. After playing, participants completed a self-report measure of shared flow (SFS). We first assessed whether SFS is valid and reliable in the context of gamelan playing and proposed a potential two-factor solution. Following this, our findings surrounding differences in significant moments of physiological synchrony between levels of experience, and between traditional and improvised playing were unclear. However, we did find relationships between physiological synchrony and shared flow. More specifically we found positive associations between shared flow and average physiological synchrony within improvised playing and negative associations within traditional playing.

This finding may reflect the high degree of collectivism and collaboration required to participate in a group improvisation, whereas a group playing a traditional piece of gamelan music may still focus on their individual parts. Further studies may wish to reflect this potential difference in shared flow experience through a different self-report measure, assessing both antecedents and outcomes, as well as potential differences between individual- and group-level experiences of shared flow. Additionally, our findings are specific to the paradigm of Western participants playing Javanese gamelan music; future work in further understanding such mechanisms could be, for example, assessed in more hierarchical Western ensembles. These suggestions, in combination with our current findings, may provide valuable contributions towards a greater understanding of the experience of shared flow dynamics in ensemble music settings.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving humans were approved by the School of Arts and Creative Technologies Ethics Committee, University of York. The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

Author contributions

HG conceptualised and designed the study, carried out the experiments, conducted the formal data analysis, and created the full draft manuscript. HG and AC developed the scripts and visualisations. AC contributed to the formal analysis of the data and the development of the overall narrative, and edited and reviewed the manuscript. HE supervised the design of the study, advised on the analyses, and contributed to the review of the manuscript. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fpsyg.2023.1214505/full#supplementary-material

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The dance of hair – toward a more powerful performance

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1. Introduction

Ever since ancient times, hair has been associated with different interpretations, and there is a solid corpus of literature which has explored understanding, symbolism and attitudes toward hair in different cultures, relating them to anthropological, social, and psychological aspects (Leach, 1958; Synott, 1987; Gheerbrant and Chevalier, 1996; c.f. Barkai, 2016; Sherrow, 2023). For example, in distant past in many cultures long loose hair were characteristic of a warrior's dignity and strenght no matter if the warrior was man or woman (Roberts, 2010; Sherrow, 2023). In Victorian era, aesthetically capturing long loose hair was often associated with sexual liberty and women's sensuality (Ebbatson, 2011). On one side hair was a symbol of strength, beauty and sexuality. However there is evidence that long loose hair as well may be related with immorality or shame of a person who is not capable of controlling his or her instinctive nature (Synott, 1987; Barkai, 2016). In some cultures long loose hair may be an indicator of a person's marital status where women gave up their long hair when they got married (Bilu, 2006). Also, Thompson (2008) suggests that, for instance in Africa, hairstyles may indicate a person's marital status, age, religion, or ethnic identity. In addition to this Afro hair is often associated with slavery and the reason for discrimination against different communities such as black people (Patton, 2006; Thompson, 2008). Thus, as a social symbol hair conveys meanings about roles, status, or attitudes uniting within its connotation both bright and dark sides of its possible meaning (Bartlett, 1994; Gheerbrant and Chevalier, 1996).

As a subject of aesthetic experience and means of communication, long hair often appears as a highly symbolic metaphor in different domains of art. Some examples include the paintings *Vampire* by Edvard Munch (1895) and *Medusa* by Caravaggio (1597), the 1960s musical *Hair*, as well as Walt Disney's 3D computer-animated film *Tangled* (2010) based on the story of Rapunzel.

In the domain of dance as a form of art, hair can be used for different single or combined purposes such as aesthetic, symbolic or instrumental ones. Hairstyles typical for a particular dance form are important elements of the overall aesthetic experience. In classical ballet, a ballerina's hair is pulled up into a high or low bun (Wulff, 2020), while contemporary dancers may have loose hair depending on the character they are interpreting. Strict hair styling is a distinctive feature of ballroom dance (Uba, 2007), and the low bun was, until recently, an imperative in flamenco dance (Ruiz, 2007). Regarding the symbolical level, hair in dance performance could be used as a metaphor for depicting different ideas related to strength, sexuality, sensuality, creativity, freedom and their opposites (Barkai, 2016), as well as different states such as grieving and mourning characterized by dramatic waving of head with long hair (Briand, 2013). Concerning its instrumental purpose, as a part of a dancer's body, hair can serve as an expressive means of dance.

This article focuses on hair as a dancing instrument and discusses how its manipulation could be incorporated into dance techniques. Taking into account three main purposes of the use of hair (decorative, symbolic and instrumental) the reason why I focus on specific hairstyle – long loose hair that stretches along the entire back – lies in our interest to explore its manipulation as a part of dance technique. In addition, I also focus on women since until now in modern literature long loose hair has been discussed only in men who dance flamenco (Washabaugh, 2020).

2. Performance, dance technique and hairstyles

Dealing with the use of hair in dance performance, I set its instrumental purpose into the framework of dance technique and the rhythmicity each dance technique assumes. Regardless of the dance form, during a performance, the dancer rhythmically moves to the music synchronizing his or her expressive body movements to the beat, where the common component of music and dance is the rhythm (Jordan, 2011). Rhythm in dance refers to the temporal structuring of movement in space, and it is the basis for the spatiotemporal synchronization of movement (Thaut, 2007; Luck and Sloboda, 2009). The kind of dance movements that would be performed and rhythmically synchronized depends on the dance technique characteristic of each particular dance form. Siegel (1972) and McFee (1992) understand dance technique as a method of dancers' physical training to attain a certain degree of physical fitness and skills so that they can perform specific dance movements (McFee, 1992, p. 211). Dance technique is also determined by a systematic approach to the entire process of dance movement (Siegel, 1972, p. 106). Usually, it includes typical handwork, footwork, headwork, turns, poses, and how movements are combined.

On the one hand, there are dance forms with specific hairstyles that are not part of the technique but an attribute of a dancer's final appearance. Classical ballet, for example, with its specific hair styling – ballet bun – focuses on the technique of the body so that with each segment, perfect form and "the aesthetics of order" of classical ballet are emphasized. Thus, the hairstyle is at the service of the entire dance form, i.e. regardless of how long it is, collected in a bun, hair is not used in the context of the dance technique. Furthermore, a ponytail, as a hairstyle characteristic of Broadway or Ballroom dance and an aesthetic requirement, remains at the level of decoration. On the other hand, there are forms in which hairstyle tends to be used as a metaphor, as a dancing instrument or both. For instance, contemporary flamenco dance from the last decade exhibits a trend for dancers, not just female but male as well (Washabaugh, 2020), to perform dance movements wearing long, loose hair, which used to be merely an exception. Such inclinations could be a metaphor emphasizing strength, sensuality and passion which are some of the main attributes of flamenco dance (Gómez Muñoz, 2008). In contemporary dance, there are also pieces where long hair symbolizes freedom, for example, in the movie *Pina* (2011). Moreover, in these dance forms, loose hair is often used as an element of the head-moving technique. In contrast, it should be mentioned that in breakdance, hair restricts dancers when performing head-spinning techniques.

2.1. The practice and use of loose hair in dance performances

When considering hair as a part of the dance technique, I will focus on long, loose hair. Two main questions should be addressed: How is the manipulation of long loose hair practiced? How and where can it be applied in dance performance?

For the dancer, the kinesthetic-vestibular system has an important role. It includes proprioception, which contains muscle and joint sensitivity (limb movement), while vestibular sensitivity refers to body and head orientation in space (Montero, 2006, 2012; Proske, 2006; Tuthill and Azim, 2018; Beck et al., 2020). Research dealing with the role of visual and proprioceptive information shows that dancers rely on the sense of vision when learning and practicing a specific step or movement sequence in front of a mirror (Dearborn and Ross, 2006; Shabbott, 2010). At the same time, they practice a specific movement in classes until they achieve proprioceptive integration of information and bodily representation of movement (Jola and Davis, 2011). Furthermore, different studies have shown that dancers rely more on vestibular and proprioceptive cues than on vision when determining body position and orientation (Golomer and Dupui, 2000; Jola and Davis, 2011; Beck et al., 2020). In performance, proprioception and the sense of vision function in a relationship of interdependence (Montero, 2006). The flow of information between the dancer's proprioceptive sensitivity and visual aesthetic sensitivity occurs in both directions (Jola and Davis, 2011; Montero, 2012). Thus, practice and use of the technique of hair manipulation are based on proprioception and vestibular sensitivity, head movement and sense of vision. Moreover, they include skin sensation as well, since long, loose hair falls on neck and shoulders.

With all this in mind, incorporating hair movement into dance technique will first assume awareness of its weight, volume and length through the sensations perceived in the skin and visual sensory modality. Secondly, it will implicate the exploration of how hair "behaves" during different movements, such as whether it turns, falls or jumps, as well as, where it tends to fall and end during frontally or diagonally positioned movements. Moreover, it will mean discovering the specific velocity at which hair moves and synchronizing it with body movement. Finally, it will require exercises of synchronization of hair manipulation, body movement and rhythm to which dance is performed, i.e. the sensorimotor coupling of dance and music.

Another question relates to the potential application of the technique of manipulating long, loose hair. I will mention a few interesting possibilities. One is related to the enhancement of the dynamics of dance. The dynamics of dance entails the speed of shifting certain dance movements and implies the change of fast and slow movements as well as pauses (Hagendoorn, 2008). Thus, training in hair manipulation could be applied to enhance dance dynamics, adding to the visual experience impression of acceleration or bringing additional liveliness and vibrancy to the movement. Moreover, it could contribute to the experience of keeping the pause, i.e. movement of stillness in dance, alive. Since the pause in dance is also related to its dynamics, a powerful use of loose hair manipulation could be applied in accentuating the pause between two dance sequences where the body remains still.

A further possibility of using hair in dance is related to situations in which the dancer's breath moves it. It has been shown that people with a prominent openness personality trait enjoy hearing the dancer breathe while performing without music, while those with a low score on this personality trait perceive the dancer's breathing as disturbing, eerie, uncomfortable and awkward (Jola et al., 2014). Considering the aesthetic impact and enjoyment that some spectators draw from dancers' breathing, long, loose hair can be intentionally used to emphasize it. For example, hair that falls over the dancer's face allows the breathing to be 'seen' but not heard. That way, the type of audience who dislike hearing the dancer's breath can also enjoy it and the aesthetical impact of dance can be achieved across all types of spectators, both those who like hearing the dancers' breath and those who do not.

Long loose hair as a part of the dance technique can also be considered in relation to the phenomenon of "visual capture". Even in other art forms long, loose hair has always been visually captive, provoking aesthetic experience and spectator's arousal (Sherrow, 2023). Jordan (2011) explains that "visual capture" occurs when the perception of music is influenced by the movement so that if the musical sequence is heard alone, it may be barely perceptible. Choreographers may use turns, jumps or a combination of the two to create visually captive movements in dance performances. These movements, combined with the technique of manipulation of long loose hair, may put a more powerful accent on the beat or a certain moment in the music.

3. Discussion

The use of long loose hair and its incorporation into dance technique raise a number of key issues which I have elaborated upon above. The first one relates to getting to know the "instrument" (i.e., hair weight, volume and length as well as its "behavior" during different movements). The second one relates to the training of how to use long loose hair to express and enhance the dynamics of dance via specific movements or via breathing. The last point relates to the manipulation of long loose hair to evoke the phenomenon of "visual capture".

However, the hair is just one element of the entire dance performance which requires a complex organization and whose final outcome and aesthetical impact depend on various factors related to the characteristics of dancers, their professionalism, level of training, costumes and make-up used, scenography, lighting, size of the stage, music etc. (Glass, 2005; Stevens, 2005; Jaeger, 2009; Geukes et al., 2023).

Although this article deals with only one aspect of dance performance, it has offered essential insight into different levels and possibilities regarding the use of long loose hair. I consider this to be important because until now, the role of hair in dance has been approached from the perspective of aesthetics (Ruiz, 2007; Uba, 2007; Washabaugh, 2020; Wulff, 2020; Sherrow, 2023), dance therapy (Barkai, 2016) or health injuries (Monselise et al., 2011; Hall et al., 2022; Wanke et al., 2022). However, to the best of our knowledge, the manipulation of hair as a part of the dance technique and its possible application in dance performance have not been fully addressed yet. Although this article provides only an overview of this topic, the incorporation of manipulation and use of hair within dance techniques with an aim to empower dance performances should be discussed and elaborated thoroughly. Future studies should be enriched by also exploring the choreographer's experience. Moreover, the investigation of its practical applications by scientist as well as by choreographers and dancers within each dance form would be fruitful and recommendable. Since the mentioned studies focused mostly on white people and those identifying as women, both performance art and science would benefit from future research dealing with application and use of long loose hair across sexes, genders, and cultures. In addition, questions connected to the possible relationship between a dancer's age, their social status, and their "body identity" (Langdon and Petracca, 2010) in relation to the use of long loose hair would be important to address to achieve more inclusive perspectives and gain greater insight into this key topic in the field of dance performance.

Author contributions

The author confirms being the sole contributor of this work and has approved it for publication.

Conflict of interest

The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Beyond the border of the athlete-centered approach: a model to understand runners' performance

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Our purpose is to move beyond the borders of the athlete-centered approach by examining the runners' environment interplay as a key factor for performance. Based on the ecological systems theory, the micro-level (intrapersonal, interpersonal, and training characteristics), meso-level (a direct association with athletes is not observed, but the environment plays an influence on the relationships built at the micro-level), and macro-level (contextual features that influence athletic systems) were theorized and contextualized as important factors for the expression of different outcomes, including performance and participation. We also conceptualized the microtime, mesotime, and macrotime as a constraint. Through this model, we aimed to provide applications and conclusions about how this conceptual model provides advances in the scientific research field. By understanding how environmental factors influence their performance, runners can make informed decisions about where and how to train and compete. Furthermore, by recognizing the role of culture and social context in shaping runners' experiences and outcomes, we can work toward creating a more equitable and supportive running culture for all.

KEYWORDS

ecological systems, cross-cultural research, endurance running, athletes' performance, coach

1. Introduction

"A wonderful harmony arises from joining together, the seemingly unconnected" (attributed to Heraclitus of Ephesus c. 500 BC).

Sport is a global phenomenon and has been integrating the contemporary debate about sustainability, peace, and human development (Lemke, 2016). The relevance of sports for nations is highlighted through two main perspectives: social and economic. As a social phenomenon, sport has the potential to help in the reduction of inequalities, empowering minorities, increasing national pride through megaevents, and contributing to social cohesion within and between communities (Spaaij, 2009). Sport is also a global market, potentially contributing to the countries' development, for example through the synergies between tourism, industry, and transport sectors (Rázvan et al., 2020).

As an expression of human excellence, sports performance is also debated in the scientific literature. The interest to improve athletes' performance, through the comprehensiveness of factors that explain/predict performance, has increased among sports science researchers (Yan et al., 2016). As a dynamic, non-linear, and multidimensional phenotype, there seems to exist a consensus that athletes' performance should be investigated through a holistic approach (Balague et al., 2013; Balagué et al., 2017). However, the athlete-centered approach (Midgley et al., 2007) overvalues individual characteristics, such as physiology, psychology, genetics, and biomechanics, as the key factors to understand athletes' performance (Moir et al., 2019; Zani et al., 2022)—dominating the scientific debate for a long time.

The athlete-centered approach is intrinsically related to the mechanical idea that compares the human body with a machine, where each part must be understood separately to provide the answer about the "final product" (Capra, 2012). Notwithstanding the relevance of this approach to comprehensiveness regarding the body mechanisms and functions (Kent and Hayes, 2021), sports performance cannot be fully understood if the subject–environment relationship is not considered. Furthermore, since the subject–environment relationship operates in an open system, the use of holistic approaches to understand the behavior that emerges from this interaction is necessary.

Sports performance is also context- and sport-dependent. These fundamental premises postulate that sports performance (at the individual or country level) reflects the own resources available at a specific timeframe (i.e., intrapersonal, interpersonal, infrastructure, and policy initiatives) to correspond to the requirements to be successful in a specific sport (Knuepling and Broekel, 2022). Furthermore, since the athletes' opportunities to be engaged in specific sports practices reflect the inputs (i.e., financial and moral support, sports practice opportunities, sports culture, and geographic features) available in athletes' day-life (Santos et al., 2019), the role of the environmental factors that can be transferred and expressed in terms of performance should be considered.

As part of the sports science field of study, the evolution of endurance sports in a scientific context was strongly influenced by the athlete-centered approach. Although the advances from these researchers, we believe that the field of study could be benefited from an approximation with an ecological approach, considering the proximal to the distal factors that can be contextualized to deeply understand the performance at the individual or country level. For example, much has been discussed about the factors that explain the success of East African runners; however, few studies considered a more contextual approach to deeply understand this phenomenon. For that, we theorized and contextualized running performance, considering both individual and environmental factors through a holistic approach.

2. Moving beyond the athletes-centered approach

The nature–nurture dichotomy is a long-standing debate in different fields of study, such as education, psychology, science, and sports (Klissouras, 2001; Knechtle, 2012; Yan et al., 2016). The belief that genetic characteristics are the most relevant factors to the expression of behavior was scientifically proposed by Galton (1875) when he postulated the impossibility of transposing genetics by training (Galton, 1875). On the other hand, behavioral theories highlight the role of the environment as the main actor in the expression of human development or the acquisition of a given skill (Simon and Chase, 1973; Ericsson et al., 1993).

In addition to the fact that this secular debate no longer finds support, since it represents a limited and deterministic approach to reality, and this dichotomization is still presented in some theoretical frameworks used in sports science research, through the use of analytical and monodisciplinary approaches (Loland, 2013; Balagué et al., 2017). For instance, since the 1960s, the comprehension of the African runner's phenomenon in the international context of running was deeply influenced by the analytic reductionism that highlights genetic, morphological, and physiological characteristics as the most important domains for performance prediction/expression (Kruger et al., 2012; Wilber and Pitsiladis, 2012; Moir et al., 2019). Narratives about genetic characteristics, morphology, and physiological parameters (i.e., maximum oxygen consumption, metabolic efficiency, and hematological parameters) were debated for many years (Wilber and Pitsiladis, 2012; Tucker et al., 2013). However, a recent comparative study investigating the relationships between ethnicities (Kalenji's—Kenya and Oromo—Ethiopia) and endurance running success concluded that causality inferences regarding the relationship between genetics and sports must be avoided, once it is both scientifically incorrect and prone to reinforcing population (racial) stereotyping (Hamilton, 2000; Zani et al., 2022). With this conclusion, the authors do not exclude the role of genetics but reinforce the importance to move forward.

The geospatial variation associated with the odds to be an elite athlete in specific places has been known as the "birthplace effect" (Smith and Weir, 2020; Faria et al., 2021; Leite et al., 2021; van Nieuwstadt et al., 2021). This phenomenon has been largely discussed and investigated in different contexts and/or sports modalities, such as sprinters (Jamaica), soccer players (Brazil), ice hockey (Canada), and endurance running (East Africa) athletes. From the set of factors usually highlighted as related to this phenomenon, the proximal features are highlighted, such as sports facilities, athlete–coach relationship, neighborhood security perception, opportunities to deliberate play, and pro-community behavior (Cote et al., 2006; Oishi et al., 2007; Balish and Côté, 2014; Wattie et al., 2018; van Nieuwstadt et al., 2021). However, few were discussed and contextualized considering the distal environment to the explanation of this phenomenon.

In the context of endurance running, aside from genetic, morphological, physiological, and training characteristics that contribute to the African runner's phenomenon (i.e., Kenya, Ethiopia) (Larsen, 2003; Zani et al., 2022), the country's historical background, the population's lifestyle characteristics, the economic development, and perspectives of social ascension and/or better living conditions through the sport need to be considered as factors related to the running training engagement and performance (Bale and Sang, 1996). For example, colonization, religious missions, and school policies were important agents in the dissemination of running in the Kenyan context. During the 1950s, British athletics coaches, athletes, and physical education teachers were designated to move to Kenya as part of an assistant program, working as role models for Kenyan runners, which was also called "cultural imperialism" (Said, 1997).

These factors highlight that Kenya, as an 'international power' in long-distance running, was developed in the long term through a connection of different factors (Said, 1997) that do not always seem easily connected. As pointed out by Sniderman (2010), the dominance or absence of some populations/nations in some sports must be explained by the shared attitudes of most members of that population, as well as governmental and public initiatives that put the country in an international showcase. Once again, in the case of Kenyan runners, changes in immigration runners' rules and travel restrictions were of relevance to increase their participation in international events (Said, 1997). However, the magnitude in which changes at the distal level can be converted into better opportunities and conditions at the proximal level is not clearly mentioned in the scientific literature.

3. A theoretical framework for runners' performance understanding

3.1. The ecological systems theory

Bronfenbrenner's (1977, 2011) ecological systems theory was first presented in 1977. The theory was developed in the context of psychology as a critique of the experimental research and interventions in this field, aiming to provide a new approach to understanding human development. According to Bronfenbrenner, the best strategy to understand human development is a holistic approach involving the subject and the environment. The ecological systems theory allows us to understand the demands of human development beyond the direct observation of behaviors through an interaction between two people. In addition, it requires examining multi-person interaction systems, considering the environmental aspects beyond the immediate situation containing the subject (Bronfenbrenner, 1977). In this case, the ecological systems theory considers different levels, including the micro-level, meso-level, exo-level, macro-level, and chronosystem (Bronfenbrenner, 1977).

Even though the theory was not developed for sports scientists, it has been applied in different contexts of sports science. Studies about the parental role in youth sports involvement (Holt et al., 2008), psychosocial stressors in women athletes (Pascoe et al., 2022), sport development programs (Burnett, 2015), effects of club characteristics on basketball players' performance (Junior et al., 2019), and physical activity promotion (Spence and Lee, 2003) used ecological systems as a framework to answer their questions and guide the hypothesis. For athletes' process development, the commitment of stakeholders, clubs, place of residence, family, and support from friends was previously associated with performance (Henriksen et al., 2010; Smith and Weir, 2020). For example, Durand-Bush and Salmela (2002) indicated that the context in which athletes were inserted during general training significantly influenced sporting success. Moreover, access to facilities and equipment and support from friends, family, coaches, and staff were relevant for practice maintenance. For track and field, Henriksen et al. (2010) showed that sports clubs play an important role in athletes' development during the training period, highlighting that a strong organizational culture, characterized by values and integral development of the athlete, was crucial for athletes' development.

As the studies are mainly centered at the proximal level, with the purpose to understand skill acquisition and establishing the relationship with the subject–task–environment (Uehara et al., 2016; Glazier, 2017), previous studies highlighted the relevance to further explore the role of distal constraints in the expression of athlete's performance (Uehara et al., 2016). In the context of sports performance, differences in cultural and socioeconomic characteristics between countries can be expressed in terms of sports programs, national events, training facilities, and scientific research, providing different environments and conditions for the athlete's development. Countries are more likely to invest in sports in which they are well-represented at an international level, but as mentioned above the context of Kenyan runners, the sports context at the country level takes time and is still related to the historical background.

Thus, it is important to understand country-specific environments, which act differently on runners' development, as well as the best model to build a friendly environment to promote athletes' performance, including cultural investigation. Since sports science, as a study field, was strongly influenced by a positivist paradigm, research questions and methods were also strongly related to a quantitative approach, interested in unidirectional causality between independent and dependent variables. These characteristics have led to the use of individual approaches to answer most of the research questions in this study area. However, when the interest is centered in to change the level of analysis from the individual level to the group level, cultural factors should be considered. Since cultural factors are important drivers in a country's engineering, the shared beliefs, traditions, costumes, and values of the group/community (Shiraev and Levy, 2010) can be linked to the emergent patterns that differentiate one successful athlete from a successful group of athletes.

3.2. Cross-cultural psychology

Cross-cultural psychology is the scientific study of the variation in human behavior considering differences under cultural conditions and also understanding how cultural practices evolve and affect human behavior in a bidirectional relationship (Shiraev and Levy, 2010). However, cross-cultural research is not only concerned with differences between countries but also with similarities (Shiraev and Levy, 2010). Cross-cultural psychology is related to several population-level disciplines that are not only concerned with individual approaches but also incorporate different domains that comprise social behaviors, personality, and group perception. Previous research on this topic examined behaviors across cultures, as shown by Inman et al. (2017), where cultural values were related to alcohol consumption, and by Cheng et al. (2013), whose results showed that external locus of control and anxiety symptoms were weaker for collectivist societies compared to individualist societies.

Cross-cultural psychology is operationalized through cross-cultural research. Cross-cultural research is used to compare the studies of cultures or countries (Buil et al., 2012). In general, the number of studies using cross-cultural approaches has increased in the last few years. This increase is related to technological advancements, migratory streams, and globalization (van de Vijver and Leung, 2021). Specifically in the sports context, this topic is embryonic, with most of the studies focusing to perform cross-cultural validation of instruments (Arthur et al., 2022; Dos Reis-Junior et al., 2022). In addition, original studies have barely explored the potential of culture to explain different behaviors/outcomes in different contexts (Balish et al., 2016). A cross-cultural comparison was performed in a study sampling subjects from Denmark, Switzerland, and Poland (Kuettel et al., 2020) to understand the role of the sociocultural context in elite sports athletes' transition. The results showed similarities and differences between countries (Kuettel et al., 2020). Similarly, it was shown that running movement patterns vary between different running groups based on the cultural relevance attributed to running (Wallace et al., 2022).

Despite culture acting as an independent variable in comparative research, in cross-cultural studies the culture is beyond the control of the researchers (van de Vijver and Leung, 2021). When cross-cultural differences are not explained by cultural differences, contextual variables (e.g., economic, social, and demographic factors) are used as a proxy for cultural characteristics (van de Vijver and Leung, 2021). These characteristics present important practical applications for study's design, as will be presented later. For the present purpose, the cross-cultural psychology approach will be used as a framework since our assumption considers that between countries' differences in social, economic, demographic, and cultural characteristics can be related to different behaviors, more precisely the performance in the running context (Segall et al., 1999).

4. Foundations for the runners' performance holistic approach

Investigating runners' performance through a holistic approach highlights that many factors influence sports success, which is intrinsically related to the athletes and the wider context where they are inserted (Hristovski et al., 2012; Renfree and Casado, 2018). Based on the scientific background that shows the role of the proximal and distal variables in the expression of an athlete's performance, we propose an approach to understanding a runner's performance. This conceptual model was developed to advance the comprehensiveness of this specific topic (Figure 1).

Running performance is the "core" of the investigation, while the cross-sectional line highlights the relationship established between the different levels. The three main aspects of our model are (1) the hierarchical relationship between three different informational levels, (2) the interaction between the different levels, and (3) the relative importance of variables between and within levels for runners' performance. To reduce the complexity and provide some understanding, performance was considered as a product (i.e., running pace, finish time, and ranking position) that emerges from the micro-level, meso-level, and macro-level interactions. The structure indicates a hierarchical organization, where the first level (micro-level) presents variables most directly related to the performance, while the third level (macro-level) brings the variables that are not usually highlighted as closely related to the expression of sports performance, but the role and relevance should be considered both directly and indirectly in athletes' day life.

Furthermore, sports performance is also related to continuity and change throughout athletes' life. For that, the main key in the model is *time* as a predictor. The time as a predictor refers to these changes, which are expected to occur in each variable during a frame of time. Since subject and environment change over time, as a result of different intrapersonal and external experiences, the performance outcomes and the process are continuously changing. As variables situated at different levels act at different timescales (Balagué et al., 2019), microtime, mesotime, and macrotime were presented similarly to the purpose of ecological systems theory. This means that microtime includes changes occurring at a proximal level of the subject, while mesotime refers to the frequency of these changes, and macrotime focuses on the changes located on a large scale of society. On the contrary, some levels of structural stability and depth are expectable within a group (Schein, 2004).

4.1. Micro-level

Micro-level comprises variables related to individual characteristics (biology, morphology, and training) and personal environment (athlete–coach relationship and athlete's family). From this lower information level of the model, the scientific literature presents a set of variables related to runners' performance (Alvero-Cruz et al., 2020; Pereira et al., 2021). For the present model, biological (age, sex), morphological [body mass index (BMI)/body composition], and training variables (frequency, volume, time of practice, and training methods used) were considered, based on previous studies that show their direct or indirect role to the expression of runners' performance (Casado et al., 2019; Alvero-Cruz et al., 2020).

Among these variables, anthropometric and body composition are the most investigated, possibly due to the low cost and practicality associated with their measurement. In general, the results show that there is a negative relationship between BMI and fat percentage with running performance (Sedeaud et al., 2014; Vincent et al., 2020; Thuany et al., 2022). Moreover, these results may be explained by factors related to the following characteristics: (a) running is considered a "weight-sensitive" sports practice (Sedeaud et al., 2014; Vincent et al., 2020), where the generation of force to sustain the body weight during displacement is the primary determinant of the metabolic cost of running, and a "simple" increase of 10% in body mass may represent an increase of ∼14% in running energy expenditure (Silva, 2019); and (b) the fact that ∼20% of the energy spent during displacement is for the acceleration of the lower limbs, so an increase in body mass may lead to loss of efficiency, as well as greater heat accumulation at a given submaximal running speed, which may compromise the exercise if high internal temperatures are reached (Fuziki, 2012).

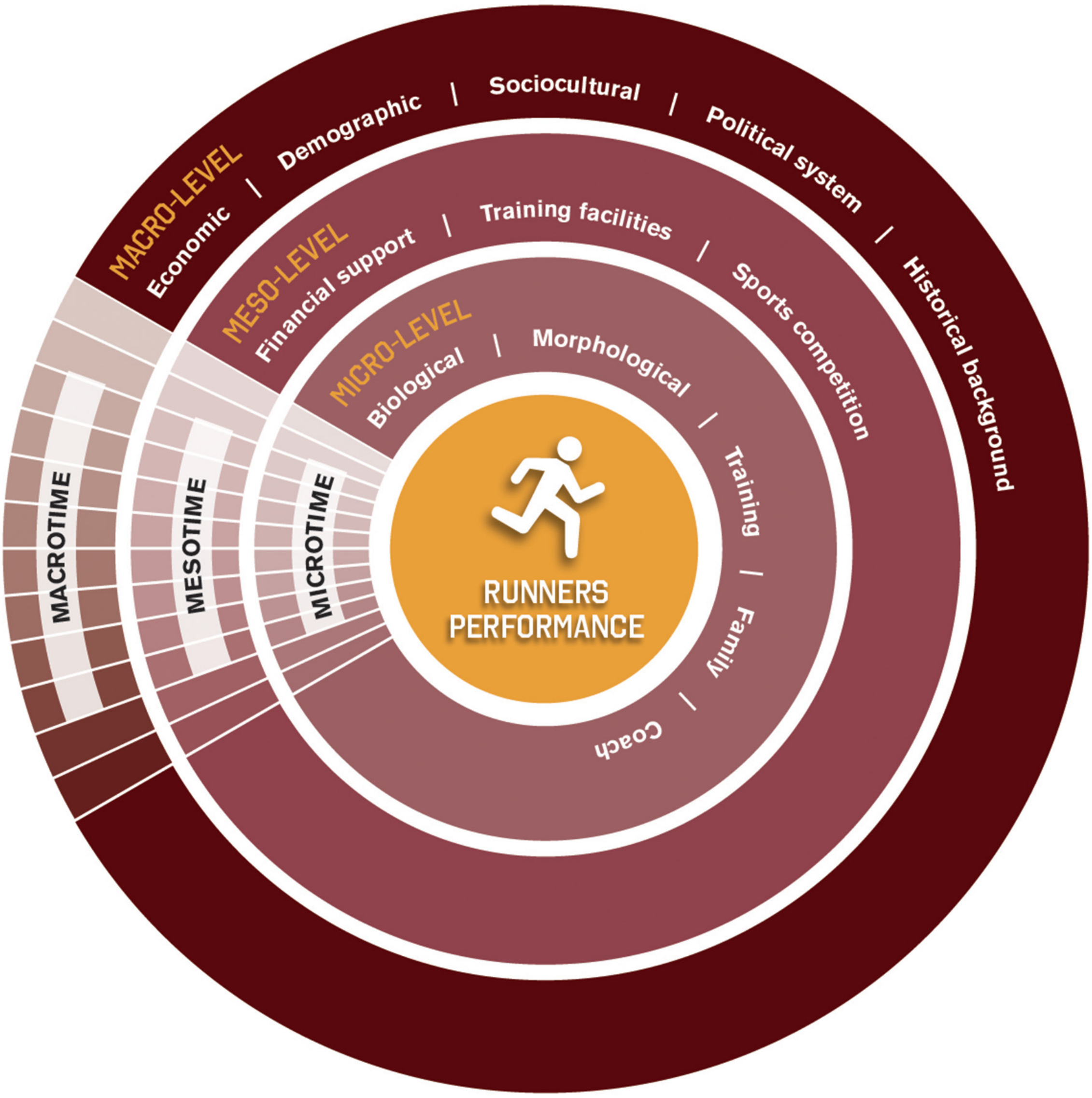

FIGURE 1
Conceptual model of runners' performance holistic approach [the figure was based on a previous study developed by Thuany et al. (2023)].

In addition, we should not ignore the intersection between anthropometric variables, body composition, and training characteristics (Thuany et al., 2022). The running speed during training sections and the body fat percentage explains ∼44% of the performance of recreational marathon runners (Gómez-Molina et al., 2017). In contrast, the association of practice time, training volume, BMI, and skinfold sum explains ∼90.3% of the variance in the half-marathon performance among non-professional male runners (Barandun et al., 2012). Therefore, biological, morphological, and training variables constantly interact to the expression of running performance (Thuany et al., 2022).

The role of the family and coach in athletes' performance was previously mentioned. Parents and coaches are the first socialization agents for sports participation and performance (Luo and Kiewra, 2020; Tessitore et al., 2021). They are responsible to transfer standards and values, providing encouragement, moral and social support, and acting as role models for sports participation. In addition to that, financial support for the acquisition of training equipment, participation in competitions in different places, and nutritional consumption are also important aspects that cannot be neglected. Similarly, coaches also encourage when athletes faced stiff competition, providing advice on the best way to succeed in sports through hard work and perseverance, providing psychological support through motivation, and spiritual support through prayers toward success and achievement (Lassalle et al., 2018). Furthermore, a study conducted with Kenyan runners' families showed that family played an important role in the development of athletic talent and influencing their performance (Mwanga et al., 2017). The same relationship was observed for training facilities and participation; however, more studies are necessary to understand how family members, coaches, and teammates influence training commitment, athletes' development, and performance.

4.2. Meso-level

In the Bronfenbrenner (1977, 2011) ecological systems theory, the meso-level is related to the environment in which subjects are not directly exposed but are directly influenced. For the present proposal, meso-level variables are less explored in the context of running performance, and for that, the variables included in the present model are related to the training environment, considering both financial support and facilities and sports competition. For young athletes' development process, the role played by financial support for training, competition participation, and full-time dedication was highlighted.

For runners, information about financial support and training facilities that are associated with running performance is limited. Endurance running is traditionally known as a discipline where sophisticated equipment is not mandatory, and the main training is performed in outdoor spaces, not requiring access and sponsorship. Despite these characteristics, resistance training—previously associated with performance outcomes in runners (Blagrove et al., 2018)—is performed in gymnasiums, sports arenas, or training centers, limiting access for some runners. In addition, participation in competitions (part of the athletes' routine) involves human, material, and financial resources. Given that some evidence shows that social ascension was related to African runners' motivation and search for performance (Onywera et al., 2006; Elbe et al., 2010), advances about the role of competition in motivation and training maintenance, as well as the role of financial support and training facilities to push the environment, in which the athlete is committed should be considered in future studies. In addition, it is necessary to fill the gaps regarding variables that can connect micro-level and macro-level.

4.3. Macro-level

Macro-level factors consider environmental features that shape the sports systems. For the present model, the macro-level comprises the economic, social, cultural, and demographic domains. In terms of influence on running performance, a direct relationship between the macro level and athletes' performance is not expectable, instead, the influence on the expression of variables situated at the meso-level and macro-level should be considered. Most of the evidence about the macro-level variables is based on studies comparing countries in the international sports context, such as Olympic Games and World Championships (Truyens et al., 2014; De Bosscher et al., 2015). Demographic factors (population size and human development index), political system, and income explained more than half of the countries' success (Bohme and Bastos, 2016). The results suggested that outputs (i.e., an Olympic medal) are different due to different inputs (e.g., economic characteristics).

Beyond these variables, shared culture and beliefs within a country can also be related to the commitment to different sports practices and performances (Bale and Sang, 1996). Rothwell et al. (2018) refer to behaviors, attitudes, beliefs, and values that shape the communities with the potential to influence the development of sports performance. However, the magnitude in which the cultural context can reduce the role of economic, demographic, and political variables is unknown, and limited information is available for specific sports disciplines (Gomes-Sentone et al., 2019; Santos et al., 2019). For example, Mazzei et al. (2023) showed that for judo, the results in previous events were the most important variables to explain the countries' performance competing in the Olympic games between 1992 and 2016. These results were contextualized considering historical and socioeconomic differences. Investigating the frequency of countries in the World Athletics ranking for sprint and endurance race events, Santos et al. (2019) showed that most of the countries ranked among endurance events are classified as medium or lower income. This result is associated with the African phenomenon. For example, Kenya and Ethiopia are ranked at 141° and 171° positions, respectively, on the human development index board, but they produce the highest number of elite endurance runners worldwide.

In addition to these aspects, other factors are documented, such as political, religious, and cultural systems and social, demographic, and sports organizations. The conclusions of these studies suggest that there is little information about the role of macro-level variables on the programs for participation in sports, and they highlight the importance of this information for decision-making on the managerial and pedagogical levels. In this sense, macro-level variables, such as environmental characteristics, politics, geographical disposition, and shared beliefs, can be related to the likelihood of participating in sports practice, training opportunities, and performance development.

5. Discussion

At the heart of our conceptual model, runners' performance is an outcome of an imbricated relationship between variables situated at different levels. Beyond individual factors related to runners' performance, future studies need to investigate running performance as a result of the relationship between subject and environment. For that, the use of different research strategies should be considered in order to provide some understanding of the pattern of interactions between different variables in specific contexts. Models based on geographic or social boundaries should be considered using cross-cultural research as a framework to guide practice. In association, changes occurring during athletes' life, as a result of personal experience, as well as those resulting from external forces must be considered. Since predicting human behavior is a challenging task, this model is not static, and neither is our purpose to provide a deterministic approach.

A better understanding of the role of environmental factors in runners' performance and being able to identify variables that connect different levels can be useful at different theoretical and practical levels. In this sense, practical applications of the present conceptual model include the creation of a nurturing environment, considering the individual characteristics in association with the environmental features, to provide good development (i.e., performance and training commitment) for all participants. In addition, the consideration of a specific environment can be useful to create a more equal and empowering environment for everyone if we acknowledge the influence of culture and social context on runners' experiences and outcomes.

For this task, a deep comprehension of the role of the time and the culture should be considered. Even though culture is also considered a complex group learning process, culture should be contextualized and investigated at different levels, including micro-level and meso-level (Schein, 2004). As one of the main social phenomena around the world, the potential of sport to act as a catalysator for human development should not be neglected. For some countries and athletes, sports are related to the possibility of economic and social ascension. These characteristics may reinforce the idea that "taking some risks" is part of the process of becoming an athlete; however, in addition to the athlete's development process, human development needs to be considered, indicating that better conditions to be engaged in training and competition are important for both outcomes: sports performance and life.

Despite the ecological systems theory being previously used as a framework in different sports contexts, some advances are mandatory. Most of these advances are related to synergic, multidisciplinary, and collaborative work between academics, stakeholders, and athletes of different places and working in different settings. Researchers with an interest to understand running context through an ecological framework are invited to use our suggestion as a starting line to understand how the subject and environment interact with each other to better express performance outcomes. As an unfinished study, we hope to be able to advance our current knowledge, advancing and filling some gaps related to the role of different environmental settings in different performance outcomes, as well as understand countries' specificities which can be of relevance for the development of friendlier environments for sports and human development.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

MT worked on the original draft preparation and review/editing. TG, KW, BK, RR, and MM revised the text. RR, TG, and MM supervised and worked on the review and editing of the manuscript.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Sticking choices in timpani sight-reading performance

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When sight-reading a score, a timpanist needs to decide in real-time which stick to use to play a specific note while interpreting the musical material. Our main point of inquiry seeks to understand which sticking patterns performers employ and how they are affected by rhythmic stability. This paper analyzes the bi-manual sequencing (i.e., sticking) patterns of 31 timpanists in a sight-reading task. We analyze their results compared to model sticking patterns common in percussion pedagogical literature. Results show that while hand dominance plays an essential role in an individual's sticking pattern, the stability of a rhythmic pattern may also dramatically influence the observed particular sticking strategies. In areas of rhythmic stability, performers largely adhered to one of two conventional sticking patterns in the literature (dominant hand lead & alternating). Where rhythmic patterns became more unstable, the performers separated into diverse sticking groups. Moreover, several performers demonstrated sticking patterns which were hybrids or an inverse of the model sticking patterns, without any impact on the success of their sight-reading abilities. Overall, no two individual performers demonstrated the same sticking pattern. In terms of percussion pedagogy, our findings suggest that performers may benefit from an awareness of the adaptability of model sticking strategies. Lastly, we make the case for further study of rhythmic stability and bi-manual sequencing by locating the difference between notational and aural complexity.

KEYWORDS
bimanual action, music performance, sight reading music, music notation, hand dominance, percussion, percussion performance

1. Introduction

Percussion performance primarily consists of players striking idiophones or membranophones with sticks, mallets, or hands to produce a sound. After the percussionist sets the instrument vibrating, they have little control over the sound. For this reason, the kinematics of the stroke defines the acoustic properties of each note (Stone, 1935; McCormick, 1983). Thus, for control of overall sound production in percussion, coordination between both hands plays a crucial role in developing the skills to perform well as a percussionist. In many ways, percussion performance is the artistic mastery of bi-manual coordination.

Timpani (also known as kettledrums) are one of the many instruments that percussionists need to master in terms of professional competencies. This type of drum consists of a large hemispheric bowl covered by a thin membrane that can be tuned and requires clear, deliberate and even gestures from both hands to achieve a desirable and consistent tone (Batigne, 1997): Inconsistent striking areas on the playing surface of the timpani, as well as minute changes in striking gestures, can produce variations in tone production (Chen et al., 2016).

Scores may often call for multiple drums (timpani) rather than a single one (timpano). When more than one drum is required, complex coordination and advanced sticking techniques are necessary to smoothly transition between instruments without disrupting sound quality. Such transitions, otherwise known as cross-overs, are focused on lateral movement across the body to preserve sticking choices while minimizing unintended strikes against the instrument or sticks themselves. Due to the long and resonant tone of a timpano, timpanists may often use their hands to dampen or mute the drum-head depending on the indicated duration of a given note. Lastly, concerning the size and pitch ordering of multiple timpani, there are two main methods; German and American ordering. In the American method, the pitch ordering is from left to right (low to high), in the same orientation as a piano. The German method is reversed, with the highest pitch on the left and the lowest on the right (high to low) (Montagu, 2002).

Given the complexity of the technique when performing across multiple timpani and the novelty of our study, we have limited our scope to observing performances on a single timpano. Our intention is to anchor our findings more closely to general percussion performance techniques.

2. Related works

While there have been many studies involving the percussion performance and sight-reading, previous works have not explicitly focused on sticking choice. Past research on percussion performance has primarily focused on the timing abilities of percussionists (Fujii et al., 2010), the kinematics of playing (Dahl, 2003; Fujii and Oda, 2009; Fujii et al., 2009; Fujisawa and Miura, 2010), or the effects of training on the sense of timing (Manning and Schutz, 2016).

Previous work directly related to this study involved an experiment with a sight-reading task which found kinematic and functional differences between the hands during percussion performance caused by handedness (Bacon et al., 2014). This study showed a clear correlation between rhythmic function and sticking choice. The players gravitated toward using the preferred hand for metrically important notes. The current study builds upon these findings with a larger pool of participating performers to explicitly test the effect of rhythmic complexity on sticking choice.

In the following subsections, we take a closer look at the surrounding literature informing our experimental focus.

2.1. Sight-reading

Sight-reading is often described as playing a piece of music that the player has never seen before, with the goal of performing all the aspects of the music as written, including correct pitches, rhythms, dynamics, and articulation markings. More specifically, sight-reading is a complex task involving fine motor skills in coordinating movement, active-memory recall when recognizing rhythmic structures, and the visual decoding of notation (Parncutt and McPherson, 2002). When sight-reading a musical score, the lack of preparation time allows an observer to witness a performer's skill level and natural performance tendencies. Performers also use sight-reading to reveal strengths and weaknesses in their playing technique and to prioritize practice time for future skill development.

It has been shown that complex sight-reading tasks require players to rely on their information-processing abilities more than their instrumental training (Kopiez and Lee, 2008). Furthermore, concerning sight-reading rhythm, a distinction can be made between an accurate rhythmic performance and what may be considered a precise clock-like internal pulse (Farley, 2014). When evaluating rhythmic content in a sight-reading exercise, barring any notable shifts or distortions in tempo, an accurate performance preserves the duration of a note in relation to its sequencing (Falle, 2011).

Current research in eye-hand coordination suggests that the distance between the gaze position of the eye in a musical score and the current position of the hands, otherwise known as the eye-hand span (EHS), can be used as an accurate evaluative method for sight-reading skill (Perra et al., 2021). In more experienced players, eye-gaze can scan further beyond their current playing position than their less experienced counterparts. Regarding notational density and tempo, score complexity plays a critical role in determining EHS distances. In terms of visual layout, spacing modifications between musical phrases in the notation of a score have been shown to increase musical legibility by demonstrating fewer sight-reading errors than unmodified notation (Stenberg and Cross, 2019).

Regarding performance expectations, there remains a strong contrast between a rehearsed, and sight-read performance. While flawless execution and creative expression remain the ultimate goals for both scenarios, the tolerance of mistakes is remarkably lower in the context of a rehearsed performance than in a sight-read one. While just a few misplayed notes could be viewed as detrimental in an orchestral solo amongst a sold-out crowd, those missed notes could be considered minor footnotes of an otherwise remarkably successful sight-reading demonstration. Moreover, while it is common in sight-reading that a single mistake may produce a string of errors, the ability to recover and conclude a given exercise confidently can also be viewed as a highly positive outcome when sight-reading. This does not minimize the stakes for common sight-reading scenarios. Sight-reading is commonly used in exams, auditions, and private lessons. Thus, while the expectations may differ concerning the ratio of correct/incorrect notes performed, the psychological pressure to perform well in the case of a sight-reading context may feel just as high as that of a high-profile performance.

2.2. Notation and rhythmic complexity

Western music notation can be seen as the intermediary between the composer and the performer. The notation communicates how a musical idea is to be performed. This can be done prescriptively in terms of what specific methods are to be used to recreate a desired sound (e.g., hit a piece of scrap metal with a hammer), or this can be done descriptively, where the notation represents the literal sound to be created (e.g., a G-sharp on the piano). Oftentimes, scores contain a mixture of the two (Kanno, 2007).

The wide variety of approaches when using Western notation speaks to the importance of standardization and the development of idiomatic forms of representation (Watson, 2006; Dimpker, 2013). At times, a piece of music may be notated in ways that, through a conflation of parameters, produces something overly complex from the performer's perspective. For example, a simple rhythm can be represented with uncommon time signatures, tuplets, note groupings, rests, and phrases. There are instances where the notation can be so dense that the music becomes impossible to play accurately (Duncan, 2010). Oftentimes, these pieces are re-notated by the performer so that the intended sounds are preserved while simplifying the notation (Talgam, 2019).

In terms of perception, the complexity of a rhythmic construct can be described in terms of its stability, where there is the expectation that tones or rhythms will repeat on a regular basis (Bigand, 1997). A sense of stability is achieved when listening to a regular periodic musical event. Although that sensation can be disrupted by introducing irregularly timed events, the general sense of stability can persist (Large, 2000).

2.3. Sticking and symmetry

When it comes to percussion performance practice, symmetrical gestures between the hands (both with and without sticks) are routinely emphasized to ensure an even sound when alternating them during a performance (Cook, 1997; Timbert and Rivalland, 2007). Performing with just one's preferred hand consistently is a non-practical solution, both economically for the player and musically. Thus, many players seek to equalize the performative capabilities between the hands in an attempt to achieve ambidexterity. Nevertheless, asymmetry in the body is naturally fundamental. It is known as laterality, which refers to the preferential use of one side of the body over the other for specific functions, such as hand preference for writing or throwing, or performing a percussive instrument (Corballis, 1983; Annett, 1996). Laterality's effect on manual behavior can otherwise be known as handedness, which has been shown to influence the performance behavior of a percussionist (Bacon, 2014). In skill-based bi-manual tasks, musicians have also been shown to exhibit less asymmetry between the left and right hands than non-musicians (Jäncke et al., 1997).

To counteract the natural behavioral asymmetry caused by handedness, a central tenet of percussion pedagogy prescribes that students spend extra time practicing to bring their non-dominant hand up to the skill level of their dominant hand, oftentimes suggesting that the student repeats exercises with the non-dominant hand three times as much as the dominant one (Delécluse, 1969; McClaren, 1994). To help foster parity during training, method books provide systematic stickings (i.e., the ordering pattern of the hands) for each exercise that balance the emphasis on the hands (Stone, 1935; Delécluse, 1969; McCormick, 1983; Goodman, 2000; Gworek, 2017). Given the complexity of assessing handedness, performance-based tasks are more reliable in assessing the balance of dominance between the hands (Kopiez et al., 2010). Thus, the study of sticking choices offers direct insight into how the natural forces of hand dominance and a performer's musical preferences interact.

When reading a piece of music in percussion performance, one generally rehearses to search for an optimal sticking that provides the most rhythmically accurate and expressively appropriate performance. Although an even-handed approach to sticking is considered an ideal outcome, when choosing a sticking order, a performer must consider the rhythmic complexity of the score, the combination of strokes that can best render the desired rhythmic phrasing, and their own physical limitations. In addition, professionals and students alike aim to develop an intuitive approach to sticking so that when they sight-read, they are most likely to automatically coordinate their hands to maximize their success in reading the notation correctly (Timbert and Rivalland, 2007; Commission nationale des programmes de lenseignement musical, 2016).

2.4. Model stickings

Due to the value placed on symmetry in percussion performance pedagogy, it would not be surprising for there to be little preference for a particular hand to play a certain type of note. However, the functional roles of the hands are often distinct (Stone, 1935; McClaren, 1994; Bacon et al., 2014). While the gesture is ideally symmetrical, the hands do not always perform equal functions when performing music (Dahl, 2003). With this in mind, previous research has shown that one's handedness, either left- or right-handed, has no inherent musical advantage (Kopiez et al., 2012).

Throughout the history of percussion, players learn that performance is often improved when relying on the dominant hand for metrically functional notes within a piece of music: the dominant hand acts as an anchor while the other hand "fills in" (McCormick, 1983). This playing paradigm has become known as "right-hand lead" for right-handed percussionists and left-hand lead for left-handed players (Stone, 1935; McClaren, 1994). The non-dominant hand performs better when automated (Peters, 1986), so percussionists maximize their rhythmic accuracy and sound quality by focusing attention on their dominant hand. For this reason, right/left-hand lead is the most popular sticking strategy for professional percussionists (McCormick, 1983).

Despite its prevalence, right/left-hand lead is not the only sticking strategy utilized by percussionists. Hand-to-hand or alternating sticking is also commonly used in conjunction with or instead of right/left-hand lead (McCormick, 1983). Instead of using the dominant hand to anchor, each hand is used equally. However, the preference for one hand is not entirely absent from this strategy since the dominant hand usually initiates each rhythmic section (Bacon, 2014).

Given the importance of both sticking strategies in percussion performance methodology, dominant hand lead and alternating are two common sticking patterns that are often referenced in percussion method books and prescribed in pedagogical exercises (McClaren, 1994; Gworek, 2017). Exercises often provide multiple sticking patterns while advising that the student also practices the same routine while reversing their sticking to provide more training for the non-dominant hand (Gworek, 2017). In this way, they highlight as well as subvert the functional differences between the hands in order to improve performance in sight-reading and prepared literature. An example of differing sticking annotations for an identical rhythm is shown in Figure 1. Figure 1 shows one rhythmic excerpt with a right-hand or dominant hand lead sticking pattern annotated, and the same excerpt with an alternating sticking pattern annotated.

Despite the explicit references to the existence of preferred sticking in method books and teaching, there has yet to be an in-depth study to show if these sticking patterns are actually employed and how the employment of these model sticking patterns may change depending on the musical context. While there might not be a clear consensus on the best-sticking choices in timpani performance, there certainly are preferences toward these two model sticking patterns in the pedagogical literature. While professionals and students may use these sticking choices in practical performance situations, other factors, such as unidiomatic notation or more complex rhythmic structures, may disrupt this trend. Furthermore, players may sometimes use these model sticking patterns for some sections of a score and not others. In our study, we aim to provide explanations for how sticking patterns change with the musical context, particularly with sight-reading.

3. Research questions and hypotheses

We explore sticking patterns when sight-reading while performing on a timpano with the following research questions:

- RQ1: Do players mostly use one of the two model stickings discussed in the literature, or are other models commonly used?
- RQ2: How does rhythmic complexity affect sticking choices?

Based on these questions, we hypothesize that:

- H1) Sticking patterns tend to gravitate toward one of these two models, especially when encountering more typical and simple rhythmic passages, and stray from them as the rhythms become more complex.
- H2) Rhythmic complexity will affect sticking choice, with sticking patterns becoming more varied as rhythmic complexity increases.

We seek to differentiate musical context's effects on sticking patterns by dividing measures into those with stable or unstable rhythms. We predict that the rhythmically stable measures will yield fewer sticking patterns among the participants, while unstable rhythms will yield the greatest number of strategies.

4. Methodology

The experimental methodology employed in this study aimed to capture participants' natural sticking strategies during sight-reading. The study adopted a between-subject cross-sectional design, with individual distances from model stickings (Hamming Distances) serving as outcome measures, with a paired Wilcoxon Rank test used as an assessment of their statistical significance. The sight-reading score was designed as a traditional rhythmic étude, featuring sectional developments introducing new material. Its legibility and comparability to typical snare-drum or timpani études was confirmed by co-author F. Marandola, an Associate Professor of Percussion at McGill University. Following the sight-reading session, the authors transcribed individual sticking patterns and organized them in a spreadsheet for analysis and comparison with our model stickings and other participants.

4.1. Score design

Participants were given a score composed specifically for this exercise, shown in Figure 2. It contains rhythms representative of standard snare-drum and timpani repertoire and gradually increases in complexity (Bacon et al., 2014). Snare-drum literature was referred to in the design of this score due to the fact that, while the experiment was performed on the timpani, it was desired the performer operate comfortably in the context of a single drum, rather than considering more complex multi-drum environments. In addition, the score was written using the snare-drum standard template in the Sibelius 6 notation software. Lastly, the score was composed such that approximately equal numbers of notes are on the beat or syncopated, ensuring that direct comparisons could be made regarding hand choice for each note type.

The score's design was of particular importance, as it was imperative to challenge the performers ability to read while also introducing them to material which would not immediately produce a large string of errors, thus rendering their performances less useful in the context of our study. In addition, it was essential to consider if or how the score could introduce a bias toward either the left or right hand. Given the authors expertise and familiarity with percussion literature, we determined that the simple rhythm at the beginning of the score allows the performer to begin with either hand with minimal pressure or attention needed to be performed correctly. Furthermore, the score was clear of any ornamental notation, such as dynamics, articulations, rolls, or tempo changes, which would disrupt or discourage a simple alternating sticking pattern.

4.1.1. Structure

The overall structure of the score can be broken down into nine sections of increasing and decreasing complexity mediated by syncopation and irregular rhythms. Syncopation can be generally described as rhythmic cues which fall outside or contradict an inferred musical pattern which has already been established (Lerdahl and Jackendoff, 1996). In the scope of our research, we define syncopation as notes which fall just after or before a beat or strong beat (i.e., an important demarcation of the time signature) but can still be located on a grid of sixteenth-note subdivisions. We also define irregular rhythms as another form of syncopation in our study as tuplets that do not fit into a grid of sixteenth-note subdivisions. Outside the scope of the audible quality of a given

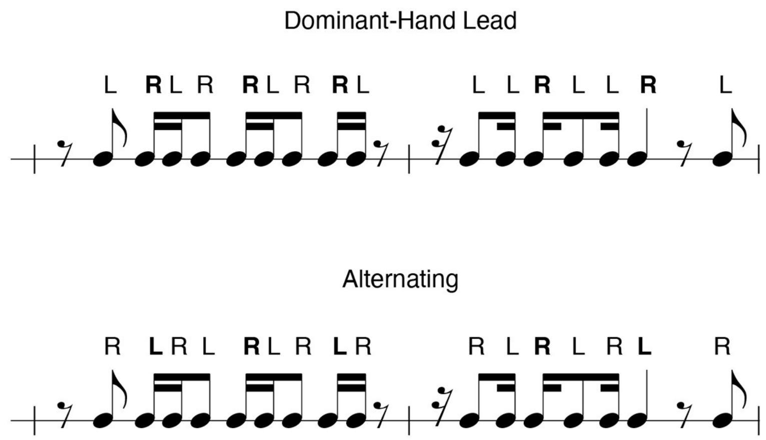

FIGURE 1
Examples of model stickings. In the dominant hand lead model, the right-hand performs metrically important beats, such as strong- and weak-beats (emboldened). In the alternating sticking, an alternating pattern is maintained throughout each measure regardless of the rhythmic content.

FIGURE 2
The entire sight-reading score used in this study, as seen by the participants.

rhythm, the score also contains a strong example of unidiomatic notation in measure 11. The visual spacing of the notes and the excess use of sixteenth-note rests obfuscates where the actual metrical markers which govern the measure reside.

Beginning with larger and simpler beat subdivisions, the score moves toward simple syncopation patterns and onto smaller beat subdivisions, complex syncopation patterns, and polymetric tuplets with periods of simple segments in between to provide a respite from the more difficult passages. The polymetric tuplets imply the existence of two overlapping metric structures; that of the tuplet (e.g., placing 3 or 5 beats in the space of 4) and that of the common notational grid. Further changes to the time signature itself consisting of 2/4, 3/4, and 4/4 time were also employed so that the performers would be challenged not only in their ability to keep accurate internal timing within a particular beat framework but also in their ability to adapt to new global timing structures in general. The insertion of simple segments in between more complex ones was done so that the performers could recover physically and mentally reorient themselves after periods of sustained musical complexity. The annotated score is shown in Figure 3.

Each beat in the sight-reading score can be evaluated using five different timing functions; strong beats, weak beats, eighth notes, sixteenth notes, and tuplets. Strong-beat and weak-beat notes consist of the primary beat values, often referred to as quarter-notes. In a 4/4 measure, these notes refer to each of the four main beats. In a typical subdivision of the beat in 4 sixteenth notes, the strong beat consists of beats one and three, while the weak beats refer to beats two and four; the eighth-note beats fall in

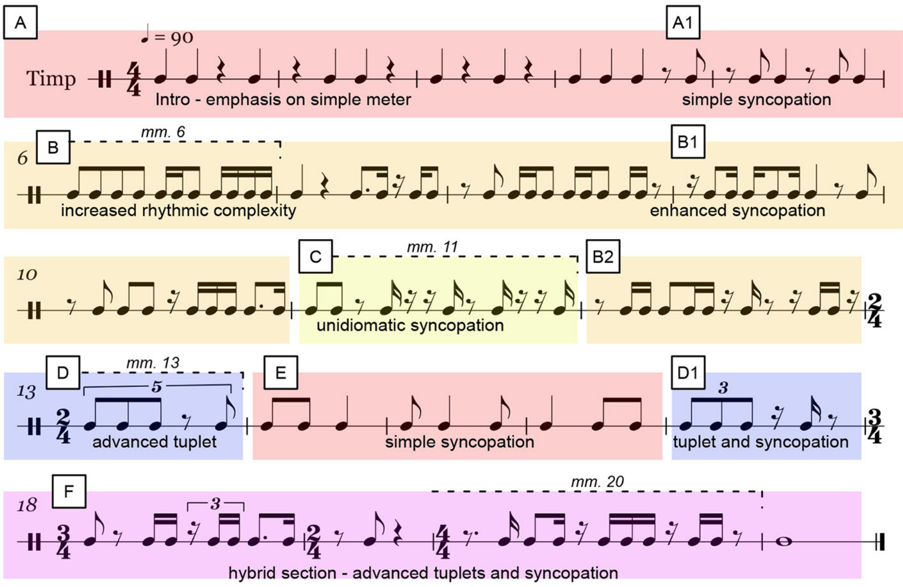

FIGURE 3
The various regions of rhythmic complexity can be seen. Color coding indicates each section in relation to musical complexity. Red **(A, A1)** relates to straightforward rhythms with minimal syncopation, followed by orange **(B, B1, B2)**, indicating further use of 16th-note subdivisions and more complex syncopation. Yellow **(C)** corresponds to complex syncopation represented by unidiomatic notation due to the groupings of 16th-note rests. Green **(E)** represents a reprieve to simple meter and syncopated patterns flanked by indigo **(D, D1)** which contains polymetric tuplets, and violet **(F)**, which contains hybrid elements of advanced tuplet use and heavily syncopated rhythms. Stable mm. 6, 20, and unstable mm. 11, 13 are marked by dashed lines.

between the strong- and weak-beat quarter-notes; the sixteenth-note values refer to notes which fall between the eighth notes, as seen in Figure 4; lastly, the tuplets in this exercise refer to irregular beat structures which cannot be evenly mapped to the grid structure of sixteenth notes. For example, the quintuplet (i.e., five notes under a bracket) found in measure 13, the sight-reading score places five eighth notes in the space of four.

In our study, we distinguish between the type of notation used to represent a specific beat and the beat function previously described, as we were not evaluating the sustained note values in the sight-reading score. In many cases, a strong beat can be represented by notation which does not indicate specifically where that beat takes place, as this refers to the length of time a note should be held. This is how we have defined the unidiomatic notation segments in the sight-reading score, which account for greater rhythmic complexity. For example, in measure 11, rests were split and grouped such as to produce an ambiguous sense of placement within the notational grid. This was done to direct the performer's attention toward maintaining their sense of internal timing, which in turn minimizes focus on expressive gestures and conscious sticking choices. In addition, standard notation formatting can be recognized by the performer and performed automatically through memorization. For functional purposes in this percussive context, we are only interested in sticking choices in relation to note-onset times.

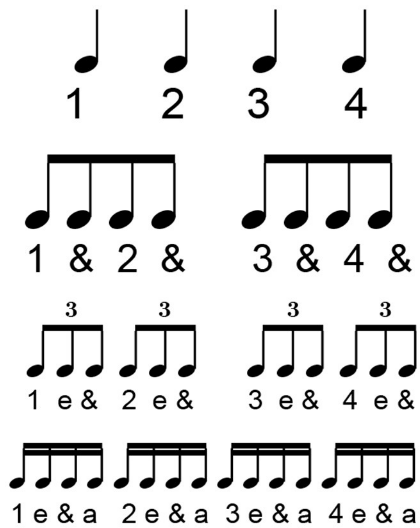

FIGURE 4
A measure containing four quarter notes subdivided into eighth notes and sixteenth notes. Notes labeled with a 1 are strong beats. All numbers are beats. "&" indicates an eighth note syncopation while "e" and "a" indicate sixteenth note syncopations with the exception of triplets.

4.1.2. Rhythmic stability

Figure 4 shows how all the beats in a measure can be subdivided from quarter notes to sixteenth notes. Looking at the bottom line of this rhythmic tree, the sixteenth notes can be divided into their various parts with the designation 1 e & a, with the first number referring to the strong beat or beat in the measure, and "e & a" referencing the further sixteenth note subdivisions of that beat.

For our study, we define stable rhythms as patterns that fit into the 16th-note subdivisions in a given measure, with very little or no syncopation. Unstable rhythms use irregular patterns, syncopation, and unidiomatic notation, including rest groupings which may obscure clear metrical markings. Unstable rhythms are generated through a combination of high syncopation levels and unidiomatic notation representation.

Our study identifies musical passages as either stable or unstable rhythms to test the effects of rhythmic complexity on sticking choices.

4.2. Choice of stable and unstable rhythms

The overall structure of the sight-reading task consisted of several sections, which gradually increased in levels of rhythmic complexity. Although the score contains many interesting examples of rhythmic content, we have selected two stable and two unstable regions for our analysis from the larger sections B, C, D and F (as seen in Figure 3) to examine our second hypothesis. These measures are of particular importance in that they represent the introduction of unique rhythmic material.

4.2.1. Stable rhythm 1–measure 6

Measure 6 is the first measure of Section B and introduces sixteenth-notes as well as the first elements of more advanced syncopation. Nevertheless, it represents a very typical rhythmic pattern that most percussionists will have seen and played many times before. Moreover, it contains no irregular rhythms which create tension with a sixteenth-note grid (i.e., tuplets).

Despite increased rhythmic complexity compared to the previous measures of the score, this section should produce a predictable sticking pattern due to there being no presence of rests, forcing more automated sticking choices onto the performer. With the dominant hand lead in particular, this measure invites this strategy more than others since the dominant hand can maintain a steady pattern. In contrast, the non-dominant hand fills in the sixteenth note subdivisions. This type of approach can be more clearly seen in Figure 5.

This predictability depends on the musical context and the fact that the preferred hand is better at producing consistent rhythm and that the non-preferred hand is better when automated (Peters, 1986). In measure 6, the larger subdivisions of quarter and eighth notes can be maintained steadily with the dominant hand. Because the music being performed is unrehearsed, the participants in the experiment will focus their attention on the oncoming notes, requiring the hands to respond automatically.

4.2.2. Stable rhythm 2–measure 20

Measure 20 is another example of stable rhythms which are more complex than the ones shown in measure 6. This measure is important as it presents a return to the original time-signature after several measures of changes in meter (from 2/4, 3/4 back to 4/4 time). Though syncopation is present, particularly on the first beat, all the notes fit into the sixteenth note grid and are played on

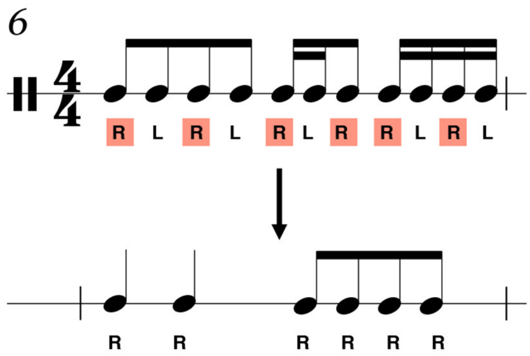

FIGURE 5
Measure 6 shows the part of the rhythm only played by the dominant hand. The highlighted R's are re-written as a reduction in the bottom half, demonstrating the larger beat functions.

every strong and weak beat. These constitute the main grid markers of the time signature.

4.2.3. Unstable rhythm 1–measure 11

Measure 11 (section C) is unique, as it was specifically composed to contain the unidiomatic representation of syncopation, where the rhythms were designed to throw-off the performer. The overabundance of sixteenth-note rests were placed to deliberately make it unclear to the performer where the strong-beat is, making it more difficult to read.

4.2.4. Unstable rhythm 2–measure 13

Measure 13 offers the first example of a rhythm that we consider to be unstable due to the presence of a tuplet. A single quintuplet which does not fit the grid of quarter-note, eighth-, or sixteenth-note subdivisions makes the automation that would occur with a dominant hand lead strategy difficult and puts this in the category of an unstable rhythm. Here we introduced a silence within the tuplet to increase the challenge for the performers.

4.3. Participants

A total of 31 participants were selected for the sight-reading task with at least one year of university-level training in percussion performance. The average age of the participants was 25.09 years of age with a standard deviation of 6.83 years. This group of participants, with many years of performance experience, can be considered quite advanced with an average of 11.81 years playing experience. Of the 31 participants, five self-identified as left-handed (P6, P7, P8, P10, and P30), and the other 26 identified as right-handed, further referred to as P1-P31. Regarding grip style of the timpani mallets, all participants employed French-style grip except for 3 (P2, P26, and P30) who employed German grip, and 2 (P4 and P13) who employed a hybrid French/American grip. All participants resided in the greater metropolitan area of Montreal, QC, Canada and were recruited over the course of three experimental periods. In addition, in each phase, all participants performed the sight-reading on a single drum with their own timpani mallets of medium-firm hardness. The first round of data included participants P1-P4 (October–November 2013) seen in Bacon (2014), the second included participants P5–P15 (November 2015–February 2016) seen in Marci (2018), and the third and most recent data phase included participants P16-P31 (June 2021–April 2022).

4.4. Experiment procedure

Participants were asked to get ready behind a single drum with their mallets in preparation for performing the sight-reading task. All experimentation phases were conducted in accordance with the REB-II ethics protocol from the McGill University Ethics Committee.

The participants were instructed to employ their preferred technical grip and to place less focus on rigorous timekeeping established by the metronome, which was set to 90 beats per minute. Performers were instructed to focus on the onset times of the rhythms in the score, with the ultimate goal being that each participant performs relaxed and comfortably.

The experiment began with the score presented in Figure 2 sitting on a music stand face down so the performer could not see the musical content of the score. When the performer was ready to begin, a proctor pressed play on a video camera, and the proctor turned over the score. Immediately after this, the metronome was used to count in the performers and was switched off at the beginning of the 4th measure. To analyze the performances, the video footage of each performer was extensively reviewed to manually compile statistics on left- and right-hand strokes, identify errors in the performer's play, and search for other unforeseen effects of handedness.

The timpano they performed on was based on the availability at the time of the experiment, which took place either at a research lab or a percussion studio. However, since the sight-reading score contained no pitch information, the fact that participants performed on different-sized timpani did not notably affect their sticking choices since they were only performing rhythms and not engaging with the drum's ability to tune. This is further bolstered by the fact that percussionists are accustomed to practicing and performing on different models as students and professionals. If the notation had required specific tuning changes, the drum size would take on much more significance, as this fact limits the range of available pitches. Tuning changes on the timpani also elicit a broader set of gestures from the performer (such as leaning closely to the drum to better sense the accuracy of the new pitch's intonation).

Following the experiment, the participants were invited to provide brief evaluations of their playing performance quality throughout the experimental process. This step was added to ensure that recorded results were the product of each performer's natural playing style.

4.5. Data analysis

Participants' sticking patterns were annotated from the videos of their performances into the score. Transcriptions of sticking choices were done by hand by the authors.

By following along with the score and watching each participant's recorded video, sticking patterns were written in the score to correspond to which hand played which note so that by the end, we had separate scores for each participant with their individual transcribed sticking choices annotated in the score.

Notes performed by the dominant hand were labeled pink, while notes performed by the non-dominant hand were labeled gray. This enabled us to have a visual overview of all the participants sticking choices for the entire score and derive statistical information regarding sticking choices concerning the beginnings of defined regions, beat type, number of sticking changes, and error rates.

Following that, certain regions of the score were extracted based on the stability of stable and unstable rhythms. We selected two stable regions (measures 6 and 20) and two unstable regions (measures 11 and 13). Once a region was chosen, we calculated error rates for that region and then reorganized the spreadsheet based on identical sticking patterns so that it would be clear to ascertain how many participants employed a given sticking pattern or how varied the sticking patterns were in a given region.

Data was analyzed by comparing sticking patterns with model sticking patterns using a threshold for errors and error classification. Score analysis was done using a classification of note and beat types and how they typically function musically. These issues are discussed in the following sections.

In this study, we used both dominant hand lead and alternating sticking pattern models as found in the literature. The model patterns serve as default sticking patterns to measure predictability in sticking choice among the participants.

4.5.1. Error classification

In identifying errors, two types of classification emerged: mistimed strikes and ghosted strikes. Mistimed strikes are defined in this study as attempted notes in relation to note-onset which were clearly outside the rhythmic time frame indicated by the notation. In the rare case where multiple mistimed strikes occur for a specific beat, these instances were recorded as a single error. Ghosted strikes are omitted notes from the score, either as initiated strikes but restrained from making contact with the timpano membrane or entirely skipped altogether.

Because a certain number of errors are to be expected when performers are engaged in a sight-reading task, we have placed a threshold on the number of mistakes we accept for each participant when discussing the results of certain data sections. For this work, we chose not to consider any participants that missed more than 20% of the notes in a given section of the score, either making a timing-based error in rhythmic execution (mistimed strikes) or omitting a note (ghosted strikes). This threshold was chosen based on the same principles applied to a student engaged in a sight-reading exam, where a certain number of errors are allowed, but if the errors reach a certain threshold, they would fail the exam. Full

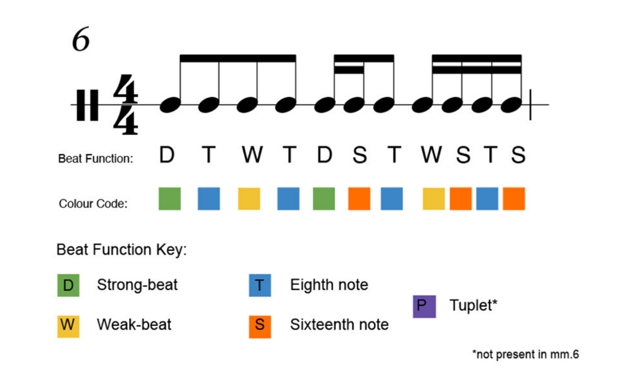

FIGURE 6
Labeled notes of the sixth measure of the score. The measure contains two strong beats, two weak beats, four eighth-note syncopations, and three sixteenth-note syncopations. Color coding is seen in sticking charts. No tuplets appear in measure 6.

TABLE 1 Distribution of rhythmic elements in the entire score.

Element	% of Score	Function
Strong-beat	20.39	Demarcates measures and half-measures
Weak-beat	20.39	Basic beat marker
Eighth note	25.24	Introduces syncopation
Sixteenth note	27.18	Enhances metered complexity
Tuplet	6.79	Obscures metering

details on the number of removed participants per section of the score can be seen in Table 2.

Lastly, due to the absence in the notation of any articulation markings and sustained rolls on the drum-head, slight variations of the drum playing surface were not considered to have any effect on the participants ability to conduct the task whatsoever and were not considered errors.

4.5.2. Beat classification

As shown in the score structure section of the paper, each note of the score was classified according to its metrical function. Strong beats, weak beats, eighth notes, sixteenth notes, and tuplets were annotated in the score as aids for analysis of the sticking patterns chosen by the performers. This provided a hierarchical map that enabled us to correlate hand preference to beat type. An example from the score can be seen in Figure 6. Table 1 shows the prevalence of different beats and rhythmic elements in the entire score.

The performance videos were annotated to determine which hand each percussionist used to play each note. The percentages of dominant and non-dominant strokes were computed for each of the five metrical groups.

5. Results

Percussionists strongly preferred to use their dominant hand for strong beats with an average 69.99% use rate for all instances in the score. In both strategies, the dominant hand starts the beginning of phrases. Despite this trend, no two players used the same sticking pattern throughout the score. Nevertheless, it is possible to find several sections where the same sticking pattern is repeated among participants. The more homogeneous sticking patterns were observed to reproduce the two model sticking strategies we referenced earlier in the paper, with the dominant hand lead strategy yielding more sticking similarities with the participants across the entire score. When model sticking patterns were not strictly adhered to, other strategies emerged either as hybrids between alternating or dominant hand lead or strategies that did not resemble the model strategies.

Furthermore, we found that musical sections composed specifically to contain unstable rhythms led to more varied sticking patterns, confirming our second hypothesis. More rhythmically stable passages generally yielded a higher percentage of model sticking strategy usage among participants and more homogeneous sticking patterns. In contrast, rhythmically unstable passages resulted in much less utilization of model sticking patterns and a greater variety of sticking strategies overall.

TABLE 2 Omissions from sectional statistics due to crossing the 20% error threshold are seen above. Only performer P30 exhibited an error rate above 20% for the entire study at 22.33%.

Section	% of score	Participant(s) P	Note range
A	9.71		1–10
A1	4.85		11–15
B	24.27	13	16–40
B1	14.56	12, 13, 15, 30	41–55
C	5.83	30	56–61
B2	7.77	10, 19, 21, 24, 27, 30	62–69
D	3.89	19, 27, 30	70–73
E	8.73	19, 21, 24, 27, 30	74–82
D1	3.89		83–86
F	16.50	7, 19, 30	87–103
mm. 6	10.67		16–26
mm. 11	5.82	30	56–61
mm. 13	3.88	19, 28, 30	70–73
mm. 20	7.76	17, 19, 23, 30	95–102
Full Score		30	1–103

5.1. Interpreting errors

In general, all the participants performed the score well: 14 participants executed an error-free performance, while seven others made fewer than three errors. The total error rate across all participants was 3.75%. Throughout performing the score in its entirety, only Participant 30 (P30) crossed the 20% for the entire score at 22.33%. When analyzing specific regions of the score, participants that locally made more than 20% of errors were removed. This was necessary to identify the sticking patterns being used, as a high number of errors would lead to a lack of clarity in data analysis. Table 2 shows a full readout of omitted participants per section.

In the following sections, we will discuss the stroke distribution at the start of each section, compare similarities in sticking for the entire score between the participants and the model stickings, then detail the striking choices for two stable regions (measures 6 and 20) and two unstable regions (measures 11 and 13).

5.2. Similarity to model stickings

Across all participants, we have made a direct comparison between the model stickings and the observed sticking choices of the participants in our study. Given the bi-manual nature of percussion performance, sticking orderings could be seen as a binary string consisting of dominant and non-dominant hand use in the case of our study. Therefore, in a direct stroke-for-stroke comparison, the maximum number of different sticking choices between a participant and a given model sticking is 103; the total number of notes in the sight-reading score, otherwise known as the Hamming Distance (Toussaint et al., 2004). The average distance from the model stickings across all participants and the standard deviation can be seen here in Table 3.

Participants showed greater stroke-for-stroke similarity with the dominant hand lead model sticking but with considerable variation between participants; the standard deviation of similar stickings between the participants was 9.96 strokes for the alternating model sticking and 17.72 for the dominant hand lead. The altefrnating hand pattern measured an average of 57 differences with the participants or 55.33% of the 103 possible notes in the score. In comparison, the dominant hand lead stood at 36.57 sticking differences or 34.5% of the total possible notes. A paired Wilcoxon Rank test demonstrated that this difference is highly significant (W = 40.5, $p < 0.001$).

5.2.1. Similarity in stable and unstable measures

In the example measures of stable and unstable rhythms shown in Table 4, we again find that the participants exhibit a closer similarity to the dominant hand lead pattern overall, with the closest stroke-for-stroke similarities found in measure 13. In this case, the average hamming distance between the dominant hand lead sticking and the performers was 3 out of 11 strokes or 27.27% measure. The stable rhythmic quality of measure 20 contained the smallest difference between alternating and dominant hand lead model stickings at 4.07 and 3.96 strokes, respectively. These hamming distances correspond to 50.87% stroke difference for the alternating lead and 49.50% for the dominant hand lead. The lack of significance was also evident with regards to the Wilcoxon Rank test results (W = 32.5, $p > 0.5$).

Overall, the four measures analyzed here represent a wide range of note values, from the largest measure note count in measure 6 (11 notes), to one of the smallest in measure 13 (4 notes). Despite difference in rhythmic stability and note count, measure 6 and measure 13 contained a similar balance in hamming distances with the two model stickings. In fact, both measures demonstrated highly significant differences between alternating- and dominant hand p values visible in Table 4.

5.3. Muting

Although participants were instructed to perform only note-onset times (i.e., not to influence note duration), muting was observed in 22.58% or 7 out of the 31 participants; P17, P19, P21, P23, P26, P27, and P30. In each case, the instance of muting was subtle and not consistently implemented throughout the reading of the score. Regarding sequences of single-hand use, the performers who exhibited instances of muting demonstrated an average longest dominant hand sequence of 5.71 strokes (out of a possible 103), as opposed to the non-muting average of 4.20 strokes. Muting performers had a slightly higher than average dominant hand performance rate at 54.91% as opposed to the non-muting average of 53.88%. In addition, muting performers demonstrated an average error rate of 9.01% as opposed to the average of 2.22% for non-muting players. Lastly, of the seven players who exhibited muting, only one was a self-identified left-handed player, which is consistent with the natural distribution of left-handed persons in the general population.

5.4. Initial stroke distribution

At the start of each section, it appears that a given note beat function has an influence which hand is used to begin the segment. The first strong beat is 90% dominant hand initiated, while the following segment first note is an eighth note, pushing the dominant hand starting percentage to 50%. This trend continued with the beginnings of other sections. For example, at the beginning of section 3 (increased rhythmic complexity), the first note is 84% dominant hand initiated.

Table 5 shows the major sections of the score in order of appearance. The type of beat each region begins with and the percentage of players that used their dominant hand to play that beat are shown.

These results indicate a preference for the dominant hand when playing strong beats. Note that with the sixteenth-note subdivision within the Enhanced Syncopation section, the preference for the dominant hand drops to 41.94%, the lowest percentage for any initial note in a given section.

5.5. Stable rhythm 1—measure 6

Measure 6 is an example of a stable rhythm pattern that is common enough to yield a predictable sticking strategy from most percussionists in a sight-reading task and is relatively easy to perform. In this measure, shown in Figure 6, we found that a dominant hand lead sticking pattern was the most common strategy used, followed by an alternating sticking strategy. This aligned with our first hypothesis, as we expected the two model sticking strategies to be the most commonly used by participants for this measure.

TABLE 3 Similarities of model stickings to performed stickings across all performers including results from a paired Wilcoxon Rank test. The total possible strokes in the score is 103.

Model sticking	Hamm Dist	Hamm % of Score	SD of Hamm	W statistic	*p* value
Alternating lead	57.00	55.33	9.96	40.5	<0.001
Dom Hand lead	36.57	33.50	17.72		

TABLE 4 Stroke similarity (i.e., hamming distance) comparisons of stable and unstable measures with the model stickings.

Quality	Measure	Strokes	Model	HD	HD %	SD	W statistic	*p* value
Stable	6	11	Alt	7.52	68.36	3.30	80.0	<0.001
			Dom lead	3.00	27.27	3.69		
	20	8	Alt	4.07	50.87	2.20	32.5	>0.5
			Dom lead	3.96	49.50	2.03		
Unstable	11	6	Alt	3.83	63.83	1.76	126.0	0.027
			Dom lead	2.47	41.16	1.80		
	13	4	Alt	3.07	76.75	1.12	31.0	<0.001
			Dom lead	1.07	26.75	1.25		

Hamming distances are displayed in stroke values, and as a percentage of notes in the given measure. In this table, the alpha level for significance was reduced to 0.0125 to correct for multiple testing.

TABLE 5 This table displays the dominant hand use on the first note of each section of the score.

Section	Beat function	Dom hand use %	% diff Alt	% diff DHL
A	Strong-beat	90.32	9.68	9.68
A1	Eighth note	48.39	51.61	48.39
B	Strong-beat	83.87	83.87	16.13
B1	Sixteenth note	41.94	58.06	48.39
C	Strong-beat	67.74	70.97	32.26
B2	Eighth note	77.42	77.42	22.58
D	Strong-beat	93.55	93.55	6.45
E	Strong-beat	70.97	80.65	29.03
D1	Strong-beat	74.19	25.81	25.81
F	Strong-beat	67.74	32.26	32.26

The beat function column indicates the kind of rhythmic function present at the start of each section, followed by the use rate of the dominant hand across all performers for that given note (Dom Hand Use %). The last two columns written as "% diff Alt" and "% diff DHL" reference the percentage of performers who did not agree with the model stickings. P30 has been included in this case due to a correct stroke occurring on each section's initial beats.

All of the participants in this section were included for consideration, as the error rates never reached or exceeded the 20 percent threshold. For measure six specifically, 16 out of 31 Participants employed a dominant hand lead sticking strategy, 9 employed an alternating sticking strategy starting with the dominant hand, and 3 employed an alternating sticking strategy starting with the non-dominant hand. Interestingly, P2 and P6 used a non-dominant hand lead sticking strategy. P8 used a different strategy altogether.

The following charts group together the participants who used identical sticking patterns. Pink squares represent the dominant hand (lighter gray when printing in B&W), and gray represents the non-dominant hand. Orange squares represent errors, and yellow represent ghost notes (notes not played). Numbers under the column labeled "note" correspond to the note number, as seen in the measure reproduced below. A legend describing the color coding of the sticking charts can be seen in Figure 7.

The largest number of participants in this region chose a dominant hand lead strategy, seen in Figure 8, followed by an alternating strategy beginning with the dominant hand, seen in Figure 9, demonstrating the popularity of our two model sticking patterns.

It is interesting to note that the only deviations that occurred from the model sticking patterns in this example were either a reversal of dominant hand lead (P2 and P6) or, in the case of

P8, where the only reason we categorized their strategy as being different was due to the errors that were made.

As shown in Figure 9, starting on the right with P5 and up to P30, the participants exhibited the alternating model sticking strategy. For P7, P20, and P29 we see an alternating sticking pattern as well but in reverse starting with the non-dominant hand. Most notably, P2 and P6 used a strategy completely opposed to the dominant hand lead: non-dominant hand lead. P8 had two ghost notes, but if not for those seems to have employed an alternating sticking pattern beginning with the dominant hand.

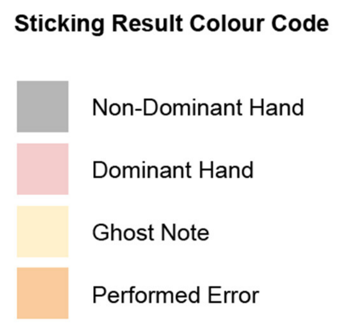

FIGURE 7
Color codes used for notating hand choices and errors.

5.6. Stable rhythm 2—measure 20

Measure 20, seen in Figure 10, contains more syncopation than measure 6, but only in the first beat. All strokes for this measure fit within a sixteenth note grid, making this a stable rhythm, albeit slightly more complex than measure 6.

Due to the error threshold in this section, any participants who made more than one error, including a ghosted note, were not included in the analysis. For measure 20, participants P17, P19, P23, and P30 were excluded, leaving a total of 27 participants.

Overall the sticking strategies were more varied than in measure 6. Interestingly, only 2 participants (P5 & P31) chose to use a dominant hand lead sticking strategy. Five participants chose a sticking pattern that began as dominant hand lead but quickly

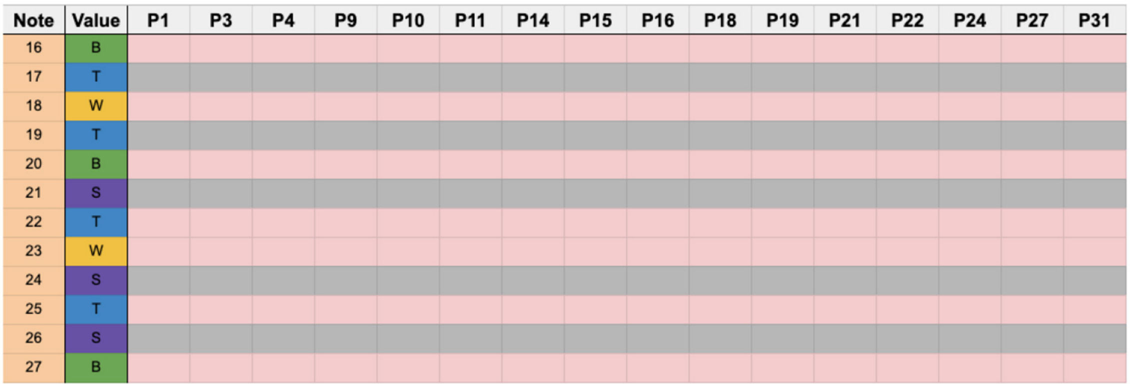

FIGURE 8
Chart showing the participants that used a dominant hand lead strategy for measure 6.

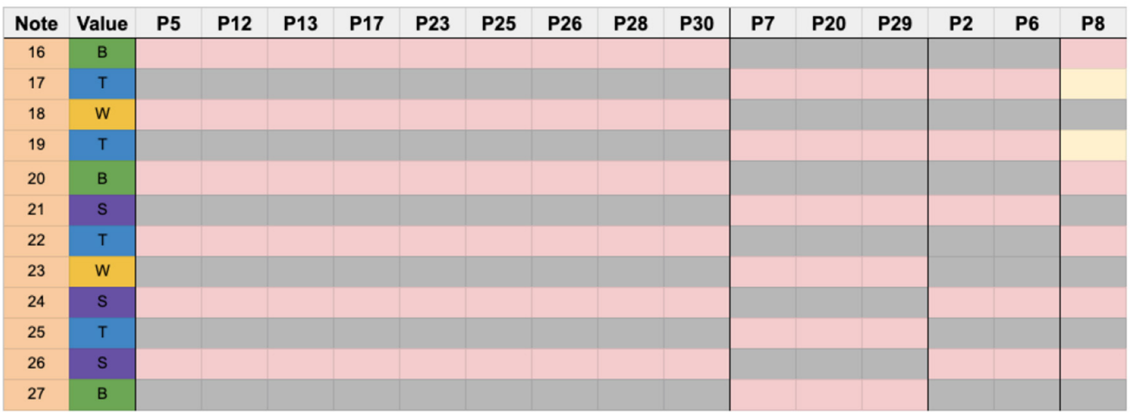

FIGURE 9
Participants who used a strategy other than that of dominant hand lead.

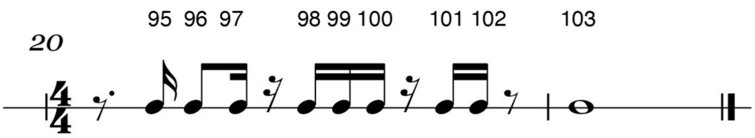

FIGURE 10
Measure 20 with note sequence identification.

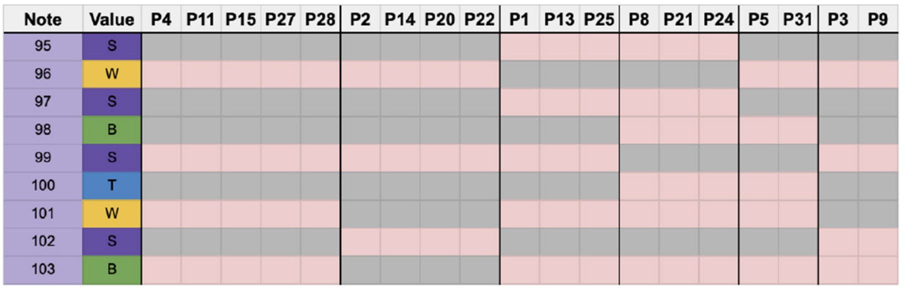

FIGURE 11
Chart showing the highest number of shared sticking choices from highest to lowest.

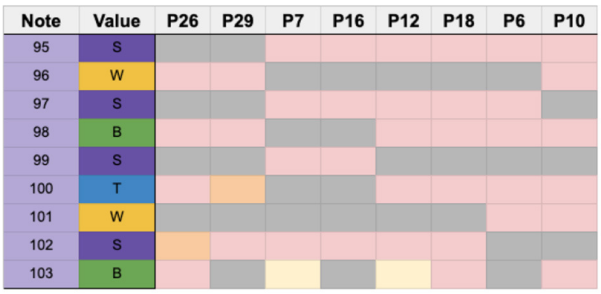

FIGURE 12
Chart showing the participants with no common sticking choice.

switched to alternating seen in Figure 11 (P4, P11, P15, P27, P28). Only 3 participants used an alternating strategy (P1, P13, P25), meaning the other five groups of participants here chose identical strategies that did not resemble either dominant hand lead or alternating (Gworek, 2017).

Finally, eight participants chose unique sticking strategies for this measure, as seen in Figure 12.

Overall, 14 different sticking strategies were identified among the participants, a large increase compared to measure 6.

5.7. Unstable rhythm 1—measure 11

Measure 11, shown in Figure 13, was defined as unstable due to the prevalence of syncopated sixteenth notes and groups of sixteenth note rests.

FIGURE 13
Complex syncopation in measure 11 with note sequence identification.

The error threshold for this region was two, and only P30 was excluded in this analysis, leaving a total of 30 participants to analyze in this region.

Figure 14 shows participants who used identical strategies in this measure. Seven participants chose the same sticking strategy, using their dominant hand to begin the section and the rest of the notes were played with the non-dominant hand (P9, P11, P14, P16, P19, P20, and P22).

In another case, five participants employed an alternating strategy which started with the dominant hand (P1, P7, P13, P23, and P29). Interestingly, five other participants (P6, P10, P17, P18, and P21) chose to do the inverse sticking of the dominant-lead group, thus leading with the non-dominant hand and completing the rest of the section with the dominant hand. Two participants (P5 and P12) chose an alternating strategy that started with the dominant hand but ended with a ghosted note. In contrast, two others chose an alternating strategy that began with the non-dominant hand (P25 and P26).

Nine out of 30 participants used unique strategies that were not replicated by any other player (Figure 15).

Compared with measure 6, which contained stable rhythms, the sticking strategies in measure 11 were more varied. For example,

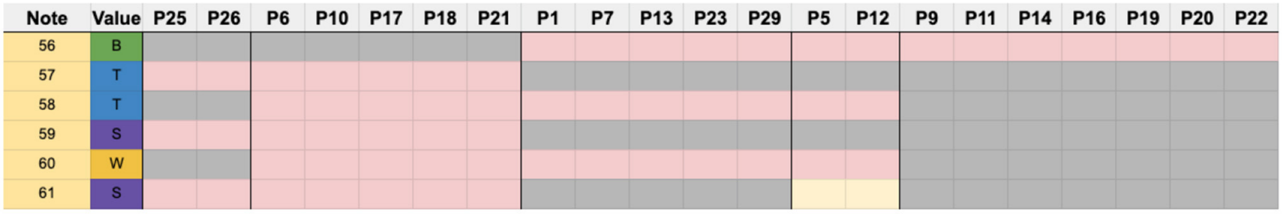

FIGURE 14
Chart showing participants who used identical strategies in measure 11 grouped together.

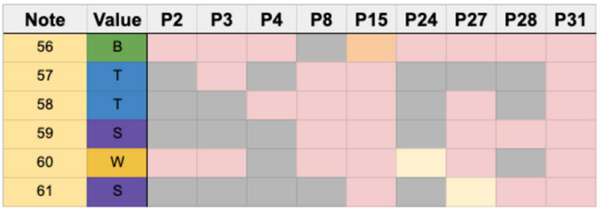

FIGURE 15
Chart showing the different strategies used in measure 11. P30 is removed due to the high number of errors.

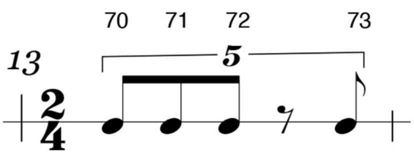

FIGURE 16
An irregular tuplet in measure 13.

the largest number of participants who used an identical sticking strategy was seven.

Overall, 14 different strategies were identified among the participants in this region.

5.8. Unstable rhythm 2—measure 13

Measure 13, shown in Figure 16, has a small number of notes; therefore, the error threshold was set to one. P30, P19, and P27 were not considered in these results. The 28 performances of participants who successfully played measure 13 are shown in Figure 17.

Out of 28 participants, 12 chose an alternating sticking strategy beginning with the dominant hand, while 7 participants chose a different sticking strategy which resembled a paradiddle beginning with the dominant hand. A paradiddle is a rudiment which begins with an alternation and then a double, such as RLRR or LRLL. Four participants used their dominant hand for all the notes, and the remaining 5 chose a variety of unique strategies. Figure 18 shows participants who shared common sticking choices. Figure 19 shows participants who chose unique strategies.

Overall, we noticed a clear trend toward a common sticking strategy of alternating with dominant hand initiation. A total of eight different strategies were utilized among participants for this measure.

5.9. Percussion sticking data

All of the sticking data available from the study discussed in this paper, a collection of sight-reading sticking data, along with the annotated score, has been made publicly available for further analysis here: https://github.com/mmwanderley2/PercussionStickingData.

5.9.1. Database organization

The structure of the sticking database takes the form of an organized spreadsheet organized primarily by player for each column and by individual notes in the score by row. Every individual performed note in the score corresponds to one of four possible outcomes and is represented in the database as follows; dominant hand (D), non-dominant hand (ND), ghost note (G), and error (E). Basic participant experience data and stated handedness can also be seen. In addition, each subsection of the score is outlined, including the individual note sequence and rhythmic function. The abbreviations for rhythmic functions can be seen in Figure 7.

6. Discussion

The principles of percussion pedagogy are generally structured to accommodate a performer's physical limitations, which includes recognizing the reliance on the dominant hand for sound quality and rhythmic accuracy (Peters, 1986; McClaren, 1994). Sticking strategies in traditional pedagogy align with this preference, emphasizing the dominant hand for rhythmically important notes. Our results confirm the influence of these pedagogical principles, as performers strongly favored their dominant hand for strong beats, partially supporting our hypothesis, and consistent with prior research (Bacon et al., 2014).

However, it is noteworthy that a few participants did not show a clear preference for the dominant hand but still performed well,

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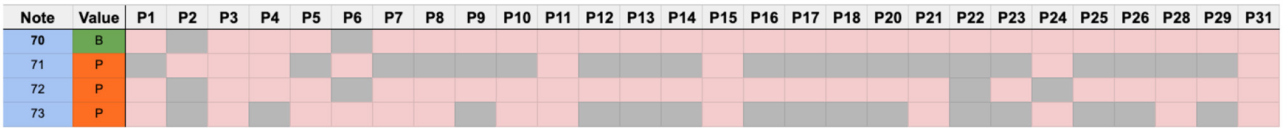

FIGURE 17
Chart showing the sticking choices of participants who successfully performed measure 13.

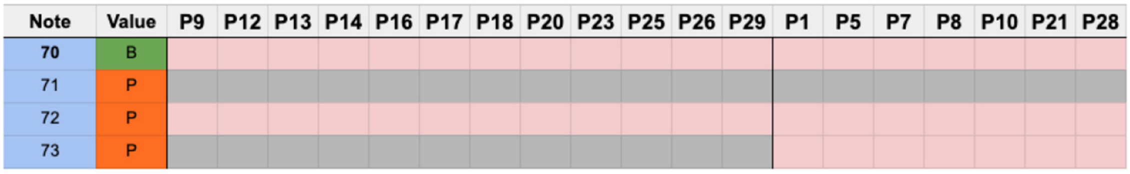

FIGURE 18
Chart showing participants who shared common sticking strategies clustered together.

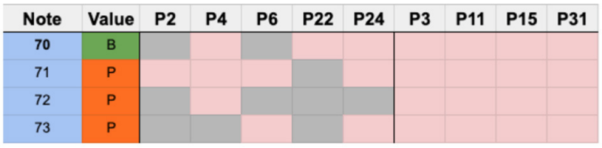

FIGURE 19
Chart showing participants who used unique strategies and a cluster that used only the dominant hand.

suggesting that model sticking strategies for teaching may not correspond directly with better performance skills in sight-reading. For example, Participants P2 and P6 deviated from the dominant hand lead strategy, starting sections with the non-dominant hand and employing alternative sticking choices. Despite these atypical patterns, they exhibited an error free performance in the sight-reading task, suggesting that strict adherence to model sticking patterns may not necessarily improve performance skills.

The emergence of alternative and hybrid sticking strategies, deviating from the model patterns, was observed when participants did not strictly follow the prescribed sticking patterns. These findings neither fully confirm nor refute our first hypothesis, indicating that other sticking patterns or hybrid approaches are also possible. However, our first hypothesis is supported by the prevalence of the two model sticking patterns in measure 6.

While increased rhythmic complexity did lead to a wider variety of sticking strategies, it was not solely responsible for this phenomenon. In measure 20, labeled as rhythmically stable, we observed the same number of different sticking strategies as in measure 11, which was considered unstable. The combination of idiosyncratic notation and rhythmic complexity may contribute to this effect. Additionally, handedness played a role in sticking choice, with left-handed players exhibiting a wider variety of sticking patterns even in stable and conventional regions of the score. This trend aligns with studies suggesting that left-handed individuals often possess more ambidextrous abilities (Lombana et al., 2022).

6.1. Use of model stickings

The results of our study showed a preference for the dominant hand lead model sticking pattern among the participants for the entire sight-reading score as well as the selected measures of analysis. This was also consistent across both stable and unstable measure examples (mm. 6, 11, 13, and 20) seen in Table 4. Hamming distances further confirmed this observation.

Musical instrument training involves demonstrations by teachers, particularly in percussion training where sticking instructions for specific musical passages are common. To consider how an instructor's personal preferences may influence students is highly informative. If a teacher favors the right-hand lead strategy, this bias may be passed on to the student. Similarly, if a teacher emphasizes perfect symmetry, students are likely to be trained in alternate sticking and may prefer it. Evaluating student-teacher learning styles can provide further insights, as the prevalent "maestro" pedagogical method and power dynamics strongly influence student behavior (Zhukov, 2007). For instance, percussionists with military-style training, such as those in marching bands, are taught specific sticking strategies with varying difficulty levels and visual style considerations. Studying sticking choices in this context offers valuable insight into the influence of pedagogical style and teacher-student relationships.

6.2. Role of stable rhythms

We chose stable rhythms that could clearly be subdivided or placed easily into a sixteenth-note grid, with little to no syncopation. Our hypothesis that model sticking would be prevalent in stable rhythms was confirmed by the fact that most participants utilized model sticking patterns in the first stable

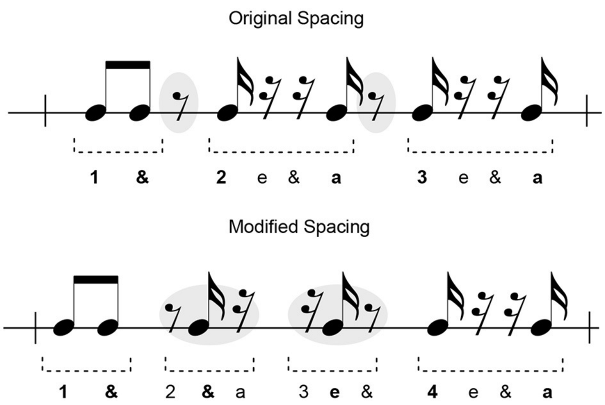

FIGURE 20
Measure 11 as shown in its original with annotation suggesting possible perceived note groupings and counting scheme (playable counts are emboldened). The modified spacing below is designed to preserve identification of major beat markers, as evidenced in the counting scheme. The gray highlights indicate the location of the loose eighth-note rests in the original presentation and location in the re-notation.

rhythm (measure 6). Not only was this an easy rhythm to execute, but it was also familiar. Many, if not all, of the percussionists would have encountered this same rhythmic pattern many times before in training and performance. For this reason and due to its simplicity, participants tended to rely more on model sticking patterns, and strategies were largely homogeneous among participants.

However, the second stable rhythm (measure 20) yielded a much wider variety of patterns. The average hamming distance between the two model stickings were only 0.11 strokes apart across all participants in this measure. The paired Wilcoxon Rank testing, seen in Table 4, further demonstrated the lack of significance in the observed difference between the two model stickings. Though there were two groups of three performers each who chose dominant hand lead and alternating, many other strategies were employed. Fourteen sticking strategies were used in the second stable rhythm, whereas only five were used in the first.

There are two likely reasons for this. First, measure 20 is less rhythmically stable than measure 6. Most of the measure contains no syncopation, though it begins with a syncopated rhythm. Secondly, the rhythm is not notated in a simple manner. Since there is always more than one way to notate a rhythm, some forms of notation can be considered to be more straightforward than others. In this measure, there are more sixteenth-note rests than necessary to communicate the rhythm (when considering just note-onset times) potentially making it more difficult for the participant to parse the notation.

6.3. Role of unstable rhythms

As shown in the examples in measures 11 and 13, unstable rhythms impact a performer's sticking strategy. Both measures yielded a wider variety of sticking patterns than in the stable rhythms, which confirms our hypothesis.

In measure 11, this rhythm was defined as unstable because of the unidiomatic notation and the amount of syncopation present, even though all the notes could be placed easily into a sixteenth-note grid. One group of participants (seven performers) utilized the alternating strategy, but no participant used a dominant hand lead strategy. In measure 13, where participants encountered a quintuplet, we found only eight strategies employed. Still, it is important to note that only one was a model sticking strategy. For example, 12 participants used an alternating strategy, but no one used a dominant hand lead strategy, which is similar to what was found in measure 11.

This can be explained by the fact that dominant hand lead is impossible with a quintuplet rhythm spanning an entire bar of two beats. Since it does not fit in a standard rhythmic grid of sixteenth notes but rather creates rhythmic tension with that grid, automation of the non-dominant hand while the dominant hand maintains a steady beat is rendered useless as a potential strategy.

6.4. The role of notation in stable and unstable rhythms

The sight-reading score used in this experiment serves as a form of musical instruction, where each note represents a specific action for the performer. The clarity of visual presentation largely impacts our interpretation of the intended expression, aligning with previous research on note spacing in sight-reading to enhance legibility and performance (Stenberg and Cross, 2019). Parsing the unidiomatic notation found in our sight-reading score may share similarities with target-distractor research, where unconventional notation can complicate the reading process for performers (Chang and Gauthier, 2020).

These findings suggest that visual perception and the "busyness" of the image may also influence performers (Rosenholtz et al., 2007). Notation examples with unidiomatic characteristics, such as cluttered note/rest groupings, could have a unique impact on performers' sticking choices, regardless of rhythm stability. Measure 11 exemplifies the influence of information presentation factors. The observed sticking patterns in this measure showed greater deviations from the model stickings compared to the entire score (as seen in Tables 3, 4). We suspect this is partly due to the unidiomatic notation. To illustrate, Figure 20 demonstrates how the original presentation of measure 11 could potentially confuse sight-readers. The spacing of note groups could create the illusion of a 3/4 measure due to the groupings of sixteenth-notes and adjacent rests. The placement of two eighth-note rests (highlighted in gray) lacks a clear association with the strong and weak beat markers. In contrast, the modified version, following (Stenberg and Cross, 2019) approach, preserves the major beat markers in relation to note groupings. The highlighted clusters indicate the correct placement of the aforementioned eighth-note rests. Although this requires validation in future tests, we predict that the second notation would be easier to read due to the preservation of strong-beat and weak-beat groupings.

6.5. Impact of handedness

While primarily focusing on hand dominance, our study revealed intriguing patterns associated with left- and right-handedness, meriting further investigation. Regarding model stickings, both left- and right-handed players deviated similarly from the alternate sticking strategy, with percentages of 53.20 and 56.12% respectively. However, right-handed performers showed a stronger resemblance to the dominant hand lead sticking strategy, with only a 32.11% difference, compared to left-handed individuals who exhibited a 58.06% difference. These percentages represent the hamming distances as a percentage of total playable notes in the sight-reading score. These findings align with observations suggesting that left-handed individuals tend to demonstrate more ambidextrous behavior than their right-handed counterparts (Gutwinski et al., 2011).

The use of sticking strategies other than the model ones by left-handed players suggests a potential influence of handedness on sticking choices. For instance, in measure 6, characterized by stable rhythm and conventional notation, only one out of 16 left-handed players employed a dominant hand lead strategy. Similarly, among nine participants, only one left-handed performer used the alternating strategy. Among the remaining six players who employed other strategies, half were left-handed.

This discrepancy between right and left-handed players may be attributed to a right-hand bias in percussion pedagogy, where teachers often teach a "right-hand lead" approach even to left-handed students. Such bias could contribute to the slightly greater diversity in stickings observed among left-handed players, as left-handed individuals have been shown to exhibit more symmetry than their right-handed counterparts.

6.6. Study limitations

Our study focused on the performance behaviors of participants on a single timpano, within the context of timpani performance. Scores and compositions often involve multiple timpani, requiring complex sticking cross-over techniques when transitioning between drums to maintain preferred sticking patterns and smooth sound. Therefore, our findings specifically pertain to single-drum performance and serve as a foundation for future research. Subsequent investigations should explore the impact of more intricate playing techniques (e.g., rolls, accents, and muting) across multiple drums in relation to handedness and sight-reading. These factors make our findings relevant to broader percussion performance practice and bi-manual interaction. We also acknowledge that the preferred setup style (German; low-high, or American; high-low) for a given performer may have an effect on their sticking pattern even in the context of playing a single timpano. Future studies on percussion performance and sticking choices can draw stronger inferences regarding handedness by incorporating independent evaluations of participants' handedness, as well as timpani setup preferences.

In terms of note timing and error detection, our study relied on the percussion expertise of co-authors Bacon, Jackson, and Marandola. While their training ensured accurate evaluation of percussion performance, employing computational methods to detect precise tempo drift after switching off the metronome could enhance future studies. Furthermore, analyzing additional performance error trends related to time-signature changes and polyrhythmic tuplets may yield valuable insights.

Lastly, muting behavior was observed in 7 out of 31 performers. Muting performers, who used their non-performing hand to influence note duration, exhibited similar performance behaviors to the rest of the group in key factors, except for a higher overall error rate: 9.01% for muting players compared to 2.22% for non-muting players. This disparity in error rates may be attributed to divided attention between note onset and duration, affecting both the playing and muting hands, warranting further investigation.

7. Conclusion

In this paper, we studied how musical context can affect sticking choice with percussionists in a sight-reading exercise. More specifically, we chose two model sticking patterns in pedagogical literature that we hypothesized would emerge more often when the participants encountered more stable rhythms.

We proposed a methodology which included a score designed for this experiment, with regions notated explicitly to test the effect of rhythmic complexity on sticking choice. A total of 31 participants, all highly trained percussionists, took part in the experiment. Sticking data obtained from the performances was compared to model sticking patterns. We used an error classification system and threshold for handling participants that made mistakes in specific regions. In addition, a system of beat classification was used to analyze rhythmic complexity and the function of model sticking patterns.

Sticking patterns reflect personal choices or strategies, as no two performers employed exactly the same sticking pattern in our study. However, it is possible to find preferences and patterns shared by many; percussionists strongly preferred to use their dominant hand for strong beats and start the beginning of phrases. Moreover, many players often used the two model sticking strategies (dominant hand lead and alternating), especially in sections that were based on stable rhythms, including those with idiomatic notation. When model sticking patterns were not strictly adhered to, other strategies emerged as a hybrid between the two models or some original pattern. Furthermore, sticking patterns varied more in sections that were either less rhythmically stable or where the notation was obfuscating the structure of the rhythm. A paired Wilcoxon Rank test of the results further demonstrated that for the entire score, the preference toward the dominant hand lead model was significant.

Although it has been proposed in the literature that performances improved when using one of two model sticking strategies, dominant hand lead or alternating, we found out that several participants used a strategy opposite to dominant hand lead or a hybrid approach, and this did not seem to affect their performance abilities. This could be due to experience, but it suggests that the model sticking strategies so commonly used in method books and teaching might not directly correlate with improved performance in sight-reading tasks. Once more, the overall performance conditions and expectations of sight-reading and a rehearsed musical performance may require different sticking strategies, challenging the "one size fits all" approach commonly seen in percussion pedagogical literature. Continued research into how sticking patterns evolve as players become more familiar with a given score may shed light on this topic. More studies on percussion sticking strategies are needed to validate this finding, as it carries important implications for pedagogical practice.

The proposed methodology could be used to test future hypotheses related to sticking choice. For example, the effect of handedness could be further explored if more left-handed players are recruited. The methodology could be used to understand the impact of notation on sight-reading performance. In addition, we found that notation may also affect sticking behavior, as note spacing, visual presentation, and unidiomatic notation could influence a player's performance behavior. Lastly, we have noted a trend among left-handed players of using unique strategies even when playing stable rhythms with efficient notation, suggesting that handedness may also play a role in sticking choice.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving human participants were reviewed and approved by REB-II McGill Ethics Committee. The patients/participants provided their written informed consent to participate in this study.

Author contributions

The original impetus for this research originated in discussions between MW and FM about movement variability in motion capture data of timpani performances. BB devised the experimental methodology in collaboration with FM and MW, composed the original score, and captured the performances of the first 4 subjects. IM took over and expanded BB's results, capturing the performances of 10 more performers. SJ captured the last set of timpanists and performed preliminary analysis on the complete data set. MW and FM have overseen this research over the past nine years. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Decision making influences movement variability and performance of high-level female football players in an elastic resistance task

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Introduction: The inclusion of sport-specific constraints in resistance training promotes the development of player abilities in an integrated way, which maximises the effectiveness of player adaptations induced by training. Considering that perceptual-cognitive abilities play a fundamental role in football, decision making could be introduced to enhance the cognitive similarity of resistance tasks to sport actions. However, it is unknown how decision making as a constraint could affect the player during an elastic resistance task. Therefore, the aim of this study was to investigate the effects of decision making of high-level female football players on movement variability and performance during an elastic band resistance task.

Methods: Twenty-three high-level female football players performed the elastic resistance task with a ball, both as attackers and as defenders without decision making (NDM) and with decision making (DM). The movement variability was quantified using the sample entropy derived from the acceleration recorded with an accelerometer placed at the lower back of each player. The passing accuracy of the attacker was quantified using a scoring scale.

Results: Results revealed that adding decision making to an elastic resistance task increased the movement variability of the defender but did not affect the movement variability of the attacker. In contrast, the passing accuracy of the attacker was reduced. Overall, the attacker had a higher movement variability compared to the defender.

Discussion: These findings suggest that decision making, as a football-specific constraint, can enhance the potential of an elastic resistance task in training. This is due to the fact that it reduces control and regularity of movement for the defensive role player and increases technical difficulty for the attacking role player. Furthermore, these effects are beneficial, as they can promote the adaptive processes necessary to optimise the performance of the players.

KEYWORDS

decision making, resistance training, movement variability, inertial measurement unit, entropy, performance, passing accuracy, football

1. Introduction

In recent years, football has become a very physical sport, as players perform a large number of high intensity actions that require high muscular power (di Salvo et al., 2009). Moreover, for these actions to be executed effectively, players should process multiple inputs from a dynamic and changing environment (Araújo et al., 2006). To enhance player performance in this context, it is necessary to integrate the diverse abilities inherent to the sport into resistance training, thereby optimizing the transfer of strength gains to sport actions (Suarez et al., 2019). Among the pivotal considerations, ensuring the dynamic correspondence of exercises stands as a fundamental factor (Araújo et al., 2007; Suarez et al., 2019). Dynamic correspondence, as outlined by Verkhoshansky and Siff (2009), refers to the ability of an exercise or training program to directly affect the athletes' sport performance, due to its similarity or specificity to sport skills—commonly known as the "transfer effect". In addition, the training principles of overload and variation must also be ensured. Collectively, these three principles constitute the foundation of the structure of levels of approximation proposed by Moras (1994), which defines a method for organizing exercises into levels from lower to higher dynamic correspondence (Fernández-Valdés Villa, 2020). Moreover, constraints can be categorized into task, individual, and environmental classes. In sport, task constraints refer to those elements that alter or restrict its execution, either through rules or added equipment (Newell, 1986). In addition, several strength and conditioning coaches use this constraint-led approach, integrating constraints specific to the sport context for this purpose, which is also highly supported by the scientific literature (Newell, 1986; Araújo et al., 2007; Davids et al., 2008). In this regard, the interaction with the ball (Moras et al., 2018; Makhlouf et al., 2022) or decision making (Gil-Arias et al., 2016; Natsuhara et al., 2020) are some football-specific constraints, while external resistance as elastic bands, dumbbells or a weighted vest are some nonspecific constraints.

Resistance training using elastic bands allows exercises with different amplitude and direction of movement (Verkhoshansky and Siff, 2009), and with different velocities (Janusevicius et al., 2017). This makes it possible to respect the dynamic correspondence of the exercises with sports movements, and to incorporate football-specific constraints into them. As a result, there has been a growing trend in the use of elastic band exercises, especially performed on the playing field itself. However, their use in resistance training does not usually follow the dynamics of effort, rate and time of maximum force production, and regime of muscular work (Verkhoshansky and Siff, 2009). In any case, this type of training has been shown to achieve similar strength gains to those achieved with conventional equipment, such as free weights or weight machines. Overall, studies on elastic bands have analyzed the effects of this equipment through different tests, assessing strength, power or muscle activity, and by using linear analyses such as mean, standard deviation (SD) or coefficient of variation (Bergquist et al., 2018; Lopes et al., 2019). To the best of our knowledge, we are not aware of any studies that have analyzed the elastic resistance training using non-linear systems, which can provide information about the structure of a signal.

In recent years, the ball has been incorporated into some resistance exercises as a specific constraint, with some studies analyzing its effect through non-linear systems. The findings revealed that the interaction with the ball involves greater anticipatory and compensatory adjustments of the body, due to the external perturbation of posture that occurs when players orientate their trunk to catch the ball, throw the ball, or make a pass (Moras et al., 2018). Besides, perceptual-cognitive abilities, which affect decision making processes, also play a major role in sport, as they are directly related to individual and team success (Bar-Eli et al., 2011). One of the basic scenarios in football in which decision making takes place is 1vs.1. In this situation, the attacker usually attempts to dribble or deceive the defender in order to pass the ball or advance on the field, avoiding the opponent stealing the ball. To achieve this, the player needs to disrupt the stability of the dyadic system they form together (Davids et al., 2006). Decision making in team sports is based on a continuous process of exploration and selection of relevant information (Bar-Eli et al., 2011). To ensure natural behavior, the task should have an experimental design as representative as possible of the conditions of the environment it is intended to simulate (Araújo et al., 2007). In general, most of the investigations examining decision making used video clips of real game situations, so that when the video was stopped, the participant could decide among the game options (Natsuhara et al., 2020; de Waelle et al., 2021); other research analyzed parameters related to decision making based on videos of match situations, such as passing angles, shooting angle and interpersonal distance (Corrêa et al., 2016); and others used videos of training match situations for participants to analyze their own decision making in an attacking action using open-ended questions (questioning) about the context of the action, the possible solutions, the selected response, and the results of the decision (Gil-Arias et al., 2016). So far, no research has been found that includes decision making in exercises with elastic resistance, which may provide a higher cognitive similarity to the task and greater representation of the sport context.

The way in which constraints cause postural destabilization to players can be measured through movement variability (MV). In this case, MV refers to execution variability, which describes the adjustments of the body between repetitions of an exercise (Cowin et al., 2022). Thus, it assesses movement regularity, and it is an indicator of motor control (Davids et al., 2003). When the player faces tasks with constraints, this can either lead to a greater effort to perform the task and, consequently, increase the difficulty, or it can increase the cognitive load, thus increasing the complexity of the task. The central nervous system, through perceptual-motor operations, explores different options offered by the degrees of freedom to find an optimized motor solution, which causes an increase in its MV (Schöllhorn, 2000). Building on this perspective, MV could describe the process of eliciting stable motor responses, providing valuable insights into the player's coordination features, as well as shedding light on the dynamics of the task (Newell et al., 1989; Mehdizadeh et al., 2015; Dhawale et al., 2017). Moras et al. (2018), in their study, demonstrated that the incorporation of a rugby-specific ball pass to a movement with inertial resistance produced an increase in the MV of the athletes. Moreover, in the situation in which the body is not able to manage the movement optimally, there is a decrease in performance (Stergiou et al., 2006). However, the relationship of MV and performance is unclear (Urbán et al., 2019) and it might depend on the nature of the intrinsic dynamics of the system and the task constraints, as suggested by Newell and Vaillancourt (2001). Nevertheless, it seems that after a period of training, an adaptation process occurs, leading to an improvement in performance and a reduction in MV (Fernández-Valdés et al., 2020; Bashford et al., 2022), indicating that motor learning takes place (Newell et al., 1989).

The analysis of MV has been approached from different perspectives (Cowin et al., 2022), one of which involves linear analysis systems using the SD or the coefficient of variation of time series data (Bashford et al., 2022). Another approach is the non-linear analyses based on entropy, which are suitable for dealing with the complexity of biological systems, as it quantifies the amount of regularity and unpredictability of point-to-point fluctuations across different time scales (Harbourne and Stergiou, 2009). Both types of analysis can provide information on the magnitude of variability and the structure of variability, although variation in how a motor behavior emerges in time is best captured by tools developed for the study of non-linear systems (Stergiou and Decker, 2011). Among the measures of entropy, sample entropy (SampEn) is one of the most widely used in sport and health sciences (Richman and Moorman, 2000; Murray et al., 2017; Moras et al., 2018; Fernández-Valdés et al., 2020, 2022). It is a method to describe the regularity and predictability of a time series, comparing patterns within a specified window (Richman and Moorman, 2000). Approximate entropy is a similar measure of complexity as SampEn, comparing patterns within a fixed window, but is less influenced by noise. Nevertheless, it is highly sensitive to the length of the time series data, as the estimation of pattern probabilities becomes less accurate with fewer data points. Instead, multiscale entropy calculates entropy at multiple scales, which allows understanding the dynamics of the system and detecting changes. However, it has a higher computational complexity, which can limit its practicality when dealing with large datasets. It divides the signal into coarse-grained time series and calculates the entropy at each scale (Costa et al., 2002). In general, SampEn is more robust to variations in time series length and can provide meaningful insights even with smaller datasets (Pincus, 1991). Entropy has been used to describe pathological conditions (Costa et al., 2002), changes in postural control (Lubetzky et al., 2015; Williams et al., 2016), assessment of running (Murray et al., 2017), tactical behavior in football (Santos et al., 2018), or movement regularity in resistance training tasks (Moras et al., 2018; Fernández-Valdés et al., 2020). In recent years, one of the methods to measure the MV has been approached by the calculation of entropy from the acceleration data collected at the lower back, using an inertial measurement unit (IMU) (Murray et al., 2017; Moras et al., 2018; Fernández-Valdés et al., 2020). This option makes it possible to quantify the MV of the athlete with data collected directly from the body, using a variable obtained directly from the accelerometer without the need for mathematical calculations. Furthermore, this location of the IMU can describe the global movement of the body due to its proximity to the center of mass (Montgomery et al., 2010).

In this regard, no research has been found that has evaluated the effect of decision making on the MV and performance of the athlete in a task with elastic resistance. This aspect would provide relevant information to understand the behavior of the body at a coordinative level and the influence on task performance when constraints involving perceptual-cognitive capacities are present in a resistance task. Therefore, the aim of this study was to investigate the effects of decision making of high-level female football players on MV and performance during an elastic band resistance task. Considering the fact that the incorporation of constraints in the task, such as decision-making and/or interaction with the ball, could lead to an increase in MV and, consequently, a decrease in performance, we hypothesized that (a) the attacking and defensive roles will have higher MV in the decision making condition (DM) compared to the no decision making condition (NDM), (b) in NDM and DM, the attacker will have higher MV compared to the defender, and (c) the attacker will reduce her passing accuracy in DM compared to NDM.

2. Materials and methods

2.1. Participants

The study involved 23 high-level female football players, all from the same club ((mean ± SD) age: 22.65 ± 5.16 years, height: 1.67 ± 0.64 m, body mass: 59.75 ± 14.08 kg). Twelve of the players belonged to the first team of the club, competing in the first women's division in Spain, Liga Iberdrola, and in the UEFA Women's Champions League in the season in which the data were taken (2021–2022); the remaining 11 players belonged to the second team of the club, competing in the second women's division in Spain, currently called Primera Federación Femenina. All players were informed of the benefits and risks of the study before signing the informed consent. All procedures complied with the Declaration of Helsinki (2013) and were approved by the Ethics Committee of the Catalan Sports Council (036/CEICGC/2021).

2.2. Data Collection

Data collection was conducted in 10 sessions during the competitive season. All the sessions were performed on the highest load day of the regular training week (three days before the match day) during the strength training session and before the football technical training session. The research task was included as part of a random order strength circuit and it took place on the field, on natural grass. Therefore, the players wore their usual football boots. In the first session, a pilot test was conducted with two players from the first team to check the task design.

In the data collection sessions, the players first performed a warm-up protocol led by the strength and conditioning coach of the team, which was identical in all sessions. Afterwards, an IMU device with an accelerometer (WIMU, Realtrack Systems, Almeria, Spain: weight: 0.07 Kg, size: 0.081 m × 0.045 m × 0.016 m) was attached to the lower back of the players, at the L4-L5 level, using an adjustable rigid belt. The IMU was set to a sampling frequency of 1,000 Hz and it was calibrated on a flat surface. A 4 K camera (Sony FDR-AX53) recording at 60 Hz was used to synchronize the accelerometer signal of the IMU with the video of each session for a further visual checking.

The research task was classified as a level 2 task from the structure of levels of approximation, which corresponds to a medium level of specificity (Moras, 1994), as a low external resistance was applied to a task with certain dynamic correspondence to some football actions. The task was performed in pairs, one player with the role of attacker and the other with the role of defender, both players facing each other. Two staff members positioned in front of the attacker, one on each side of the defender, were in charge of passing and receiving the ball. Both attacker and defender moved forward and backward at the same time within the delimited space, with an elastic resistance attached behind their waist. The attacker received the ball when she reached the most

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advanced point of the movement and she had to pass the ball to one of the staff members with a single touch. The task was repeated multiple times. In each repetition, the attacker received the ball alternately from each side. Two conditions of the task were conducted, without decision making (NDM) and with decision making (DM). In the NDM condition, the attacker received a voice command from one of the researchers when she was at the rearmost point of the movement indicating the side to return the ball. In this case, the defender did not participate actively, but only had to move forwards and backwards in synchronization with the attacker. On the other hand, in the DM condition, the defender had the objective of intercepting the ball after the attacker had passed it, making a real active defense. The attacker had the objective to get the ball to one of the two staff members, so she had to decide the best passing option. In this case, the DM condition of the task simulated a 1vs.1 situation of the game. In both conditions, NDM and DM, the attacker was asked to move as fast as possible, and no instructions were given about which foot she should contact the ball with (see Figure 1).

Referring to the elastic resistance, two circular elastic bands joined together were used for each player. The elastic band of higher resistance was attached to a fixed point close to the ground, and the elastic band of lower resistance was attached to the waist of the player, using a training belt and a carabiner. The movement space of the players was delimited with flat cones, so that the back boundary coincided with the beginning of the deformation of the elastic ensemble and the front boundary with a deformation equivalent to 150 N, resulting in a space of 2 m, measured *in vitro*. A maximum force of 150 N was selected, as it corresponds to a low external resistance that made it possible to perform a movement with a specific technical component (i.e., ball passing). The separation between the players when they were both at their forward boundary was 0.5 m. The two staff members were positioned at the level of the point at which the elastic band of the defender was attached to the support structure, with 8 m distance between them.

Each player performed a total of 16 sets of 12 repetitions of the task, 8 sets as an attacker and 8 as a defender, always with a different partner. For each role, 4 of the sets were made in the NDM condition and 4 in the DM condition, in random order. In each data collection session, each player only performed 2 sets of each role. In NDM, the passing direction of the attacker was also randomly pre-set, although the same number of passes to the right as to the left (6 and 6) was ensured.

Eleven of the 12 repetitions of each set were selected, always discarding the last one, where the intensity of the movement normally decreased. On the one hand, for the analysis of MV, the acceleration signal from the data obtained with the accelerometer of the IMU was used, which corresponded to the module of acceleration in the three coordinate axes. The SPRO 951 software (version 1.0.0, Realtrack Systems, Spain) was used to process the acceleration signal and synchronize it with the video. The acceleration data were not filtered to accurately analyze the variability within the time series, as Craig et al. (2020) did, following the recommendation of Mees and Judd (1993). The SampEn of the acceleration signal of each set was calculated based on the algorithm presented by Richman and Moorman (2000). A preliminary analysis confirmed that the results of SampEn calculated on the raw acceleration signal were consistent with those calculated on downsampled data, such as to 200 Hz. On the other hand, to calculate the task performance of the attacker, the accuracy of her passes was analyzed using the mean repetition score. Each pass was scored with 0, 1 or 2 points, depending on the minimum distance between the ball, i.e., ball trajectory, and the point where the receiving staff member was at the instance when the ball was released from the foot of the attacker. For this purpose, a video analysis was performed using Kinovea software (version 0.9.5). The criteria for scoring were 2 points for a distance (d) of $d \leq 1$ m, 1 point for $1 < d \leq 2$ m and 0 points for $d > 2$ m. The mean repetition time and the root mean square of the acceleration without gravity (RMS ACC) were calculated to check whether there were differences in the duration and magnitude of acceleration between the sets.

2.3. Statistical analyses

Continuous variables were summarized as mean and standard deviation (see Supplementary material). Since the data were not

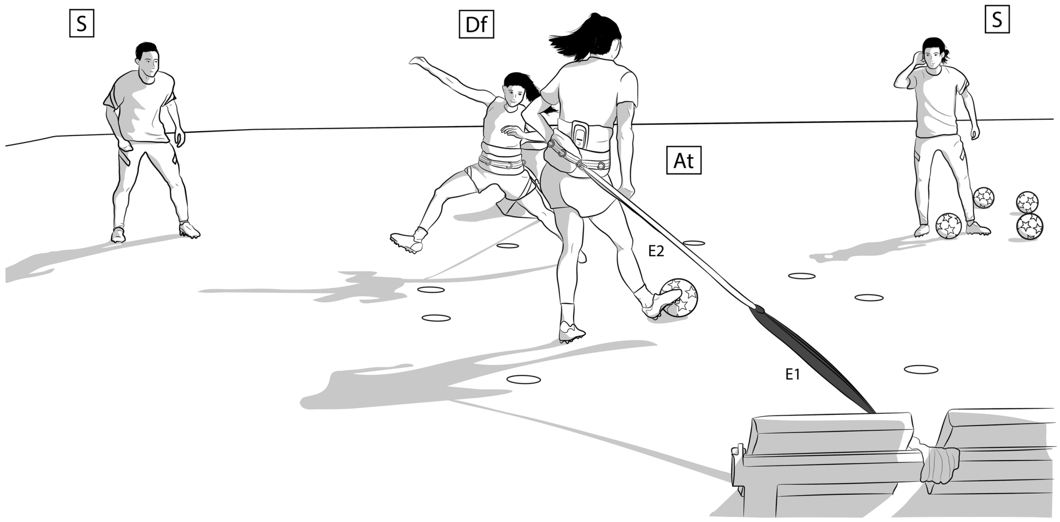

FIGURE 1
Design of the task. At, attacker; Df, defender; S, staff member; E1, elastic band 1, of higher resistance; E2, elastic band 2, of lower resistance.

normally distributed (Shapiro–Wilk test was performed), they were log-transformed. Subsequently, to analyze the effects of the player role (attacker/defender), the decision making condition (DM/NDM) and the interaction of both factors in each response variable (MV, RMS ACC and mean repetition time), a linear mixed model was performed, where participant was the random effect. The degrees of freedom were corrected using the Kenward-Roger method (Kenward and Roger, 1997). Additionally, comparisons were performed within factors and were assessed via effect size (ES) using 95% confidence intervals. Thresholds for ES were: 0.2 trivial; 0.6 small; 1.2 moderate; 2.0 large; and > 2.0 very large. Finally, regarding the passing accuracy of the attacking player, the comparison between decision making conditions was assessed by a Wilcoxon-signed rank test, and Pearson correlation was performed to analyze the relationship between MV and passing accuracy. Differences between the first and second team players in MV and passing accuracy were tested using Student's t-test for independent samples. For all statistical tests, a nominal significance level of 5% (value of $p < 0.05$) was applied. The statistical analysis was performed using R-Gui (v4.1.2, The R Foundation for Statistical Computing, Vienna, Austria).

3. Results

The MV obtained by the female football players was described with the SampEn (mean ± SD). The MV of attackers was 0.170 ± 0.017 arbitrary units (a.u.) in NDM and 0.174 ± 0.013 a.u. in DM, and the MV of defenders was 0.134 ± 0.010 a.u. in NDM and 0.157 ± 0.019 a.u. in DM. The passing accuracy of attackers was 1.674 ± 0.178 points in NDM and 1.553 ± 0.177 points in DM. Regarding the RMS ACC, attackers obtained 0.155 ± 0.064 g-force (g) in NDM and 0.148 ± 0.048 g in DM, whereas defenders obtained 0.143 ± 0.055 g in NDM and 0.135 ± 0.060 g in DM. The mean repetition time of the attacker was 1.884 ± 0.116 s (s) in NDM and 1.895 ± 0.140 s in DM, and that of the defender was 1.877 ± 0.118 s in NDM and 1.872 ± 0.149 s in DM. The MV values obtained for each team were for the attackers of the 1st team 0.167 ± 0.017 a.u. and for those of the 2nd team 0.178 ± 0.014 a.u.; and for the defenders of the 1st team 0.142 ± 0.018 a.u. and for those of the 2nd team 0.151 ± 0.019 a.u. Regarding the passing accuracy of the attackers, the first team obtained 1.592 ± 0.142 points and the second team 1.612 ± 0.113 points.

Considering that the data were not normally distributed, modeling was done with the logarithmic transformation of the MV, RMS ACC, and mean repetition time variables. The two main factors of the model using the log(MV) variable (decision making condition and role) were found to be statistically significant (F (64.230) = 25.968, $p < 0.001$; F (64.248), $p < 0.001$, respectively). In addition, the interaction using the log(MV) between both factors was significant (F (64.262) = 14.204, p < 0.001). Differences between NDM and DM were found in the defensive role (p < 0.001) but not in the attacking role ($p = 0.352$) (see Figure 2). Moreover, there were differences between the defender and the attacker in both conditions of decision making ($p < 0.001$ in NDM and in DM) (see Figure 3). There was no interaction between the two factors using the log(RMS ACC) and log (mean repetition time) variables ($p = 0.814$ and $p = 0.259$, respectively). These results are explained below in accordance with the research hypotheses.

As mentioned above, due to the significance of the interaction between decision making condition and role, when players took the attacking role, no differences in MV were found between NDM and DM, with a small ES (p = 0.352, ES = 0.27, 95%CI: −0.32 – 0.86). On the other hand, when players took the defensive role, the MV was higher in the DM condition than in NDM, with a large ES ($p < 0.001$, ES = 1.56, 95%CI: 0.89–2.22) (see Figure 4). Regarding the RMS ACC and the mean repetition time, there were no differences between NDM and DM in any of the player roles, as the interaction between decision making condition and role was not significant for these variables.

Due to the significance of the interaction between decision making condition and role, in both decision making conditions the attacker showed higher MV compared to the defender, with a very large ES in NDM ($p < 0.001$, ES = 2.61, 95%CI: 1.81–3.42) and moderate in DM ($p < 0.001$, ES = 1.07, 95%CI: 0.45–1.69) (see Figure 4). Despite this, the RMS ACC and the mean repetition time showed no differences between attacker and defender in any of the decision making conditions, as the interaction between decision making condition and role was not significant for these variables.

Concerning the passing accuracy of the attacker, it was decreased in DM compared to NDM, with a moderate ES (V = 208.5, $p < 0.01$, ES = −0.68, 95%CI: −1.29 – −0.08) (see Figure 5). Moreover, no correlation between MV and passing accuracy of the attacking player was found, in either NDM ($r = 0.098$) or DM ($r = -0.033$). Therefore, it has been shown that decision making did not affect the MV of the attacker but did affect her passing accuracy. Finally, no differences were found when comparing the first team with the second team in MV ($t = -1.716$; $p = 0.101$ in attacker and $t = -1.176$; $p = 0.253$ in defender) and neither in passing accuracy ($t = -0.358$; $p = 0.724$ in attacker).

4. Discussion

This study aimed to investigate the effects of decision making of high-level female football players on MV and performance during an elastic band resistance task. The main findings suggested that adding decision making to a forward-backward movement task with ball and elastic resistance increased the MV of the defender but did not affect the MV of the attacker. In contrast, the passing accuracy of the attacker was reduced. Overall, the attacker had a higher MV compared to the defender.

Surprisingly, there were no differences in MV between NDM and DM in the attacker, but there were differences in MV in the defender. For the attacking role, adding a decision making to the task performed (i.e., DM condition) did not significantly increase MV compared to the NDM condition, although a slight upward trend was observed (see Figures 2, 3). Finding no differences could indicate that the incorporation of decision making, which increases the uncertainty of pass direction (Vilar et al., 2012), did not make the task sufficiently complex to achieve a modification of movement regularity. Although the defender performed a defensive action similar to a game situation, the decision making of the attacker can be considered simple, due to reduced contextual information and limited response options (Czyż, 2021). Incorporating decision making into the task presumably involves the exploration and selection of information, which confers characteristics of a real game situation (Williams et al., 1999; Araújo et al., 2007). However, this was not sufficient to alter the regularity of the movement. Even so, it

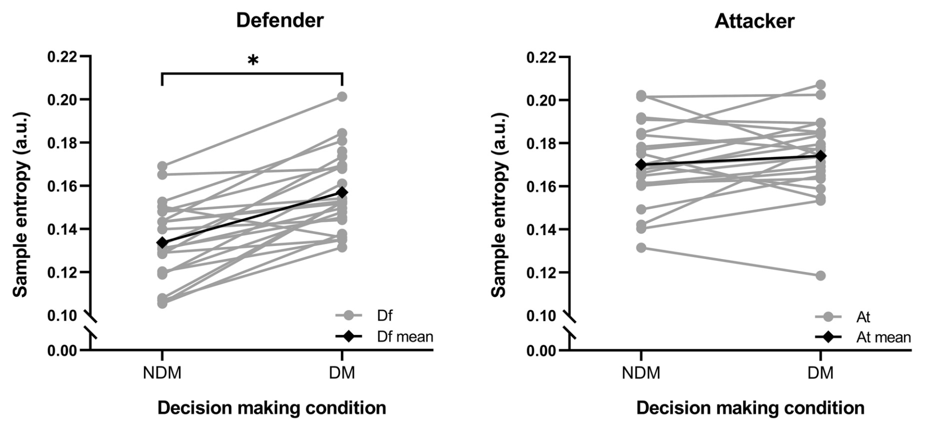

FIGURE 2
Individual movement variability described using sample entropy of the attacker and defender roles and the mean of the roles, comparing the no decision making (NDM), and decision making (DM) conditions. The significant differences are shown as * ($p < 0.001$). At, attacker; Df, defender; a.u., arbitrary units.

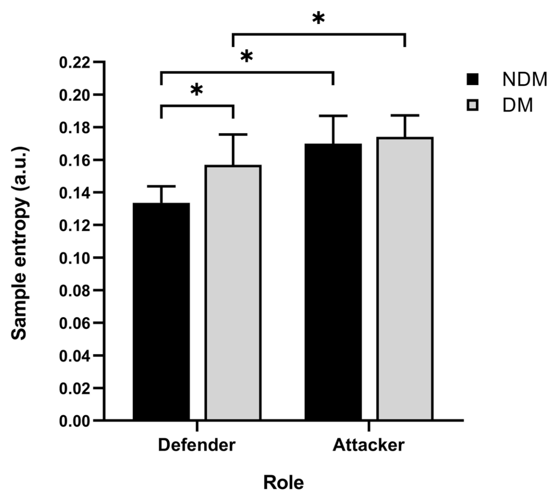

FIGURE 3
Comparison of movement variability described using sample entropy between decision making conditions and roles. It shows the sample entropy values (mean and 95%CI) of the defender and the attacker low back acceleration signal in the two decision making conditions: no decision making (NDM) and decision making (DM). Significance values come from the repeated measures model with log-transformation and only statistically significant differences are shown as * ($p < 0.001$). a.u., arbitrary units.

cannot be claimed that both conditions (NDM and DM) had similar signal structure and/or complexity. At the same time, the fact that in the DM condition the players have not experienced an increase in MV could also be due to a possible anticipation of the attacker, taking into account that at the high level, players are able to make accurate predictions from the body movement of their opponents based on postural cues, such as the hip movement (Causer et al., 2017). To avoid anticipation, the opponent should hide his/her postural cues as much as possible. In addition, it is probable that the MV of the attacker could be increased through more complex decision making by adding contextual information (Murphy et al., 2019), for example, by increasing the number of players in the task, or by promoting changes in the interpersonal distance between the ball carrier and the second defender, among others (Travassos et al., 2012a). This would force information filtering in a bottleneck form, as assumed by theories of attention and information processing in parallel order (Broadbent, 1958). In this case, a larger number of action options would be generated than in the DM condition of the present study, which could compromise the MV of the attacker (Murphy et al., 2019). Another explanation for the similar MV results obtained when comparing DM and NDM could be the fact that the body has mechanisms to maintain regularity of movement in the presence of certain constraints (Dhawale et al., 2017). Travassos et al. (2012b), reported changes in regularity of the ball velocity when passes were emergent (i.e., with a large number of possibilities for action), in comparison with predetermined passes. This could indicate that uncertainty on passing direction affects the ball more than the human body.

Regarding the defender, differences in MV were found when decision making was introduced, compared to NDM. In the NDM condition, the players moved forwards and backwards linearly, following the rhythm of the attacker, without the need to adjust their position according to the ball or the opponent. In contrast, in the DM condition, the defender aimed to intercept the ball once the attacker made the pass; therefore, she had to adapt her position and movement to the ball and to her opponent, which was reflected in less regularity of movement. In this condition, the task simulated a 1vs.1 situation of the game, in which the attacker and her marking defender operate as a dyad, considered as a dynamic system with emergent interactions triggered by the interrelation of constraints. Therefore, the movements made by the attacker with the aim of altering the stability of the dyadic system probably affected the defender, increasing the MV (*cf.* Araújo et al., 2006; Davids et al., 2006). Along the same lines, the study developed by Corrêa et al. (2016) suggested that the ball carrier was more successful in dribbling when the interpersonal distance with his marking defender, as well as the angle between the passing and intercepting vector were more variable. The authors noted that this large variability could lead to greater unpredictability for the defending player and, consequently, greater complexity in his/her decision making about how to avoid the dribbling of the attacker.

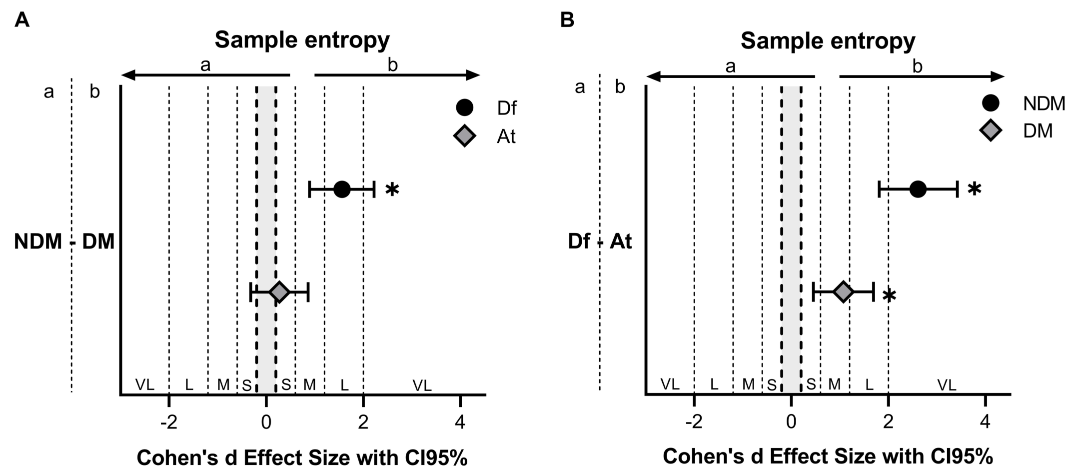

FIGURE 4
Effect Size using Cohen's *d* of the sample entropy differences between decision making conditions **(A)** and player roles **(B)**. The error bars indicate the uncertainty in the changes of the average with a 95%CI. * indicates significant differences ($p < 0.001$). NDM, No decision making; DM, decision making; Df, defender; At, attacker; S, small; M, moderate; L, large; VL, very large; CI, confidence interval.

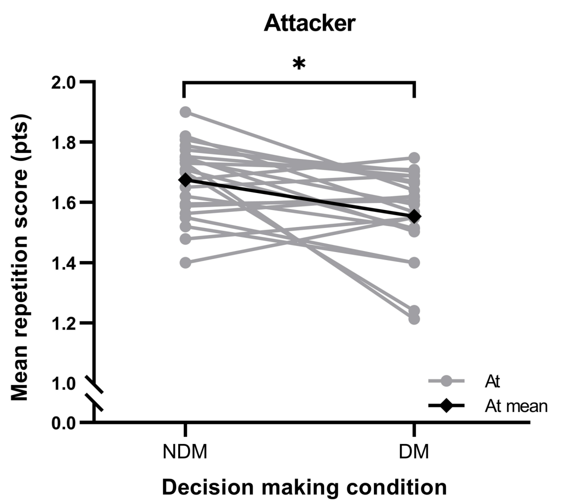

FIGURE 5
Individual passing accuracy described using mean repetition score of the attacking role and the mean of the role, comparing the no decision making (NDM) and decision making (DM) conditions. The significant differences are shown as * ($p < 0.01$). At: attacker; pts.: points.

The attacker showed a higher MV than the defender, with and without decision making. These results can be attributed, in part, to the fact that the attacker, in contrast to the defender, had to pass the ball. The ball pass, which was made with a single touch, involves an interception of a moving object. For a correct interception, it is necessary to perceive and anticipate the trajectory of the ball by capturing information about its position, the direction, and velocity of its displacement, and the acceleration or deceleration it undergoes in its path (Stone et al., 2015). In the present study, the attacker had to perform a continuous forward-backward movement with an elastic resistance in order to make a successful pass. For this purpose, she had to coordinate the starting moment of the approach run, and adjust her velocity and direction to adapt to the trajectory and velocity of the pass made by the staff member. At the same time, she also had to orient her body to immediately make the pass to the chosen or pre-planned side. As the attacker and defender obtained similar RMS ACC and mean repetition time, it can be affirmed that the higher MV obtained by the attacker reflects this perceptual-motor process. The increase in MV found by Moras et al. (2018) when incorporating a rugby-specific ball pass to a movement with inertial resistance was attributed to a change in the coordination patterns of the system or a combination of movement stability and adaptability that induced this specific constraint. Therefore, it could be considered that the interaction with the ball results in a detriment to the movement control or coordination of the athlete (Moras et al., 2018), and this occurs regardless of whether the pass is made with the upper or lower limbs.

Decision making affected the attackers, impairing their passing accuracy. This result could be expected if we consider that the attacking player had to manage more information in the DM condition. In this condition, interrelationships between attacker and defender and the decision making constraint were closer to the competitive performance environment than in the NDM condition, although the possibilities of action and, consequently, the uncertainty of the direction of the pass were limited. The similarity of the DM task to a real game could be also improved through the participation and interaction of a larger number of players. It seems that the addition of a second defender may influence passing accuracy even more than the immediate defender, due to changes in their interpersonal distance (Travassos et al., 2012a). These aspects expand the contextual information, entailing greater cognitive effort and attentional load (Czyż, 2021). This forces players to constantly explore the environment to discover the best action solution based on the immediate demands of the task, compromising their technical accuracy (Travassos et al., 2012a), and slowing down their reaction time

(Mudric et al., 2015). The fact that the defender acts directly to steal the ball in the DM condition promotes the adoption of an external focus of attention (Chua et al., 2019), constraining the search space and altering the perception-action coupling employed in the task, which alters the affordances perceived (Pacheco et al., 2019). Natsuhara et al. (2020) reported that in attacking situations with multiple players, 5 vs. 4, and no external resistance, the player receiving and passing the ball mainly paid attention to the attacker-opponent-space relationship. Similarly, the attacker in the task performed in the present study could have had the focus of attention on these external elements. Furthermore, before and during the execution of the task, the attacking players also had to perceive and anticipate the trajectory of the pass made by the staff member, adapt to it, while orienting their body or part of it, in order to make the pass to the chosen side. The attentional diversification could imply a discontinuous information acquisition that must be finally integrated to structure the motor response (Stone et al., 2015). In contrast, in the NDM condition, in the absence of opposition, the attentional strategy could have been different. The attacker probably focused more attention on her own execution and body position than in DM, although she also paid attention to the ball and the target, which may have contributed to the achievement of a higher passing accuracy. Nevertheless, it should be noted that tasks that promote external focus of attention enhance motor learning of athletes (Waite et al., 2022). The lower performance obtained in the DM condition indicates that passing efficacy is reduced when a decision making is added, so it could be considered that the DM condition was more complex for the attacking role than the NDM condition. Reduced passing accuracy should never be considered as a negative factor but should be considered as a necessity to promote the progress of athletes. However, in reinforced-based tasks, an appropriate balance between hits-misses must be established to favor learning (Dhawale et al., 2017).

In the present study, no correlation between MV and passing accuracy of the attacking player was found, in either NDM or DM. Urbán et al. (2019) also found no correlation between variability structure and performance in a cyclic pointing movement task when it was constrained by the target and the reward. Although the relationship between MV and performance depends on the nature of the intrinsic dynamics of the system and the constraints of the task (Newell and Vaillancourt, 2001), the results obtained in the present study could be related to the players' expertise level. Evidence shows that expert athletes tend to be more regular in their movements than novices (Davids et al., 2008; Bashford et al., 2022), and furthermore, the practice of a movement or motor skill tends to reduce its MV (Fernández-Valdés et al., 2020; Sutter et al., 2022), which can be used as an indicator of sport expertise. In this sense, it could be expected that the group of high-level female football players included in the present study, belonging to the first and second teams, would show differences in MV and passing accuracy when comparing both teams. Although no differences were found in either variable, the t-test and mean comparisons showed a downward trend in the MV of the first team compared to that of the second team, in line with previous studies (Davids et al., 2008; Bashford et al., 2022). In addition, the players in the current study occupied different playing positions, which implies an inconsistent level of specific motor skills. In this sense, in the study of Fernández-Valdés et al. (2022), conducted with rugby players, differences in MV in tackling were found when comparing players from two playing positions, forwards and backwards. Therefore, it is not surprising that the players in the present study achieved different passing accuracy scores with different MV values. However, the potential relationship between years of expertise and/or playing position with the MV obtained in the research task has not been examined. What can be affirmed is that there are different ways of facing the task, with a relationship between MV and passing accuracy specific to each player, which assumes the existence of individualized and identifiable movement patterns (Couceiro et al., 2013; Urbán et al., 2019). In broad terms, four groups can be defined according to the relationship between passing accuracy and MV. (1) A first group with a high level of accuracy and low MV: It corresponds to the players with greater mastery of the task. The low MV would indicate a reduced room for improvement, thus resulting in poor trainability of the task, which does not favor the achievement of new training adaptations. In this case, some authors suggest modifying the task or adding constraints to increase its complexity (Moras et al., 2018). (2) A second group with a high level of accuracy and high MV: In this case, despite successfully achieving the task objective of passing the ball to the receivers with high accuracy, the trainability of the task would be high, as there would be room for improvement in terms of control and regularity of the movement. (3) A third group with a low level of accuracy and high MV: For these players, the task would be excessively challenging, as they not only failed to achieve the task objective successfully but also did not reach a high level of control and regularity of movement. In this case, it would be appropriate to continue training to improve performance and decrease MV, although in certain players it may be necessary to decrease the difficulty or complexity of the task (Fernández-Valdés et al., 2020; Sutter et al., 2022). Finally, (4) a fourth group with a low level of accuracy and low MV: These players would not have mastered the task to achieve their goal successfully and performed it with very regular and rigid movement, which is sometimes associated with a pathological situation or a history of injury (Stergiou and Decker, 2011). Nevertheless, it is worth noting that most of the players in this study belonged to the second group, with high accuracy and high MV. The high MV could be explained by the fact that, although the task was based on known and well-trained skills, the addition of the elastic resistance was a new challenge that altered their motor control. Considering that the effectiveness of resistance training to improve sport performance depends, in part, on motor control and coordination (i.e., MV) and task performance (i.e., passing accuracy), a high MV could be considered beneficial to enhance motor adaptations, because more of the task space is explored (Dhawale et al., 2017).

5. Conclusions and practical applications

Introducing decision making to a forward-backward movement task involving ball and elastic resistance resulted in increased MV for the defender and compromised the passing accuracy of the attacker. Overall, the attacker showed a higher MV than the defender. These findings suggest that the inclusion of decision making as a football-specific constraint can enhance the trainability or potential of an elastic resistance task. It is a useful strategy to reduce the control and movement regularity of the defensive role player, while increasing the complexity of the task for the attacking role player. Both effects can prove beneficial in promoting player development.

This type of tasks can be used to implement training with a stronger dynamic correspondence to sport actions, integrating conditional, coordinative, and cognitive abilities, with the aim of improving performance or optimizing the readaptation process, especially in the final stages of injury recovery. Moreover, the MV together with the passing accuracy allow to determine the mastery level of the players, as well as to define the task, which can be used for the individualized prescription of training. Finally, it should be considered beneficial to switch player roles in tasks with external resistance and decision making in order to enhance the players' adaptive capacity, regardless of their playing position in competition.

Data availability statement

The datasets generated during the current study are included in the article/Supplementary material, further inquiries can be directed to the corresponding author.

Ethics statement

The studies involving humans were approved by Ethics Committee for Clinical Research of the Catalan Sports Council. The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

Author contributions

ST and GM conceived and designed the study. ST, GM, JG, and CP-CB conducted the test and collected the data. ST and BF-VV processed the data. ST and GM did the statistical analysis and wrote the original draft. GM supervised all the process. All the authors interpreted the results, revised, edited, and approved the final version of the manuscript.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fpsyg.2023.1175248/full#supplementary-material

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Brain optimization with additional study time: potential brain differences between high- and low-performance college students

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This study investigates potential differences in brain function among high-, average-, and low-performance college students using electroencephalography (EEG). We hypothesize that the increased academic engagement of high-performance students will lead to discernible EEG variations due to the brain's structural plasticity. 61 third-year college students from identical majors were divided into high-performance ($n = 20$), average-performance ($n = 21$), and low-performance ($n = 20$) groups based on their academic achievements. We conducted three EEG experiments: resting state, Sternberg working memory task, and Raven progressive matrix task. Comprehensive analyses of the EEG data from the three experiments focused on power spectral density (PSD) and functional connectivity, with coherence (COH) employed as our primary metric for the latter. The results showed that in all experiments, there were no differences in working memory ability and IQ scores among the groups, and there were no significant differences in the power spectral densities of the delta, theta, alpha1, alpha2, beta, and gamma bands among the groups. Notably, on the Raven test, compared to their high-performing peers, low-performing students showed enhanced functional connectivity in the alpha 1 (8–9 Hz) band that connects the frontal and occipital lobes. We explored three potential explanations for this phenomenon: fatigue, anxiety, and greater cognitive effort required for problem-solving due to inefficient self-regulation and increased susceptibility to distraction. In essence, these insights not only deepen our understanding of the neural basis that anchors academic ability, but also hold promise in guiding interventions that address students' diverse academic needs.

KEYWORDS

high-performance students, low-performance students, EEG, power spectral density, functional connection

1. Introduction

Students' academic performance is influenced by a multitude of factors, and extensive literature exists on this topic (Tracey et al., 2012; Kurup and Subramanyam, 2014; Burger and Naude, 2020; Vrapi et al., 2022). However, when it comes to the academic performance of college students, there is a consensus: high-performing students tend to dedicate significant time and effort to their studies, while low-performing students often allocate less study time, leading to higher rates of academic failure (Montes Iturrizaga, 2012; Cerna and Pavliushchenko, 2015).

Previous research has linked low-performance students to a lack of interest in their majors, leading to inadequate high-quality study time and subsequent academic failure (Wang and Eccles, 2013). Other studies have found that high-performance students tend to set high goals for themselves, and increased learning motivation is stimulated by high learning goals, thus resulting in more time invested in learning. At the same time, low-performance students have lower academic standards for themselves, while learning motivation is not high. Consequently, they invest less time in learning (Martínez-Monteagudo et al., 2018). This trend has been consistently observed in educational research, establishing that high-performing students invest more time in studying at universities, while low-performing students allocate less time to academics (Díaz-Mora et al., 2016).

Learning is a highly mentally consuming activity, especially during high-intensity learning, and the demand of the brain for blood is six times higher than usual (Hampshire et al., 2019), At the same time, learning is also a high-training activity for the brain. There is a large amount of evidence showing that hard study can effectively train the brain. As we continue to learn, think, and practice in a specific field, the synaptic plasticity of the brain in this aspect will be significantly enhanced (Taya et al., 2015; Weicker et al., 2016). This is because the brain has structural plasticity, in which it usually learns to modify the connections between synapses to acquire new brain structures and new behavioral capabilities (Poldrack, 2000; Kolb et al., 2003). Consequently, the divergent college experiences of high-performance and low-performance students create contrasting brain environments, prompting the question of whether these two groups exhibit distinct brain characteristics, detectable through EEG features.

Therefore, divergent college experiences (self-disciplined vs. indulgent approaches) have given rise to two distinct brain groups exposed to contrasting environments (consistent vs. minimal stimulation). Therefore, do the brains of these two groups exhibit differences, and can these disparities be discerned in electroencephalogram (EEG) features? It can be postulated that students from the same major and university possess no significant differences in brain function upon entering university. Admissions criteria for the same major at the same university tend to be consistent (e.g., equivalent college entrance examination scores), which, to a degree, filters for IQ and other brain functions related to learning ability (e.g., working memory). The variation in IQ among students within the same major at the same university is anticipated to be negligible, a notion supported by research dating back to the 1950s (Plant and Richardson, 1958). In our study, we selected third-year students from the same major at a highly competitive university with exceptionally high college entrance examination scores as participants. It can be assumed that among this cohort of third-year students, no significant differences in brain functions associated with academic abilities existed between high-performance, average, and low-performance students upon their admission to the university. Otherwise, they would not have been accepted into the university and major with identical admissions criteria. It is worth noting that the highly selective admission criteria of this university, predicated on exceedingly high college entrance examination scores, can be regarded as a form of cognitive and brain function ability selection. Thus, if the brains of high-performance and low-performance students exhibit differences in EEG after 3 years of college life, the primary explanation is that the brains of high-performance students have undergone comprehensive training due to rigorous studying, while low-performance students have experienced limited study and insufficient brain training. This is the central theme that our study endeavors to investigate and substantiate. We acknowledge that there are other factors that can influence brain function ability, such as alcoholism (Correas et al., 2015; Kim et al., 2020), medication use (Coullaut-Valera et al., 2014), sleep disorders (Peter-Derex et al., 2021), and neurological or brain disorders (Alturki et al., 2020). To mitigate the impact of these confounding factors, rigorous subject screening was conducted to exclude individuals who may be affected. By employing this stringent selection process, we aimed to minimize their potential influence and ensure the integrity of our study outcomes.

2. Theoretical basis and research hypothesis

Brains that have undergone training are anticipated to exhibit significant differences compared to untrained brains, and these substantial disparities can be discerned in resting-state EEGs, as corroborated by numerous studies (Vernon et al., 2003; Angelakis et al., 2007; Karbach and Schubert, 2013; Rose et al., 2015). For instance, a recent investigation conducted at Stanford University demonstrated an increased involvement of the hippocampal learning and memory system in the brains of college students exhibiting positive academic attitudes and diligent study habits in mathematics (Chen L. et al., 2018). Resting-state EEGs of long-term meditators differed markedly from those of control group participants, particularly at the lateral frontoparietal lobe electrodes. Long-term meditators exhibited an elevated ratio of γ-band activity (25–42 Hz) to slow oscillation activity (4–13 Hz; Lutz et al., 2004). After a three-month period of intensive meditation training, patients with attention deficit disorder exhibited enhanced brain function by increasing the phase consistency of θ-band oscillatory neural responses in the forebrain and reducing response time variability (Lutz et al., 2009).

Even in aging and deteriorating cerebral cortices, the resting EEG of trained brains exhibits marked distinctions compared to their untrained counterparts. Following training, cognitive control capacity is enhanced among older adults aged 60–85 years, accompanied by improvements in sustained attention and working memory. These individuals demonstrate a decrease in multitasking costs relative to active and no-contact control groups, surpassing the performance of untrained 20-year-old subjects, with sustained gains for a duration of 6 months. Additionally, age-related impairments in neural markers of cognitive control, as assessed via EEG, were alleviated by multitasking training (e.g., augmented midline frontal theta power and frontal-posterior theta coherence; Anguera et al., 2013).

The aforementioned investigation substantiates the discernable disparities between trained and untrained brains concerning power spectra and resting functional connectivity. On one hand, high-performance students have devoted considerable time to academic pursuits at the university level, receiving extensive cerebral stimulation over multiple years. Conversely, the brains of low-performing students have not been subjected to equivalent cognitive training. Are there significant variations in the resting EEG patterns between these two cohorts? Building upon the research outlined above, we formulated our initial hypothesis:

> *H1*a: High-performing and low-performing third-year students majoring in the same course at the same university will display differences in their whole brain power spectrum of resting-state EEG.
>
> *H1*b: High-performing and low-performing third-year students majoring in the same course at the same university will exhibit differences in the functional connectivity (coherence) of their resting-state EEG.

Trained cerebral cortices exhibit substantial dissimilarities from untrained ones, extending beyond resting states to encompass task states as well. This is most prominently demonstrated in working memory tasks, where functional training has been shown to enhance the brain's working memory capacity (Weicker et al., 2016). Theta and alpha bands in the frontal region have traditionally been considered the two frequency bands most intimately associated with working memory (Klimesch, 1999a; Wei and Zhou, 2020), Nevertheless, recent findings indicate a strong connection between the delta band and working memory (Akturk et al., 2022). Another EEG metric reflecting working memory alterations is the brain network index. In working memory tasks, the functional connectivity of trained brains' neuronal networks within the frontal–parietal and occipital regions undergoes change (Anguera et al., 2013; Langer et al., 2013). A wealth of evidence supports the notion that working memory serves as a predictor of academic achievement (Swanson and Alloway, 2012). Studies have elucidated the relationship between fluid intelligence and complex learning (Wang et al., 2013), and indeed, working memory measurements have consistently demonstrated a superior ability to forecast academic aptitude compared to intelligence metrics (Alloway et al., 2013). Titz and Karbach (2014) conducted a comprehensive examination of research spanning two decades on working memory training and its influence on academic performance. Their analysis unveiled constrained yet consistent evidence endorsing the positive impact of process-based complex working memory training on academic skills, particularly in the domain of reading comprehension. These advantages were observed among children presenting cognitive and academic deficits, as well as in cognitively healthy students (Titz and Karbach, 2014). Based on this evidence, we formulate the following hypotheses:

> *H2*a: High-performing third-year students from the same university majoring in the same course and performing the same working memory task will exhibit superior working memory compared to their low-performing counterparts.
>
> *H2*b: The brain power spectrum of EEG will differ between high-performing and low-performing third-year students from the same university majoring in the same course and performing the same working memory task.
>
> *H2*c: The brain functional connectivity (coherence) of EEG will differ between high-performing and low-performing students from the same university majoring in the same course and performing the same working memory task.

In addition to working memory tasks, trained cerebral cortices display marked disparities in EEG parameters relative to untrained counterparts during tasks assessing global cognitive function. Numerous studies have demonstrated that, despite possessing equivalent IQ scores, high- and low-performing students exhibit significant neural differences in EEG tasks related to general brain function. For instance, Staudt and Neubauer assessed the cerebral activity of adolescents with average IQ scores who were classified as academic achievers and underachievers. They discovered that high-performing students exhibited greater posterior brain activation than their underperforming peers during Posner letter-matching tasks (Staudt and Neubauer, 2006). Further research has indicated that, among students with uniformly high IQ scores, underachievers displayed reduced prefrontal activation compared to high achievers when engaged in creative tasks (Bergner and Neubauer, 2011). However, the participants in the aforementioned investigations were not drawn from the same university or academic discipline. Consequently, we sought to determine whether significant differences in EEG parameters exist between high- and low-performing students within the same university and major with respect to comprehensive cognitive ability tasks. This inquiry prompted the formulation of our third hypothesis:

> *H3*a: There will be no significant IQ difference between high-performing and low-performing third-year students in the same university and major.
>
> *H3*b: The brain power spectrum of EEG will differ between high-performing and low-performing third-year students from the same university majoring in the same course and performing the same comprehensive ability task of brains.
>
> *H3*c: Concerning the comprehensive ability task of brains, there will be differences in the function connection (coherence) of EEG between high- and low-performance third-year students.

3. Materials and methods

3.1. Subjects

A total of 76 third-year students majoring in Business Administration from a reputable business school were initially recruited for this study, all of whom entered their college course with comparable college entrance examination scores. Prior to the experiment, left-handed students, students with neurological disorders, students with alcoholism or sleep disorders, and those who had recently consumed psychotropic drugs were excluded. Among the remaining students, 69 were selected based on the weighted scores of their previous five semesters. The top 15% were designated as "high-performance students," the bottom 15% as "low-performance students," and those within the 45–55% score gradient were assigned to the "normal student group," which served as the control group. This classification was established by the teaching office of the participants' university and solely relied on academic performance within the students' major. After preprocessing EEG data, an additional 8 participants were excluded because their valid data segments did not reach 80%. In accordance with common practices in neuroscience research and considering previous literature and resource constraints, a sample size of approximately 60–70 participants was deemed appropriate for EEG studies (Rogasch et al., 2015; Harris et al., 2020; Pavlov et al., 2021; Shadli et al., 2021).

The final sample consisted of 61 subjects with an average age of 20.4 ± 0.87 years, including 36 females. All participants provided informed consent prior to their involvement in the study. The sample included 20 high-performance students (12 females), 21 normal students (13 females), and 20 low-performance students (11 females) (Table 1). To account for the average weekly study time of all students, excluding university class time, data were obtained not from the subjects themselves but from two roommates of each participant through interviews with their counselors, thereby mitigating potential exaggeration of self-reported study time. Additionally, information regarding the number of failed courses for each participant over the past five semesters and their absenteeism records for the current semester were collected from the university's academic affairs office. These supplementary data provided a comprehensive understanding of the academic performance and behavior of the study participants.

3.2. Materials and procedures

An Enobio20 EEG system (NeuroElec) was employed for the experiments, with recordings adhering to the international 10–20 system's 20-conductive polar cap. Electrode impedances were set at a 10 kOhm threshold, and electrode positions are depicted in Figure 1. The right ear clip electrode served as the reference electrode, and the equipment's sampling rate was 500 Hz. Experiments were conducted in a laboratory under DC lamp illumination, with subjects donning EEG helmets, sitting on a cushioned sofa, and facing a 23-inch monitor with a 60 Hz refresh rate. Feedback and output were acquired through an Xbox controller on the participants' thighs. Prior to the experiment, subjects adjusted their seating for maximum comfort and relaxation, with only the right thumb controlling the joystick. E-prime 3.0 was used for loading all experimental materials.

3.2.1. Experiment 1: resting electroencephalography

Before commencing the experiment, participants were briefed on precautions for the EEG experiment, including avoiding movement, talking, frequent blinking, and significant facial expressions. Equipped with this knowledge and the EEG apparatus, subjects' resting EEG data were collected for 5 min while they focused on a central "+" symbol displayed on the screen and remained relaxed. In the realm of neuroscientific investigations, particularly for scenarios necessitating swift evaluations or preliminary screenings, a 3–5 min recording of resting-state EEG is deemed sufficient to capture the brain's fundamental activities and potential anomalies (Pfurtscheller et al., 2012). Such a duration not only captures essential neural dynamics but also ensures feasibility and efficiency in data acquisition. This perspective aligns with recent findings that have utilized short-duration EEG recordings to elucidate brain dynamics and their clinical implications (Niedermeyer and Da Silva, 2005). In line with this understanding, the data duration adopted in our study, specifically a 5-min resting-state EEG recording, is both academically acceptable and methodologically sound.

3.2.2. Experiment 2: Sternberg working memory (STB) task

The STB paradigm materials were sourced from the Psychology Software Tools official website (PST experiment number 3012) and implemented using E-prime3.0 (PST Admin, 2022). This classic experimental scheme is widely employed in working memory research to assess subjects' storage and retrieval of items in short-term memory (Raghavachari et al., 2001; Brookes et al., 2011). First, a series of letters (one letter/s; eight letters in total) were shown to the

TABLE 1 Demographic characteristics of study participants.

Student type	Average age	Age standard deviation	Female count	Male count
High-performance students	20.00	0.79	12	8
Normal students	20.62	0.97	13	8
Low-performance students	20.45	0.89	11	9

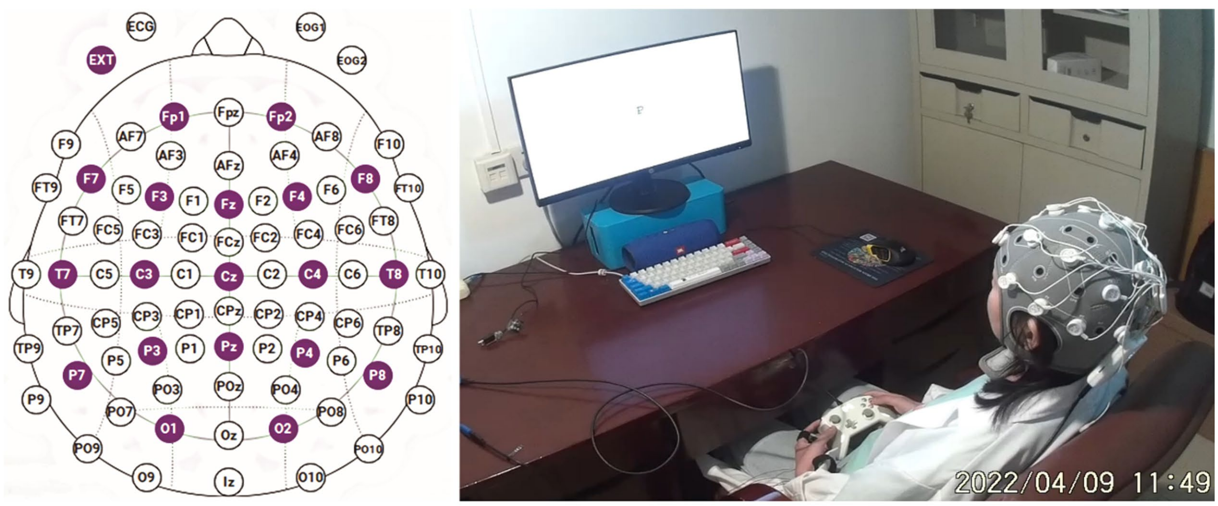

FIGURE 1
The electrode position map and on-site experimental photo.

subjects. Among the displayed letters, the participants had to memorize the black letters. At the same time, the participants were not required to remember green letters. The ratio of black to green letters was 7:1 (the default setting in the STB experimental paradigm).

Subjects are required to memorize these letters in short-term memory. After all the letters were displayed, the subjects were required to memorize them, using their short-term memory, and keep them for 8 s. Then, they were shown seven target letters. Subjects were required to judge whether the target letters had appeared in the previous memorization process. If the target letters matched the previously displayed letters, the subjects quickly pressed the A button on the handle. The participant quickly pressed the B button on the handle if the target letter was new. There was a 5-s pause after all the subjects had finished their answers. The next experimental cycle would then begin. This study was conducted for two experimental cycles of 5 min. The entire experimental process is shown in Figure 2.

3.2.3. Experiment 3: comprehensive brain ability task

Experiment 3 utilized materials from the Raven Progressive Matrices on the Psychology Software Tools website (PST experiment number 34568; PST Admin, 2023). In this test, the comprehensive ability of the brain of the subject is examined through a series of regular geometric figures (Figure 3). This test evaluates subjects'

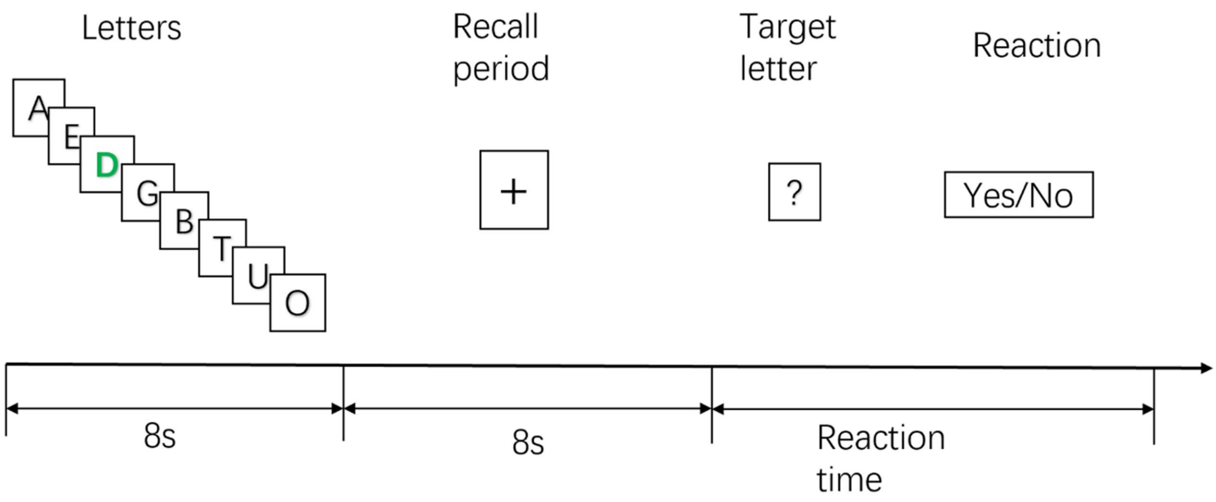

FIGURE 2
Sternberg working memory (STB) experimental diagram.

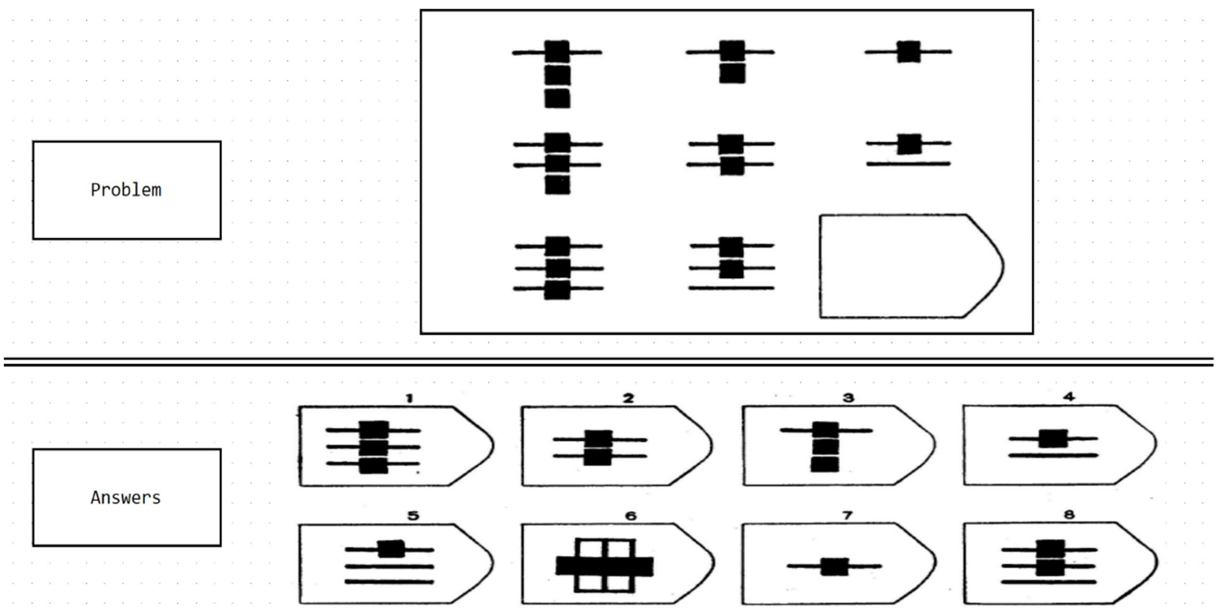

FIGURE 3
Diagram of the Raven test experimental set used in this study. Source: Raven progressive matrices from the PST website (PST experiment number 34568).

comprehensive brain abilities through a series of regular geometric figures (Figure 4). The Raven test, which assesses various psychological resources such as task-related knowledge, working memory, attention, and decision-making (Friedman et al., 2019), is an appropriate measure of comprehensive brain ability, boasting high reliability, validity, and independence from cultural constraints (Raven, 2000). The Raven test, in combination with EEG, has been widely endorsed for evaluating comprehensive brain ability (Schabus et al., 2006; Amin et al., 2015; Friedman et al., 2019). Subjects completed the 40-min experiment using an Xbox controller to select correct geometric figures. Due to the impracticality of analyzing the full 40-min EEG data from each participant—resulting in several 100 gigabytes of data and exceeding our computer system's capacity—only the initial 5 min of EEG data from each participant were analyzed, which is sufficient for most EEG analyses.

3.3. EEG data analysis

3.3.1. Electroencephalography raw data preprocessing

EEGLAB (version 2021), operating on MATLAB R2021b, was employed for data preprocessing (Delorme and Makeig, 2004). Initially, band-pass (1 and 100 Hz) and notch filters (48–52 Hz) were applied. Data were segmented into 2-s intervals, and the ICA analysis was conducted using the ADJUST1.1.1 plug-in to eliminate artifacts such as blinking, eye movement, electromyography, and Electrocardiogram. Data segments exceeding ±100 μV were removed. Post-preprocessing, approximately 80% of each subject's valid segments were retained.

3.3.2. Frequency domain analysis

Power spectral density (PSD) reveals the energy distribution of EEG signals across various frequency bands and electrodes. This study employed a fast Fourier transform (FFT) to conduct PSD analysis on three groups of subjects participating in three experiments. The analyzed frequency bands included delta (1–4 Hz), theta (4–8 Hz), alpha1 (8–9 Hz), alpha2 (10–13 Hz), beta (13–30 Hz), and gamma (30–80 Hz). The PSD is computed using the Fourier Transform and is defined as follows:

$$\mathrm{PSD}(f) = \frac{1}{T}\left|\mathcal{F}\{x(t)\}\right|^2 \quad (1)$$

Where:

$\mathrm{PSD}(f)$ represents the Power Spectral Density at frequency f, measured in $\mu V^2 / Hz$.

T is the total duration of the EEG signal in time.

$x(t)$ is the EEG signal in the time domain.

$\mathcal{F}\{x(t)\}$ denotes the Fourier Transform of $x(t)$

This formula provides a quantitative measure of the EEG signal's power distribution across various frequencies. The unit of the PSD is $\mu V^2 / Hz$, which is in accordance with the standard conventions for EEG analysis. A MATLAB2021-based programming script was utilized to facilitate the aforementioned process.

3.3.3. Functional connection analysis

The linear relationship between two signals at a particular band or frequency point is measured with coherence (COH; Niso et al., 2013). Suppose that $X(t)$ and $Y(t)$ represented the EEG signals from different electrodes (or brain regions) X and Y, respectively. First, the time domain signal is converted to the frequency domain using the constant frequency domain conversion method of the fast Fourier transform. For each frequency f, its power spectral densities $S_{xx}(f)$ and $S_{yy}(f)$ and their cross-power spectral densities $S_{xy}(f)$ were calculated. Accordingly, the coherency function $K_{xy}(f)$ is computed coherently using the following formula:

$$\boldsymbol{K_{xy}(f)} = \frac{\boldsymbol{S_{xy}(f)}}{\sqrt{\boldsymbol{S_{xx}(f) S_{yy}(f)}}} \quad (2)$$

Then the following formula is used to calculate the coherence value at frequency f:

$$\boldsymbol{COH_{xy}(f)} = \left|\boldsymbol{K_{xy}(f)}\right|^2 \quad (3)$$

The coherence index ranged from 0 to 1. $COH_{xy}(f) = 0$ means that there is no linear dependence between $X(t)$ and $Y(t)$ at frequency f. The larger the coherence value, the stronger the

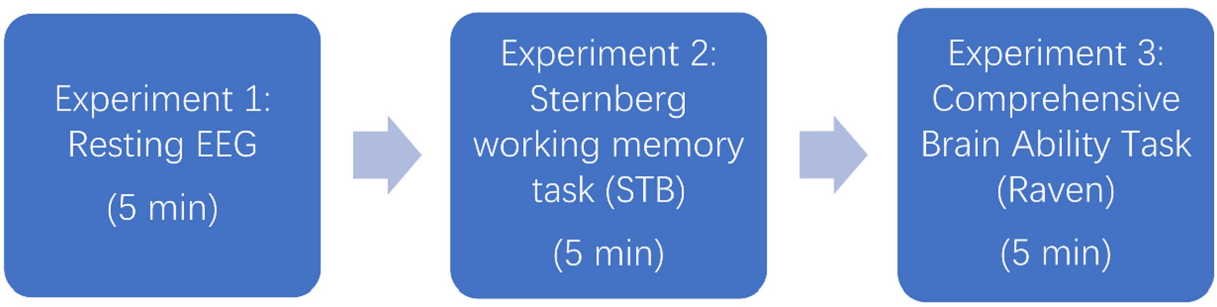

FIGURE 4
Experimental flowchart.

statistical dependence between the two signals, and vice versa. Coherence (COH) is a widely used measure in EEG data analysis to assess the functional connectivity between two regions of the brain. Essentially, it quantifies the consistency of the phase difference between signals from two separate EEG channels. A high coherence value indicates that the two regions (or channels) are functionally connected or are working together, while a low coherence suggests little to no connection. In this study, a programming script based on MATLAB2021 was used to realize the above process.

3.3.4. Multiple comparison correction

The first kind of error (false positive) in statistics is controlled by the significance level a, if m independent comparisons are made, especially when the value of m is large, even if there is no difference between the samples under the two conditions, the probability of being detected with one or more false positives is considerable. Still, it cannot be guaranteed to be below the significance level a. In this study, the false discovery rate (FDR) method is used to correct multiple comparisons. The FDR was the most commonly used tool for multiple comparisons in the current EEG analysis. This method ensured weak control of the overall first-class error rate. The overall first-class error rate can only be effectively controlled if the original assumptions are accurate (Wu et al., 2011). We employed the "*mafdr*" function in MATLAB 2021 for implementing multiple comparison correction. The value of p for false discovery rate (FDR) was set at a threshold of 0.05.

4. Results

4.1. Weekly study time and academic performance

Table 2 presents the ANOVA analysis results for academic performance, weekly study time, number of absences, and number of failed courses among the three subject groups. The statistical analysis was conducted using SPSS 27, employing one-way ANOVA with dependent variables "Average study time per week," "Weighted average grade score," "Number of failed courses," and "Number of absenteeism," with the factor of "Academic performance group." Statistical tests such as the Welch test, Tukey's *post-hoc* multiple comparison test, and the Games-Howell test were applied when equal variances were not assumed.

Table 2 revealed that students with lower academic performance dedicated less time to studying each week, while those with higher performance demonstrated greater self-discipline, investing more time in their studies. Students with average performance exhibited intermediate weekly study times between these two groups. Additionally, the low-performance group experienced higher absenteeism rates and more failed courses compared to the high-performance group, who maintained perfect attendance and had no failed courses. The normal-performance group fell between the high- and low-performance groups regarding absenteeism and failed courses. The stark contrast between the low-performance group's high absenteeism and minimal study time and the high-performance group's exemplary self-discipline and attendance underscores the significance of self-regulation and dedication in academic achievement.

4.2. Resting-state spectrum analysis

In the 5-min resting-state experiment, the spectrum analysis of the three groups of subjects is depicted in Figure 5. No significant differences were observed in the PSD of the three subject groups in the delta, theta, alpha1, alpha2, beta, and gamma bands after the FDR correction. The average PSDs of all 19 electrodes in six frequency bands were extracted to gain a deeper understanding of the overall PSD. An analysis of variance (ANOVA) was conducted on the three subject groups, and no significant differences were identified among them, as shown in Table 3. Consequently, H1a was not supported. No notable differences were observed in whole-brain spectral power between high- and low-performance students concerning resting EEG.

4.3. STB experimental score (working memory ability) and frequency domain analysis

The scores from the STB experiments were imported from E-prime 3.0 to SPSS 27 for analysis. In the STB working memory task, one-way ANOVA was employed to assess potential differences in "memory accuracy" and "reaction time" among the three subject groups. The box plot revealed no abnormal values in the data. Levene's test for homogeneity of variances confirmed that each group's variance was homogeneous ($p_{\text{correct-rate}} = 0.50$; $p_{\text{reaction-time}} = 0.41$), The Shapiro–Wilk test indicated that each group's data did not conform to a normal distribution ($p < 0.05$). However, the one-way ANOVA is relatively stable when deviating from the normal distribution, particularly when each group's sample size is approximately equal. The non-normal distribution did not significantly impact the probability of committing type I errors, allowing for direct testing. The results demonstrated no statistically significant differences between the three subject groups in terms of correct rate and reaction time ($F_{\text{correct-rate}} = 1.38$, $p > 0.05$; $F_{\text{reaction-time}} = 1.85$, $p > 0.05$). These findings indicated no significant differences in working memory among the three subject groups (Table 4), suggesting that H2a was not supported. No notable differences were observed in working memory ability between high- and low-performance students.

In the STB working memory task, the spectrum analysis of the three subject groups is displayed in Figure 6. No significant differences were detected in the PSD of the three subject groups in the delta, theta, alpha1, alpha2, beta, and gamma frequency bands following FDR correction (Figure 6). The average PSDs of 19 electrodes in six frequency bands were extracted. The results of the variance analysis for the three groups are presented in Table 5. No significant differences were found among the three groups across all frequency bands. Consequently, H2a was not corroborated. No differences were observed in the whole-brain power spectrum between high- and low-performance students concerning working memory tasks.

4.4. Raven test results and frequency domain analysis

A one-way ANOVA was employed to determine if there were any differences in the IQ of the three subject groups, using the

TABLE 2 Descriptive statistics and ANOVA results of the "average weekly study time," "academic achievements," "Number of failed courses" and "Number of absenteeism" of the three groups in this study.

Descriptives									
		N	Mean	Std. deviation	Std. error	95% confidence interval for mean		Minimum	Maximum
						Lower bound	Upper bound		
Average study time per week	High performance	20	36.15	4.91	1.36	33.18	39.12	30.00	46.00
	Normal students	21	20.08	3.96	1.14	17.56	22.60	10.00	25.00
	Low performance	20	1.54	1.80	0.50	0.45	2.62	0.00	6.00
	Total	61	19.24	14.98	2.43	14.31	24.16	0.00	46.00
Weighted average grade score	High performance	20	85.13	0.97	0.27	84.54	85.71	83.20	86.31
	Normal students	21	77.16	4.26	1.23	74.45	79.87	70.00	80.94
	Low performance	20	55.21	7.11	1.97	50.91	59.50	41.02	65.07
	Total	61	72.38	13.79	2.24	67.84	76.91	41.02	86.31
Number of failed courses	High performance	20	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Normal students	21	0.50	0.67	0.19	0.07	0.93	0.00	2.00
	Low performance	20	5.00	3.08	0.85	3.14	6.86	3.00	15.00
	Total	61	1.87	2.91	0.47	0.91	2.83	0.00	15.00
Number of absenteeism	High performance	20	0.08	0.28	0.08	−0.09	0.24	0.00	1.00
	Normal students	21	0.67	0.89	0.26	0.10	1.23	0.00	2.00
	Low performance	20	10.31	4.85	1.35	7.37	13.24	0.00	19.00
	Total	61	3.76	5.55	0.90	1.94	5.59	0.00	19.00

ANOVA						
		Sum of squares	df	Mean square	F	Sig.
Average study time per week	Between groups	7801.03	2.00	3900.51	272.31	0.000
	Within groups	501.34	58.00	14.32		
	Total	8302.37	60.00			
Weighted average grade score	Between groups	6219.17	2.00	3109.59	133.21	0.000
	Within groups	817.01	58.00	23.34		
	Total	7036.19	60.00			
Number of failed courses	Between groups	195.34	2.00	97.67	28.73	0.000
	Within groups	119.00	58.00	3.40		
	Total	314.34	60.00			
Number of absenteeism	Between groups	848.51	2.00	424.25	50.79	0.000
	Within groups	292.36	58.00	8.35		
	Total	1140.87	60.00			

results from the Raven test. The Shapiro–Wilk test revealed that the data for each group followed a normal distribution ($p > 0.05$). Levene's test for homogeneity of variances indicated that the data variance for each group was homogeneous ($p = 0.88$). The ANOVA results showed no significant differences in IQ among high-, low-, and average-performance students ($F = 0.48$, $p > 0.05$; Table 6). Consequently, hypothesis H3a was supported.

In the Raven test task, the spectrum analysis of the three subject groups is presented in Figure 7. No significant differences were observed in the PSD of the three subject groups for the delta, theta, alpha1, alpha2, beta, and gamma frequency bands following FDR correction (Figure 7). The average PSDs of 19 electrodes in six frequency bands were extracted, and the ANOVA results for the three subject groups are displayed in Table 7. No significant differences were found among the three groups across all frequency bands. As a result, hypothesis H3b was not supported. No significant differences were detected in the whole-brain power spectrum between high- and low-performance students concerning the comprehensive brain ability task.

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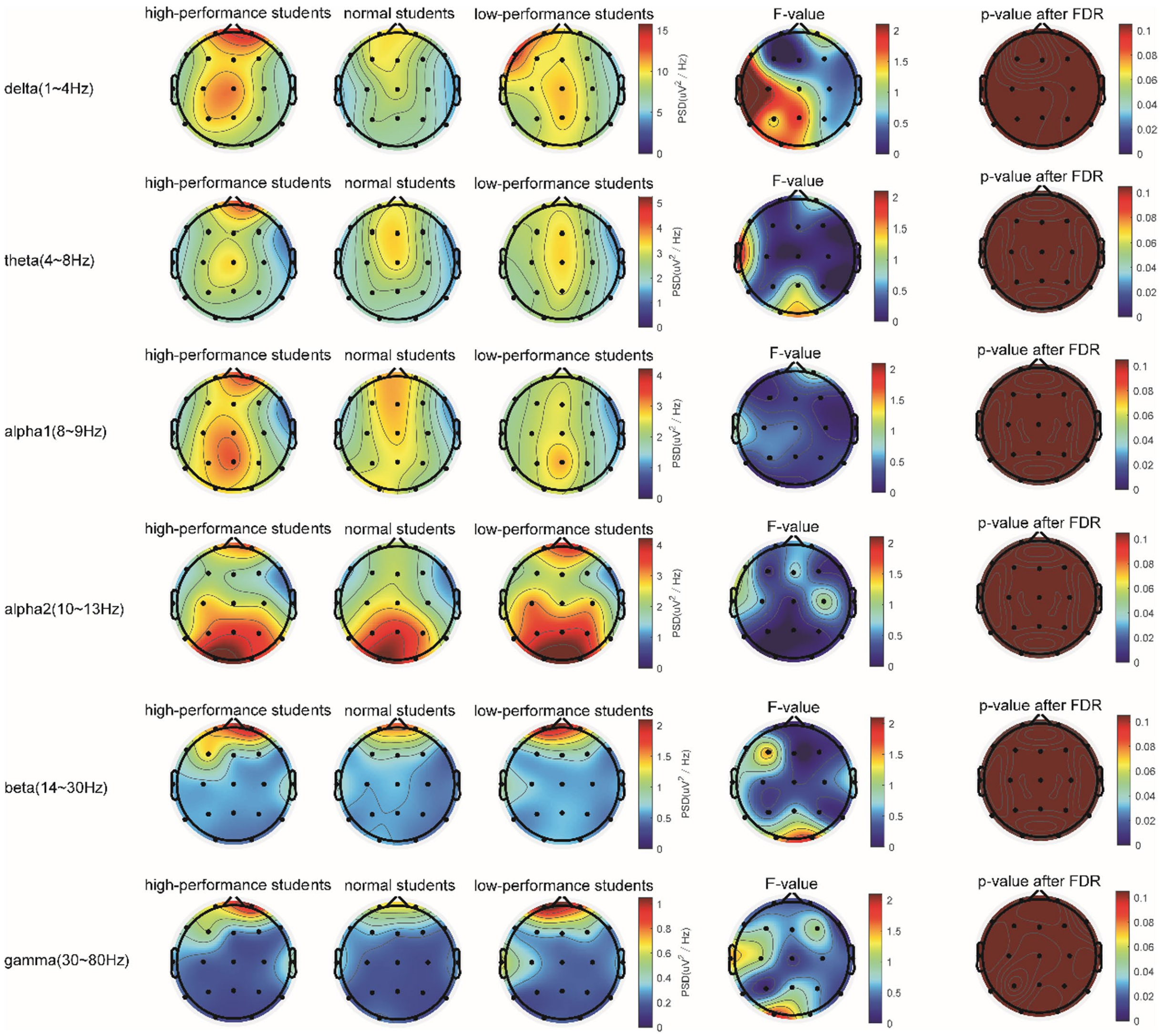

FIGURE 5
Comparison of the PSD in the δ, θ, α1, α2, β, and γ bands of the three groups of subjects evaluated in the resting state.

TABLE 3 Analysis of variance for whole-brain PSD (averaged over 19 channels) among the three subject groups in the resting state.

	df	F	Sig.
Delta	2	0.91	0.41
Theta	2	0.19	0.83
Alpha1	2	0.19	0.83
Alpha2	2	0.15	0.86
Beta	2	0.17	0.84
Gamma	2	0.44	0.64

4.5. Functional connectivity analysis results

Following FDR multiple comparisons and corrections, a significant difference was observed solely in the functional connectivity between high- and low-performance students in the alpha1 bands during the Raven test. Students with lower performance exhibited elevated coherence (COH) values within the alpha1 frequency range (8–9 Hz) when compared to their high-performing counterparts. This was particularly evident in the functional connectivity between frontal and occipital regions, as evidenced by the channels F3-O2, F3-O1, F4-O1, and F4-O2. Consequently, hypothesis H3c was supported (Figure 8; Table 8). In the resting state and STB task, no differences were detected in the functional connectivity across all frequency bands (e.g., delta, theta, alpha2, beta, and gamma) among the three student groups ($p > 0.05$). As a result, hypotheses H1b and H2c were not supported.

5. Discussion

In this study, we conducted three experiments: resting state, working memory task (STB test), and brain comprehensive ability task (Raven test) to investigate the characteristics of neural oscillation and functional connectivity among three college student groups (high-, average-, and low-performance students). The experimental results revealed no significant differences in power spectral densities across delta, theta, alpha1, alpha2, beta, and gamma bands among the

TABLE 4 Descriptive statistics and ANOVA results of the STB experimental results.

Descriptives		N	Mean	Std. deviation	95% confidence interval for mean		Min	Max
					Lower bound	Upper bound		
Correct-rate (%)	High-performance	20	0.88	0.09	0.82	0.93	0.71	1.00
	Normal students	21	0.82	0.11	0.74	0.89	0.63	0.96
	Low-performance	20	0.81	0.12	0.74	0.88	0.50	0.92
Reaction-time(ms)	High-performance	20	1471.68	714.70	1039.79	1903.57	874.92	3328.79
	Normal students	21	1469.18	508.08	1146.36	1792.00	998.92	2724.92
	Low-performance	20	1122.63	261.89	964.37	1280.89	694.21	1513.00

ANOVA		Sum of squares	df	Mean square	F	Sig.
Correct-rate (%)	Between groups	0.03	2.00	0.02	1.38	0.27
	Within groups	0.41	58.00	0.01		
Reaction-time(ms)	Between groups	1034911.35	2.00	517455.68	1.85	0.17
	Within groups	9792249.65	58.00	279778.56		

TABLE 5 Analysis of variance for whole-brain PSD (averaged over 19 channels) among the three subject groups during the STB task.

	df	F	Sig.
Delta	2	0.74	0.48
Theta	2	0.37	0.69
Alpha1	2	1.28	0.29
Alpha2	2	0	0.99
Beta	2	0.1	0.91
Gamma	2	0.2	0.82

student groups in all three experiments. Additionally, in the STB working memory experiment, no significant differences were found among the three student groups concerning the correct rate, reaction time, and power spectral density of each frequency band. Consequently, it can be concluded that the working memory of low-performance students was not impaired compared to that of high- and average-performance students, and the working memory ability of high-performance students was not significantly superior. Furthermore, no significant differences were observed in IQ scores or power spectral density among the three student groups in the Raven test, indicating no significant differences in IQ or working memory among the students.

Previous studies have demonstrated the effectiveness of working memory training for individuals with cognitive or attention impairments, resulting in substantial gains in working memory performance (Dahlin, 2011). However, research suggests that the effects of such training on healthy individuals are more modest, with only small improvements observed (Loosli et al., 2012; Karbach et al., 2015). According to the compensation theory, high-performing individuals may benefit less from cognitive interventions because they are already functioning at an optimal level, leaving less room for improvement (Titz and Karbach, 2014). It is important to note that our participants, including high-, average-, and low-performing groups, all scored above a very high threshold on the college entrance examination and were admitted to the same university and major. Our university is a highly selective institution with a very high admission threshold, and if the low-performing group had cognitive deficits, they would not have been able to gain admission to the same university and major as the high-performing group. As such, although the high-performing group may have improved their working memory abilities through 3 years of rigorous academic study at the university, this improvement would be minimal. This explains why we did not find a significant difference in working memory performance among high-, average-, and low-performing students in the same university and major.

Spectrum analysis reflects the characteristics of local brain regions, while functional connections indicate the interaction between different regions. In terms of functional connectivity, this study found a significant difference between high- and low-performance students during the Raven test, which was concentrated on the functional connections of the alpha1 bands. Previous studies have demonstrated that in ordinary individuals, rapid formation and dissolution of functional connections can be observed through the synchrony and asynchrony between different brain regions (Herrera-Díaz et al., 2016). In other words, for normal brain functioning, both synchrony and asynchrony of brain regions are required (Friston, 2000; Stam and de Bruin, 2004). The dynamics of functional brain connections can be impaired in two ways: neuronal over-connection or over-disconnection (Stam and van Straaten, 2012).

During the Raven IQ test, low-performing students demonstrated increased coherence (COH) values in the alpha1 band (8–9 Hz) relative to high-performing students, specifically in the functional connectivity between the frontal and occipital regions (F3-O2, F3-O1, F4-O1, F4-O2). The prefrontal lobe is associated with higher cognitive functions such as executive functions, decision-making, and attention,

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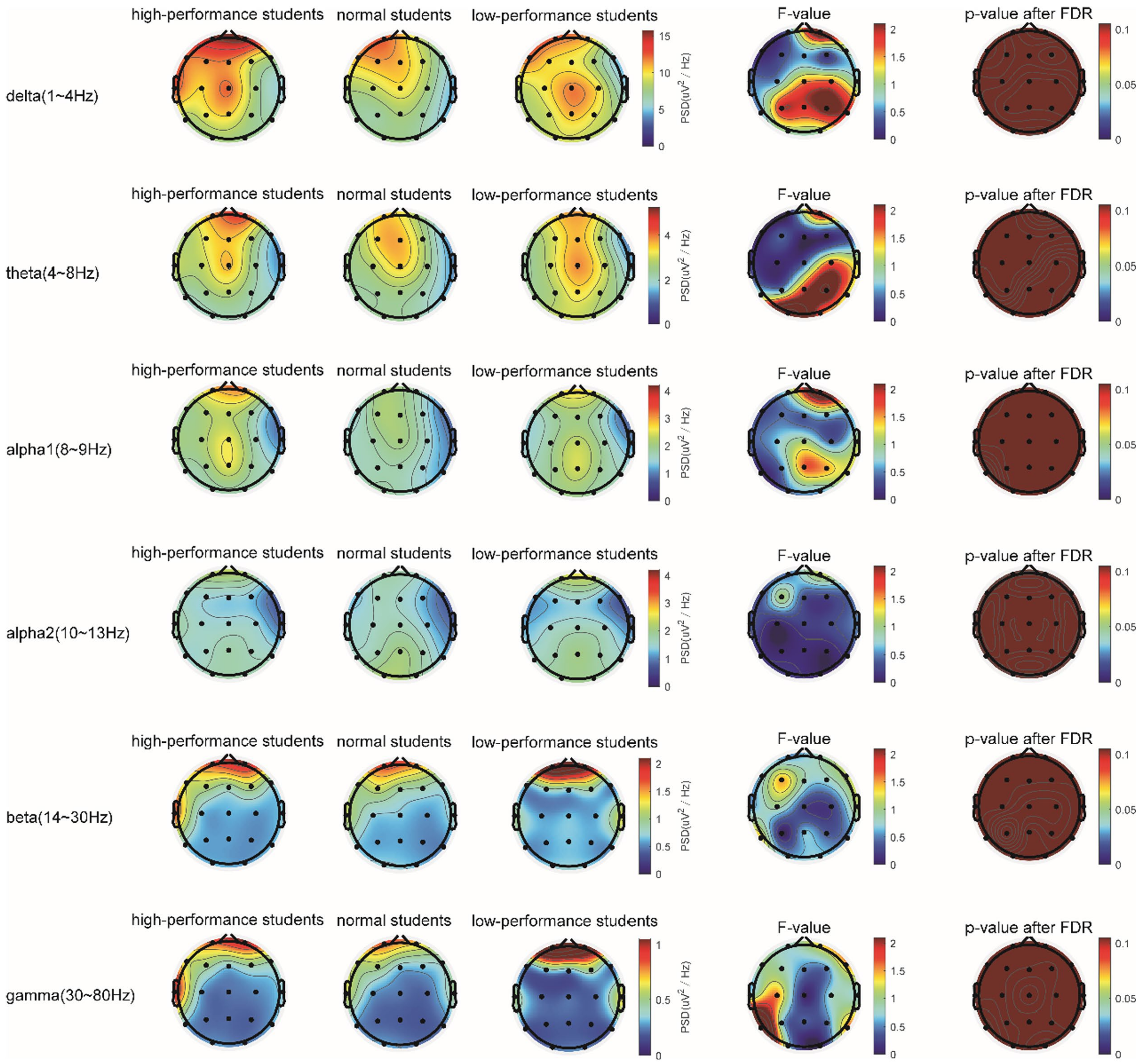

FIGURE 6
The comparison of PSD in the δ, θ, α1, α2, β, and γ bands of the three groups of subjects in the STB test.

while the occipital lobe is implicated in visual processing. It is posited that low-performing students may adopt a problem-solving strategy on the Raven IQ test that emphasizes information exchange between the frontal and occipital lobes, resulting in augmented functional connectivity within the alpha1 band (Damoiseaux et al., 2006). The most plausible rationale for this observation is that low-performing students might necessitate greater energy expenditure for concentration, suggesting an increased cognitive effort in problem-solving. Alpha waves, particularly in the alpha1 band (8–9 Hz), are typically enhanced during relaxed, closed-eye, or introspective thinking states. The brain might be more inclined to enter such states when attention is diverted, leading to elevated functional connectivity in the alpha1 band. As a result, increased functional connectivity in the alpha1 band could indicate that low-performing students require additional energy to maintain focus during problem-solving (Klimesch, 1999b). Low-performing students might be more susceptible to attentional distractions while engaged in the task. This diversion could lead to heightened alpha1 band functional connectivity, as these students demand more cognitive effort to sustain focus (Eichele et al., 2008). Attentional distractions can result in diminished synchronization of task-related brain regions. When attention is directed toward a specific task, task-related brain regions exhibit increased synchronization. Attentional distractions may induce a decrease in synchronization and a relative enhancement of functional connectivity within the alpha1 band (Doesburg et al., 2009). Attentional dispersion may prompt the brain to continually alternate between processing external stimuli and internal information. In such cases, the functional connectivity of the alpha1 band could function as a "regulator" among different brain regions, allowing the brain to dynamically transition between processing external stimuli and internal information (Palva and Palva, 2007). Additionally, low IQ and poor working memory could contribute to elevated COH in the alpha1 band within frontal and occipital areas (Kane and Engle, 2002). However, the results from our STB and Raven

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TABLE 6 Descriptive statistics and ANOVA results of the Raven test IQ score.

Descriptives IQ	N	Mean	Std. deviation	95% confidence interval for mean		Min	Max
				Lower bound	Upper bound		
High-performance	20	113.46	3.89	111.11	115.81	107.00	122.00
Normal students	21	113.42	3.15	111.42	115.42	110.00	119.00
Low-performance	20	112.15	4.32	109.54	114.76	105.00	122.00

ANOVA IQ	Sum of squares	df	Mean square	F	Sig.
Between Groups	14.16	2.00	7.08	0.48	0.62
Within Groups	513.84	58.00	14.68		
Total	528.00	60.00			

tests negate this possibility, as no significant disparity was found between IQ and working memory among low- and high-performing students.

Another explanation that may lead to the increased functional connection between alpha1 bands is that low-performance students were more prone to fatigue than high-performance students in the task of the comprehensive ability of the brain. Brain fatigue can also lead to increased functional connections in the alpha1 bands, because the brain needs more effort to stay alert and focus (Tanaka et al., 2012). The power of alpha and theta bands has been proven to be a reliable indicator of fatigue-related nerve changes (Zhang et al., 2016; Hsu and Jung, 2017; Majumder et al., 2019). The latest research in cognitive science explores the interaction between brain regions after performing fatigue tasks. The functional connections of the frontal, central, and parietal lobes are closely related to mental fatigue (Liu et al., 2010). Studies have found that the functional connectivity of post-fatigue tasks is closer to that of pre-fatigue tasks, which indicates that the human brain strengthens coupling when tried to maintain information transmission until the required tasks are completed (Chen J. et al., 2018; Han et al., 2019). Compared with the awakened state, the alpha and theta bands in the sleepy state have a higher phase coherence (Chen J. et al., 2018). Therefore, the results of this study probably reflect that low-performance students have not studied hard enough for a long time and that their brains have not been sufficiently trained. Therefore, they are more prone to fatigue than high-performance students in dealing with tasks that consume their brains. However, the brains of high-performance students have been fully trained after 3 years of hard work in college, and their brain anti-fatigue ability is significantly more potent than that of low-performance students regarding comprehensive brain tasks.

A third potential explanation for the observed phenomenon is anxiety, which might contribute to heightened functional connectivity between the frontal (involved in emotion regulation) and occipital lobes (related to visual processing), resulting in increased activity within the alpha1 frequency band (Etkin and Wager, 2007). Extensive research suggests that college students with poor academic performance are more likely to experience mental health issues, with anxiety and depression being the most prevalent psychological concerns (Andrews and Wilding, 2004; Hysenbegasi et al., 2005; Conley et al., 2015; Liu et al., 2022). Anxiety could lead to compromised autonomic regulation within the brain. In states of heightened anxiety, the brain may struggle to effectively regulate its activity, leading to elevated activity in the alpha1 frequency band (8–9 Hz). This could suggest that low-performing students necessitate greater effort in problem-solving due to their brains' inability to efficiently self-regulate and adapt to task demands (Miskovic and Schmidt, 2010). Anxiety may also give rise to distraction. During states of elevated anxiety, individuals may be more susceptible to distractions from external stimuli and internal thoughts, which could contribute to increased activity in the alpha1 frequency band as the brain demands more effort to maintain attentional focus (Bishop, 2009). Lastly, anxiety might induce hyperactivity between the frontal and occipital lobes. In anxious states, functional connectivity between the frontal (involved in emotion regulation) and occipital lobes (related to visual processing) may be amplified. This enhanced functional connectivity could result in increased activity in the alpha1 frequency band, indicating that the brain requires additional effort to process the task at hand (Etkin and Wager, 2007).

6. Limitations

Although our analysis of high- and low-performance students based on study time and absences suggests that the latter group may exhibit reduced self-discipline and indulgence, this conclusion is indirectly inferred. The inclusion of a self-report questionnaire in the study could have provided more direct evidence, albeit with the limitation that students might not be truthful in their responses, particularly regarding sensitive topics such as video gaming habits and partying frequency. Furthermore, we did not account for potential factors influencing motivation, including medical history, physical activity, meditation practice, and social interaction, which may have affected the students' academic performance and should have been

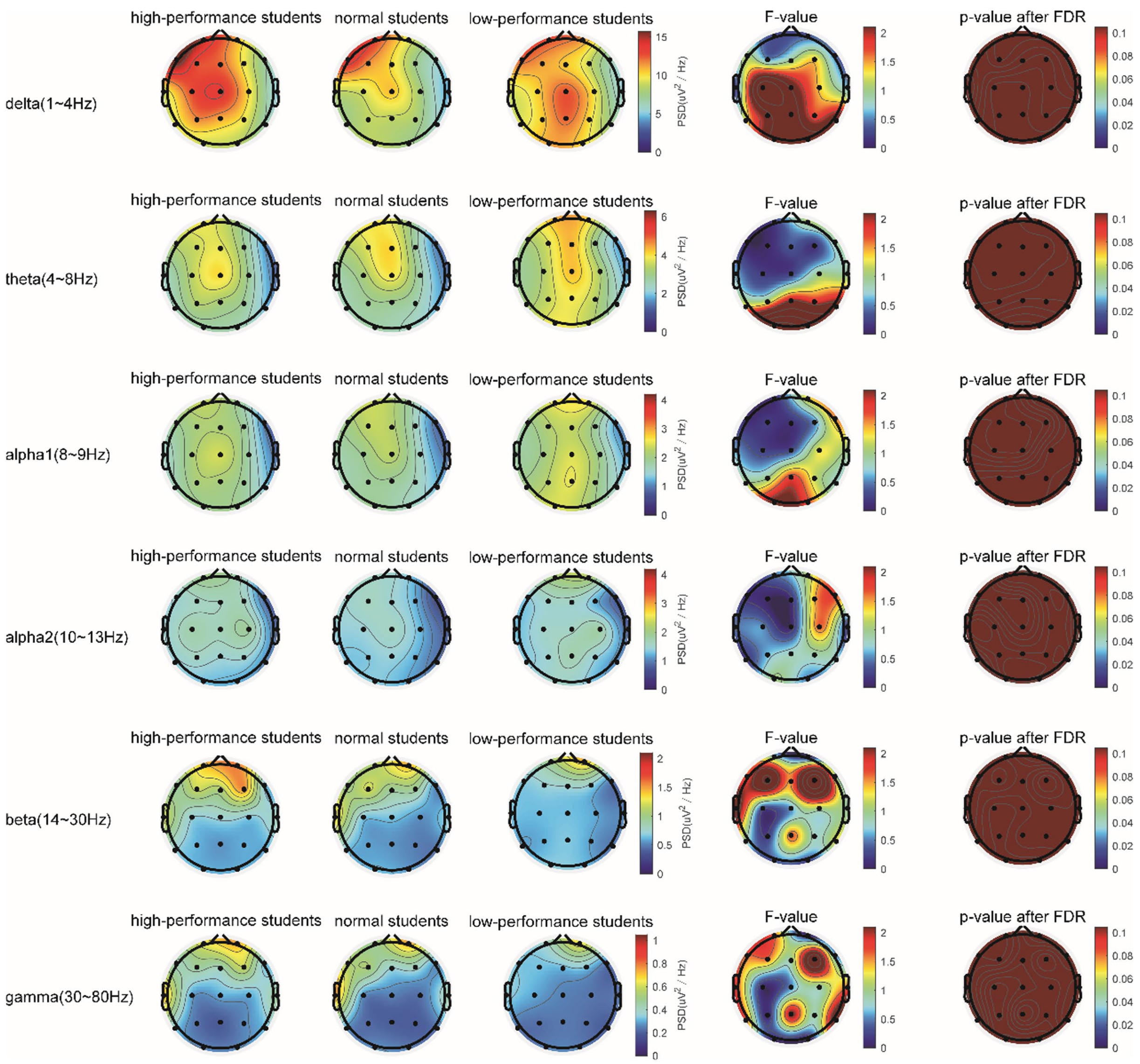

FIGURE 7
The comparison of the PSD of power spectral density in the δ, θ, α1, α2, β, and γ bands among the three subject groups in the Raven test.

TABLE 7 Analysis of variance for whole-brain PSD (averaged over 19 channels) among the three subject groups during the Raven task.

	df	F	Sig.
Delta	2	1.40	0.26
Theta	2	1.17	0.32
Alpha1	2	0.89	0.42
Alpha2	2	0.49	0.62
Beta	2	1.42	0.25
Gamma	2	1.41	0.25

considered in our study design. Our sample was limited to participants from a single university, and we lacked information on family income levels. Notably, research has identified anatomical differences between high- and low-income students that correlate with academic achievement test scores (Mackey et al., 2015).

To address these limitations, we propose conducting a three-year longitudinal study. Repeating the experiments with the same cohort of students at two distinct time points during their college experience (upon university entry and in their third year) would enable longitudinal comparisons between high- and low-performance students. This approach could elucidate the differences between trained and untrained brains by comparing data from freshmen and third-year students. While such a research project would be time-consuming, it could be designed in the future to yield more robust evidence.

7. Conclusion

In summary, this investigation examined the characteristics of neural oscillations and functional connectivity among high-, average-, and low-performing college students in resting state, working memory

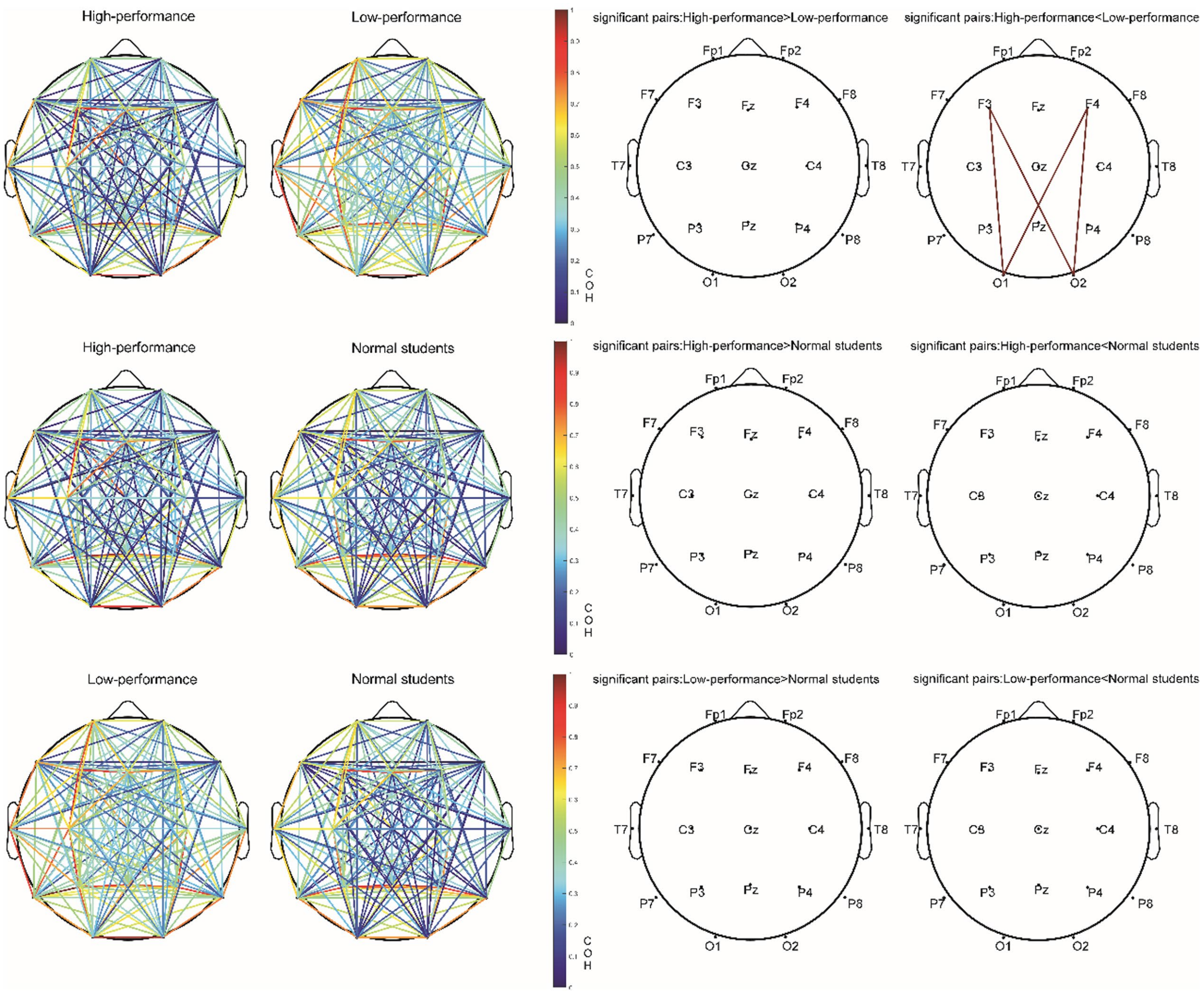

FIGURE 8
The COH value of the alpha1 (8–9 Hz) band and electrode pair with significant difference (corrected by FDR) in the Raven test experiment.

TABLE 8 T-test results of the COH values of the four electrode pairs with significant differences in the alpha1 frequency band between high- and low-performance students in the Raven test experiment (corrected by FDR).

Electrode pairs	df	T-value	Sig.
F4-O1	38	−4.03	1.31E-04
F3-O1	38	−3.46	6.83E-04
F4-O2	38	−4.32	5.36E-05
F3-O2	38	−3.47	6.63E-04

task (STB test), and brain comprehensive ability task (Raven test) conditions. The findings revealed no substantial differences in power spectral densities, working memory, or IQ scores across the three student groups.

In light of our experimental findings, it is important to note that Hypotheses H1a, H1b, H2a, H2b, H3a, and H3b were not supported by the data. No significant differences were observed among high-performing, average, and low-performing students in terms of IQ, working memory, and neural metrics such as Power Spectral Density (PSD) across the three experimental conditions.

However, a minor optimization was observed in high-performance students' brains compared with low-performance students, primarily manifested in their enhanced concentration, increased fatigue resistance, and reduced anxiety during complex cognitive tasks. This difference is evident in the functional connectivity variations between the frontal and occipital regions in the alpha1 frequency band. Hypothesis H3c received substantial empirical support. Notable differences were found between the high-performing and low-performing student groups in functional connectivity during complex cognitive tasks. Specifically, enhanced functional connectivity was observed in the low-performing student group at brain regions F3-O2, F3-O1, F4-O1, and F4-O2.

The insights gleaned from this research enhance our comprehension of the neural foundations of academic performance and may bear implications for devising targeted interventions and strategies to assist students with diverse levels of academic achievement. Future studies should concentrate on further clarifying the underlying mechanisms and factors contributing to the observed differences in functional connectivity and investigating the potential advantages of targeted interventions to bolster cognitive performance among low-performing students.

Data availability statement

The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found at ScienceDB, https://www.scidb.cn/s/F7z6Jr.

Ethics statement

The studies involving humans were approved by Hubei university Ethics Committee. The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

Author contributions

ZX paper writer, experiment host, data analysis, and operation. PZ, MT, MZ, and YL laboratory assistant. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fpsyg.2023.1209881/full#supplementary-material

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Soccer's AI transformation: deep learning's analysis of soccer's pandemic research evolution

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Introduction: This paper aims to identify and compare changes in trends and research interests in soccer articles from before and during the COVID-19 pandemic.

Methods: We compared research interests and trends in soccer-related journal articles published before COVID-19 (2018–2020) and during the COVID-19 pandemic (2021–2022) using Bidirectional Encoder Representations from Transformers (BERT) topic modeling.

Results: In both periods, we categorized the social sciences into psychology, sociology, business, and technology, with some interdisciplinary research topics identified, and we identified changes during the COVID-19 pandemic period, including a new approach to home advantage. Furthermore, Sports science and sports medicine had a vast array of subject areas and topics, but some similar themes emerged in both periods and found changes before and during COVID-19. These changes can be broadly categorized into (a) Social Sciences and Technology; (b) Performance training approaches; (c) injury part of body. With training topics being more prominent than match performance during the pandemic; and changes within injuries, with the lower limbs becoming more prominent than the head during the pandemic.

Conclusion: Now that the pandemic has ended, soccer environments and routines have returned to pre-pandemic levels, but the environment that have changed during the pandemic provide an opportunity for researchers and practitioners in the field of soccer to detect post-pandemic changes and identify trends and future directions for research.

KEYWORDS

soccer, football, pandemic, COVID-19, research trend, topic modeling, BERT, data science

1. Introduction

Currently, soccer is the sport with the largest participation and population. Furthermore, the repercussions and revenues generated by soccer worldwide not only affect sports but also have social, economic, and even cultural impacts (Jakar and Gerretsen, 2021). Asken and Rabinovici (2021) reported that approximately 270 million people are actively involved in soccer, which is proof of the sport's enormous sociocultural and economic impact. Given the large number of people involved in soccer, it is unsurprisingly the most widely and heavily studied of all sports. Indeed, academics are conducting research on all ages and levels of soccer players (Svensson et al., 2016; McFadden et al., 2022; Beavan et al., 2023). Soccer-related research is published in most academic disciplines, including sports sociology, sports science, computer science, engineering, and medicine, with a strong interdisciplinary approach (Williams et al., 2020).

However, on March 11, 2020, the World Health Organization (WHO) declared the highest pandemic alert for COVID-19, specifically categorizing it as a "pandemic" (Wu et al., 2021) and warning that the global spread of COVID-19 was not just a public health crisis but also one with political, economic, social, and cultural implications (Lopez-Bravo et al., 2020). The sports sector was similarly affected by the pandemic. While the responses of national sports leagues varied, international leagues saw a complete suspension of sporting events at all levels (Sivevska and Popeska, 2020). Throughout the pandemic, professional sports leagues had limited or banned spectator attendance; major events like the Olympics and various sports leagues canceled or postponed (Elkhouly et al., 2022), and soccer is no exception.

The COVID-19 pandemic has majorly impacted professional soccer around the world. In Europe, most leagues temporarily suspended play in 2020–2021 to help contain the spread of the virus (Mazza et al., 2022). For a time, players were only allowed to train at home to reduce the risk of infection (Marshall et al., 2022). Team training varied from country to country, league to league, and club to club, but it was conducted carefully and with many controls in place. The COVID-19 pandemic has impacted soccer in a unique and unprecedented way, and this unusual phenomenon has led to a subtle shift in research topics during the pandemic, with some researchers addressing topics related to the pandemic itself.

For example, since the temporary lockdown, leagues have had to play more games than usual in a short period of time to finish on time, and there have been reports of a noticeable increase in player variability and injuries due to long breaks and a lack of training (Seshadri et al., 2021). Studies of possible performance declines during COVID-19's disruption of matches and soccer-related training have shown declines in sprint and jump tests, which may be related to a reduction in soccer-related (group) training during lockdown (Pierros and Spyrou, 2023). Several studies have examined actual performance and injury rates before and after COVID-19 disruptions in matches and training in several European professional men's soccer leagues (Thron et al., 2021, 2022). However, it is difficult to determine how specifically and evenly these studies can be applied to the broader field of soccer research. Moreover, overall research trends may have been affected by the COVID-19 pandemic without directly referring to it. This study constitutes another effort to discover and understand these phenomena.

A careful examination of the arguments so far suggests that the COVID-19 pandemic has caused many changes in the soccer landscape and that soccer-related research has also been affected. This observation implies that we can detect some changes in soccer research before and after the pandemic, but we need specific solutions to analyze them more objectively and quantitatively. The development of soccer is growing quantitatively and qualitatively with an exponential increase in research and a multidisciplinary approach. A significant amount of research and empirical reporting is published in academic articles, but extracting this extensive and heterogeneous of knowledge is a complex task. While analyses such as Delphi and meta-analyses are essential, they do not fully capture the scale, scope, and complexity of soccer research. Therefore, it is necessary to consider data science-based approaches to organize the domain knowledge of a large and specific field (Lyu and Costas, 2022). Keyword-driven subject area segmentation with natural language processing can reveal how the vast complexity of knowledge that makes up sports literature is related (Bruner et al., 2010). This rationale can be usefully applied to gain insight into the enormity of soccer research and the various research considerations that have arisen before and after the COVID 19 pandemic. In this study, we used a topic modeling algorithm called BERTopic (Bidirectional Encoder Representations from Transformers Topic) (Grootendorst, 2020), a topic modeling technique that leverages transformers (Vaswani et al., 2017) and class-based term frequency–inverse document frequency (c-TF–IDF) to identify well-studied research areas in the COVID-19 literature related to soccer.

Using topic modeling to study research trends can provide useful information along with new ideas for future research (Lee et al., 2021, 2022). These results can be used to form a body of knowledge by quantitatively analyzing a large number of papers and qualitatively interpreting the discovered knowledge structure to find certain patterns in scattered data (Miyata et al., 2020). The probability distribution of words in a document has no intuitive meaning, but researchers can interpret the meaning of a particular topic and extract insights so that the extracted topic can be used as important information representing the document (Kim et al., 2022). In addition, because multiple related papers are used for analysis, it is possible to discover the relationships between key research topics and various subtopics in the academic field and intuitively explore the knowledge structure by visualizing research results (Park, 2020).

In this study, we use topic modeling with journal articles to analyze the knowledge structure of soccer-related research published before (2019–2020) and during (2021–2022) the COVID-19 pandemic. By comparing the content of the research agendas for the two periods, we aim to determine if there are differences in academic and research interests in soccer before and during the COVID-19 pandemic. In other words, we contrast the trends in soccer-related research topics during the two periods to provide insights into changes, future predictions, and implications.

Therefore, this study aims to comprehensively identifying and comparing the changes in research interests, topics, and trends from before COVID-19 to during the COVID-19 pandemic.

To address the research aims, the research question was set as follows.

> Q1. What are the topic areas of soccer research before, during, and after the COVID-19 pandemic?
>
> Q2. What are the topical areas of soccer research organized from the extracted topics?

> Q3. How have the topics and topic areas of soccer research changed before, during the COVID 19 pandemic?

2. Background

2.1. Document embedding

In topic modeling, document embedding is used to convert the raw text of a document into a mathematical representation that can be compared semantically, i.e., documents containing the same topic are semantically similar. This technique is commonly used in topic modeling, which is the process of identifying latent topics in a corpus of text documents. To perform the embedding step in this study, we used BERTopic's Sentence-BERT (SBERT) (Reimers and Gurevych, 2019), which is a method for encoding sentences or short texts into dense vector representations using Bidirectional Encoder Representations from Transformers (BERT). These vectors capture the meaning and context of the sentence or text, making them useful for various natural language processing (NLP) tasks, including document similarity and clustering.

2.2. Term frequency–inverse document frequency

One weighting method for representing text is term frequency–inverse document frequency (TF–IDF). The basic idea is to create a vector for each document in the corpus, where each element of the vector represents a specific feature or term of the document. The value of the element is typically a weight that reflects the importance of the feature in the document. A TF–IDF value is determined according to the relative frequency of a word in a specific document based on its frequency in the document and its rarity across all documents in the corpus. The TF–IDF is given by Equation (1) below, where the weight of the word i in the document j is W_{ij}, N is the number of documents, tf_{ij} is the frequency of the word i in the document j, and df_i is the number of documents that contain the word i (Zhang et al., 2011).

$$W_{ij} = tf_{ij} * \log \frac{N}{df_i} \quad (1)$$

2.3. Topic modeling with BERT

Topic modeling is an analytical, unsupervised learning model that discovers topics in a corpus. In this sense, a topic can be defined as a repeated pattern of terms (Gunjan et al., 2021). Recently, deep-learning-based models such as BERT have shown exceptional performance in various NLP tasks, including document embedding and topic modeling called BERTopic (Grootendorst, 2020). BERT is a pre-trained language model that uses a transformer architecture to encode text into dense vector representations. These vectors capture the context and meaning of the text, making them useful for many downstream NLP tasks, including topic modeling. The algorithm uses three primary phases to produce a topic's distribution for a set of documents. First, it creates sentence embedding. Second, it creates clusters of semantically similar sentences. The last step includes creating topic representation with c-TF–IDF. We elaborate on each step in the Methods section.

Initially, BERTopic works by generating dense vector representations of each document in a corpus using BERT or SBERT; we take the sentence embedding from our documents. These embeddings, however, are primarily used to cluster semantically similar documents and are not directly used in generating the topics.

Primarily, the BERTopic technique utilizes two algorithms: uniform manifold approximation and projection (UMAP) and hierarchical density-based spatial clustering of applications with noise (HDBSCAN) (Campello et al., 2013). UMAP reduces the dimensionality of the document embeddings before clustering (McInnes et al., 2018). Specifically, UMAP is a powerful dimensionality reduction technique that preserves the original structure into a low-dimensional structure, facilitating more efficient and effective clustering.

The second algorithm, HDBSCAN, is a powerful clustering algorithm that can automatically determine the number of clusters in the data, making it a valuable tool for unsupervised text analysis. Additionally, HDBSCAN can handle noise and outliers, which is particularly important when dealing with large and complex datasets. HDBSCAN provides a robust and efficient method for unsupervised topic modeling in social science research. By leveraging advanced NLP techniques and clustering algorithms, BERTopic can capture the nuances and subtleties of natural language and produce highly interpretable topics that can provide deep insights into the underlying structure and meaning of textual data.

The standard TF–IDF equation is used to calculate the importance of each term within each topic rather than across the entire corpus. In contrast, c-TF–IDF defines the importance of a word within a class (topic) (Grootendorst, 2020) and treats all documents in a single class as a single document. Equation (2) finds the c-TF–IDF of each word, where W_{ic} is the weight of word i in class c. The frequency of word i in class c is tf_{ic}. A is the average number of words per class, and f_i is the frequency of word i across all classes.

$$W_{ic} = tf_{ic} * \log\left(1 + \frac{A}{f_i}\right) \quad (2)$$

Finally, by calculating the c-TF–IDF score for each term within each topic, BERTopic can identify the most important terms for each topic rather than across the entire corpus. These important terms can then be used to label and interpret the resulting topics, providing a more accurate and specific representation of the underlying themes and trends within the data.

3. Methods

3.1. Data collection

Soccer studies before and during the COVID-19 pandemic were collected by searching the Web of Science (WOS). Articles were collected from the following indexes: Science Citation Index, Science Citation Index Expanded, Social Sciences Citation Index, and Arts & Humanities Citation Index. Keywords were used in the searches, including "soccer" and "football." The research data from before COVID-19 included 3,956 studies from 2019 to July 2020, and the research data from the period during the COVID-19 pandemic included 3,423 studies from 2021 to July 2022. Irrelevant articles were excluded from the collected data.

First, we excluded papers regarding "football" that focused on the National Football League (NFL) in the United States and the Australian Football League (AFL) in Australia. However, articles that presented a comparative approach to soccer were allowed. Articles that were not journal articles (news articles, letters to the editor, research reports, conference proceedings, books, etc.), did not have an abstract, or were written in a language other than English were excluded. The research flow and procedures for this study are shown in Figure 1.

3.2. Data pre-processing and topic modeling

This paper proposes a two-step approach for topic modeling in soccer data. The first step involves pre-processing the data to extract relevant information and enhance the original data representation, while the second step uses BERTopic to generate topics that preserve the semantics of the original data representation. The BERTopic algorithm is based on word-embedding models and is capable of identifying relevant topics in the data (Grootendorst, 2020). Specifically, we used a BERT-based embedding model to extract meaningful topics from soccer research data obtained from the WOS. The pre-processing step included data cleaning, tokenization, stemming, and stop-word removal. The following procedure provides an overview of the methodology used in this paper.

1. Data Cleaning: We extracted only English text from the research data using regular expressions to minimize noise in the dataset that might impact topic extraction. We converted all textual contents within the dataset into lowercase to ensure consistency.
2. Stemming: We applied the Snowball Stemmer technique to reduce the word variation in the data and reduce the number of unique tokens in the dataset (Gurcan and Cagiltay, 2023). The remaining words in the dataset were reduced to their stems (e.g., the words "plays," "playing," and "played" were all represented as "play").
3. Stop-Word Removal: We removed common stop words such as "the," "and," and "in," which do not carry significant meaning. Likewise, we filtered out generic words (e.g., "literature," "paper," and "study") that were frequently observed in the articles but did not contribute to the creation of semantically consistent topics. To edit the stop-word list, we utilized NetCorp's library to modify the stop words. In this way, we ensured that only the words with a single meaning were included in the dataset.
4. Vectorization: Next, we converted the pre-processed text into a numerical format that can be used for analysis, which is embedding. Each document was embedded using the implemented BERT model. We used SBERT to manufacture high-quality contextual word and sentence vector representations.
5. Topic Modeling: Finally, we used BERTopic to perform topic modeling on the pre-processed and vectorized soccer data. BERTopic is a state-of-the-art topic modeling algorithm that utilizes transformer-based language models such as BERT or Sentence-BERT to generate document embeddings, which are then clustered using hierarchical clustering algorithms such as HDBSCAN. This process results in a set of topics, each with a list of important terms and their corresponding weights, which can be interpreted and labeled by the researcher.

In summary, the methodology used in this study consisted of data cleaning, stemming, stop-word removal, vectorization using BERT, and topic modeling using BERTopic. This method enabled us to perform topic modeling on the soccer data systematically and efficiently, while also accounting for potential noise and variations in the data. We implemented the pre-processing steps because we believed they would be beneficial for reducing noise and variation in the data while also having a negligible impact on the semantics of the soccer data. The resulting topics and insights can be used to inform decision-making and analysis in the field of sports and medicine.

As a result of the above method, 47 topics were generated in 8 Topic Areas from the pre-COVID-19 period, and 51 topics were generated in 8 Topic Areas from the period during the COVID-19

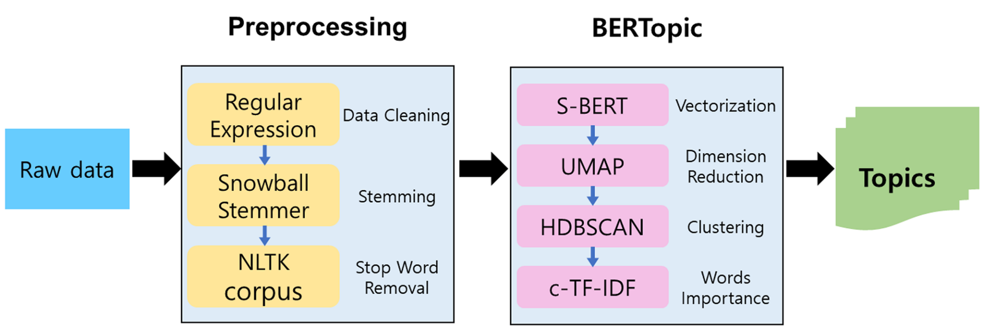

FIGURE 1
Methodology overview. Research overflow consists of data collection, pre-processing, topic modeling using BERT, and topic analysis.

pandemic. Clusters of keywords with unclear identities were deleted from the generated topics (Gurcan and Cagiltay, 2022). Therefore, 1 topic was deleted from the pre-COVID-19 pandemic period and 5 topics were deleted from the period during the COVID-19 pandemic.

From the topic modeling results, we first examined the topic areas and keyword clusters of soccer-related articles published before the COVID-19 pandemic; second, we examined the topic areas and keyword clusters of soccer-related articles published during the COVID-19 pandemic. Then, we defined the research topics using the topic areas and clusters mapping the research areas in the two periods and deduced the changes in topic approaches and future directions through comparison.

4. Results

4.1. Soccer research trends: 2018–2020

The soccer research Topic Areas for the pre-COVID-19 period (2018–2020) and the keyword composition for each Topic Area are shown below. The results of topic modeling for soccer research in the pre-COVID-19 period are shown in Table 1.

Topic Area-1 was labeled "Social Sciences-1: Psychology & Sociology" related to soccer and includes the following Topics. Topics 7, 15, and 24 were identified as psychological topic areas. Specifically, Topic 7 was clustered with keywords about team or athlete efficacy based on the coach's leadership style. Topic 15 was clustered with keywords that explored various variables related to parents that affect youth and children soccer players. Topic 24 was clustered from straightforward keywords like psychology to keywords about soccer player motivation and burnout. Topic 38 was clustered around validated interventions for soccer players' mental health, with keywords ranging from players' social skills to mental-healthcare-related smartphone applications (mindmax, MindMax LLC, Duxbury).

On the other hand, Topics 10 and 46 were found to be clustered around soccer-related sociology topics. Topic 10 clustered keywords related to identifying the social and environmental determinants (age, born, talent, etc.) of the relative age effect (REA) on soccer players. Topic 46 clustered research topics related to soccer player talent identification and development; we also found one soccer business and one technology topic in this Topic Area. Topic 37 was clustered with keywords related to identifying changes in soccer game decision-making following the introduction of video assistant referee (VAR) systems, and Topic 41 was clustered with keywords related to exploring market value determinants (such as foreign players) of each club in professional soccer leagues.

Next, Topic Area-2 has the domain name "Social Sciences-2: Business & Sociocultural" as related to soccer and includes the following Topics. Topics 8, 23, and 29 were identified as detailed research topics related to the soccer business. Topic 8 was clustered with keywords exploring the determinants of stadium attendance in soccer leagues. Topic 23 was clustered with keywords related to evaluating the financial performance of a soccer league or club. Topic 29 was clustered with keywords representing topics such as sponsor, sponsorship, and loyalty that affect the formation of a fan's brand image of a club or league. Topics 0 and 22 were identified as sociocultural themes. Topic 0 was clustered into thematic keywords dealing with soccer fans' culture and political ideology, and Topic 22 was clustered under topic keywords dealing with sociological issues, including the perceptions, stereotypes, gender roles, and identities of female soccer players.

Topic Area-3 was labeled "Sport Science & Technology" as related to soccer and includes the following Topics. Topic 5 was clustered with keywords related to data analysis, which is related to team performance topics such as ball possession, shots, and score. Topic 9 was clustered with keywords representing research related to power analysis using a team's pass network and prediction model. Topic 12 was clustered with keywords related to research on the structural response of stadium roofs to wind, temperature, etc., in terms of structural engineering. Topic 12 was clustered with keywords that propose, apply, and validate algorithms for image-processing tracking systems that recognize opposing robots and balls for soccer robot functions. Topic 45 was clustered with keywords related to the technique of exploring the determinants of how to import variables that generate revenue from soccer matches.

Topic Area-4 has the domain name "Sport Medicine-1: - Injury" as related to soccer and includes the following Topics. First, Topics 1, 20, and 44 were clustered with research keywords related to injuries in the "lower limb" area, such as "knee," "hamstring," "pelvic," "groin," and "adductor," and dealt with the factors and symptoms of such injuries. In addition, "nfl" appeared in Topic 19, which is a keyword for the American NFL, and was identified as a topic generated in the process of comparing injuries according to the sport characteristics of American football and soccer.

Research on head-related injuries was also identified. Topic 25 was clustered under the subject keywords "acceleration" and "impact magnitude," which explored acceleration and impact magnitude depending on the head region studied. Topic 42 was clustered under topic keywords related to monitoring impact exposure and measurement based on athlete recall through Headcounter, an athlete self-report questionnaire on headers. Topic 36 was clustered with keywords representing topics that explored differences in bone mineral content and bone mineral density according to demographic characteristics, such as sport and gender, and the types of injuries they cause. Topic 16 consists of keyword clusters representing topics related to myocardium injuries in soccer players.

Topics 3, 26, 28, and 32 consist of topics related to lifestyle and environmental factors that lead to injury. Topics 3 and 28 were clustered with topic keywords that explore the relationship between injury risk, injury-triggering factors, and injury incidence in elite soccer players and school elite players. Topic 26 was clustered with keywords describing topics related to energy expenditure, nutrient intake, and weight control in soccer players and their relationship to performance and injury. Topic 32 was clustered with keywords describing topics related to infiltration for safe and effective turf surface stability, including topics comparing injury rates and player fatigue on natural and artificial turf.

Topic Area-5 was labeled "Sport Medicine-2: Brain Injury" as related to soccer and includes the following Topics. Topic 11 is centered on chronic traumatic encephalopathy in soccer players and is clustered with topic keywords covering dementia, sequelae such as Alzheimer's, and delaying and preventing tau protein through immunization. Topic 43 was clustered under the topic keyword "concussion," which explores the relationship between soccer players' cognitive abilities, history of ADHD, etc.

TABLE 1 Topic modeling results—soccer research before COVID-19.

Topic Area-1 Social Science-1: Psychology, Sociology, and Business	**Topic 7**	**Topic 10**	**Topic 15**	**Topic 24**	**Topic 37**	**Topic 38**	**Topic 41**	**Topic 46**
	Coach	rae	Parents	Psychology	Reference	Mental	Market	Talent
	Leadership	Age	Youth	Motivation	Decision	Health	Value	Develop
	Style	Born	Children	Burnout	Research	Mindmax	Club	Identify
	Team	Player	Sport	Need	Make	Social	League	Football
	Efficacy	Talent	Practice	Climate	var	Men	Foreign	Financial
Topic Area-2 Social Science-2: Psychology and Socialcultral	**Topic 0**	**Topic 8**	**Topic 22**	**Topic 23**	**Topic 29**	–	–	–
	Fan	Market	Women	Club	Fan	–	–	–
	Football	Attend	Gender	Financial	Brand	–	–	–
	Culture	Uncertainty	Sport	Sport	Sponsor	–	–	–
	Article	League	Football	Football	Sponsorship	–	–	–
	Politic	Stadium	Identify	League	Loyalty	–	–	–
Topic Area-3 Sport Science and Technology	**Topic 5**	**Topic 9**	**Topic 12**	**Topic 40**	**Topic 45**	–	–	–
	Goal	Model	Robot	Wind	Technique	–	–	–
	Team	Predict	Algorithm	Stadium	Revenue	–	–	–
	Possess	Network	Propose	Temperature	Import	–	–	–
	Shot	Pass	System	Roof	Match	–	–	–
	Score	Team	Image	Degree	Variable	–	–	–
Topic Area-4 Sport Medicine-1: Injury	**Topic 1**	**Topic 3**	**Topic 16**	**Topic 19**	**Topic 20**	**Topic 25**	**Topic 26**	–
	Knee	Injury	Cardiac	nfl	Groin	Head	Intake	–
	Degree	Incidence	Cardiovascular	Combination	hip	Impact	Nutrition	–
	Strength	Rate	Ventricular	Injury	Pain	Acceler	Energy	–
	Hamstring	Muscle	Myocardi	Tear	Injury	Magnitude	Diet	–
	Muscle	School	Left	Labral	Adductor	Linear	Carbohydrate	–
	Topic 26	**Topic 28**	**Topic 32**	**Topic 36**	**Topic 42**	**Topic 44**	–	–
	Intake	Injury	Turf	Bone	Head	Pelvic	–	–
	Nutrition	Risk	Artificial	bmd	Header	Injury	–	–
	Energy	ci	Surface	bmc	Headcount	Factor	–	–
	Diet	Factor	Infiltration	Female	Exposure	Hamstring	–	–
	Carbohydrate	Season	Nature	Male	Impact	lbp	–	–
Topic Area-5 Sport Medicine-2: Brain Injury	**Topic 11**	**Topic 43**	–	–	–	–	–	–
	Brain	Symptom	–	–	–	–	–	–
	Tau	Cognit	–	–	–	–	–	–
	cte	Concuss	–	–	–	–	–	–
	Traumat	adhd	–	–	–	–	–	–
	Head	History	–	–	–	–	–	–
Topic Area-6 Sport Science-1: Performance	**Topic 17**	**Topic 39**	**Topic 47**	–	–	–	–	–
	Body	Strength	COD	–	–	–	–	–
	Fat	nh	rag	–	–	–	–	–
	Equate	Sprint	fs	–	–	–	–	–
	Composite	Maturity	Test	–	–	–	–	–
	Mass	Jump	Direct	–	–	–	–	–

(Continued)

TABLE 1 (Continued)

Topic Area-7 Sport Science-2: Physiology and Nutrition in Performance	**Topic 4**	**Topic 6**	**Topic 13**	**Topic 21**	**Topic 18**	**Topic 31**	**Topic 34**	**Topic 35**
	Vitamin	hr	Distance	Cortisol	Load	gps	Pitch	Sleep
	Supplement	Heart	Speed	Testosterone	Week	System	Format	Night
	Blood	Min	Match	Salivari	Train	Track	vs	Quality
	Exercise	Rate	Demand	Mood	Workload	gen	Size	nap
	Level	hrv	Accelerate	Sweat	Season	Distance	Distance	Even
Topic Area-8 Sport Science-3: Visual Skill in Performance	**Topic 2**	**Topic 14**	**Topic 27**	**Topic 30**	–	–	–	–
	Jump	Kick	Visual	Creative	–	–	–	–
	Train	Ball	Saccad	Task	–	–	–	–
	Sprint	Foot	Screen	Mental	–	–	–	–
	Group	Velocity	Eye	Control	–	–	–	–
	Improve	Leg	Task	Condition	–	–	–	–

Topic Area-6 was labeled “Sport Science-1: Exercise Performance” as related to soccer. In this Topic Area, Topic 17 was clustered into topic keywords that explored the relationship between soccer performance and complex body composition, such as player weight, body fat percentage, and body mass index (BMI), from various perspectives. Topic 39 was clustered with topic keywords that explored the relationship between maturity and soccer performance from various perspectives, including players' basic physical fitness factors such as strength, jump, and sprint. Topic 47 was clustered with keywords that addressed topics related to soccer players' athletic performance, such as change of direction (COD) and reactive agility.

Topic Area-7 was labeled “Sport Science-2: Biology & Performance & Nutrition” and includes the following Topics. Topic 4 was clustered with keywords related to nutrition and performance, including nutritional intake, eating habits, and blood measurements for validation. Topic 6 was clustered with keywords representing research related to the role of the heart, such as heart rate and cardiac output in athletes' performance during competition and training. Topic 13 was clustered with keywords representing the demands of athletic performance for effective performance in a match, such as distance, speed, and acceleration. Topic 18 was clustered with keywords that explored the relationship between an athlete's training load during the season and their performance. Topic 21 was clustered into topics that explored biological studies such as sweat production, cortisol and testosterone secretion, and mood during athletic performance such as competition and training. Topic 31 is clustered with keywords that refer to performance measurement research topics using digital devices such as GPS, such as distance markers and player tracking, which are used to measure performance in athletic and training situations. Topic 34 is clustered with keywords that explore the performance and physiological responses of youth or adult players to soccer field dimensions, such as exercise volume and exercise characteristics. Topic 35 was clustered with keywords related to analyzing sleep habits such as insomnia in soccer players or exploring the effects of interventions such as effective sleep and NAP to improve performance.

Topic Area-8 was labeled “Sport Science-3: Visual Skill in Performance.” In this Topic Area, Topic 30 was clustered under the following research topic keywords: “cognitive control,” “cognitive state,” and “psyche in soccer-specific creative expression.” Topic 27 was clustered under the topic keywords exploring the level of soccer players' saccade eye movements and its relevance to tasks and performance in different settings and interventions. Topic 14 was clustered under topic keywords related to factors that contribute to an effective kick, such as kick speed, angular velocity, and foot (right or left) use. Topic 2 was clustered under research keywords related to jump training interventions for various performance enhancements, including sprinting, one of the most important motor skills in soccer. The pre-COVID (2018–2020) Topic Areas and Topics are shown in Table 1.

4.2. Soccer research trends: 2021–2022

The soccer research Topic Areas for the period during the COVID-19 pandemic (2021–2022) and each Topic's keyword organization are as follows, and the topic modeling results for soccer research from this period are shown in Table 2.

Topic Area-1 is a soccer-related domain named “Social Sciences-1: Business & Sociology with Covid-19” and includes the following Topics. Topic 1 is clustered with research topic keywords related to Corporate Social Responsibility (CSR) and Customer Relationship Management (CRM), which are common in the sports business field. Topic 8 clustered together topics related to player transfers in European soccer leagues and exploring league and club financial factors. Topic 31 was clustered under the keyword “socio-business,” which refers to soccer club branding; franchise culture, such as fan and club communication; and socio-business research that explores the social identity of clubs for business and, in the process, community club activities and fan identities. Topic 37 is clustered under the keyword “socio-business,” which refers to studies exploring the effects of home advantage, focusing on unattended professional soccer matches in the context of COVID-19. Topic 0 was clustered with topic keywords that explored the socio-scientific factors affecting performance from various perspectives, including match-play analyses of players during matches.

Topic Area-2 was labeled “Social Science-2: Psychology & Sociocultural with COVID-19” as related to soccer and includes the following Topics. Topic 23 was clustered into keywords that represented general psychological research topics such as soccer players' perfectionism, self-efficacy, and coping strategies for various negative psychological factors. Topic 3 was clustered under keywords

TABLE 2 Topic modeling results—soccer research during COVID-19.

Topic Area-1 Social Science-1: Business and Sociology	**Topic 0**	**Topic 8**	**Topic 1**	**Topic 31**	**Topic 37**	–	–	–
	Team	Club	Social	Club	Home	–	–	–
	Match	Transfer	crm	Brand	Advantage	–	–	–
	Play	Financial	Intern	Vote	Crowd	–	–	–
	Pass	Market	csr	Climate	Covid	–	–	–
	Game	European	Response	Fan	ha	–	–	–
Topic Area-2 Social Science-2: Psychology and Socialcultral	**Topic 3**	**Topic 5**	**Topic 9**	**Topic 11**	**Topic 14**	**Topic 23**	**Topic 28**	**Topic 38**
	Coach	Politic	Cognitive	Fan	Women	Self	Mental	Fan
	Leadership	Nation	Visual	Fandom	Gender	Psychology	Anxiety	Sexual
	Parent	Identity	Task	Media	Men	Perfection	Health	Homosexual
	Question	Culture	Skill	Social	Coverage	Efficacy	Depress	Men
	Education	Media	Eye	Club	Nation	Cope	Covid	Masculine
Topic Area-3 Sport Science and Technology	**Topic 15**	**Topic 17**	–	–	–	–	–	–
	Video	Robot	–	–	–	–	–	–
	Track	Learn	–	–	–	–	–	–
	Detect	Agent	–	–	–	–	–	–
	AI	Humanoid	–	–	–	–	–	–
	Target	Algorithm	–	–	–	–	–	–
Topic Area-4 Sport Medicine-1: Lower Limb Injury	**Topic 3**	**Topic 26**	**Topic 47**	–	–	–	–	–
	algorithm	cai	groin	–	–	–	–	–
	Strength	Ankle	Pain	–	–	–	–	–
	Torque	Land	hip	–	–	–	–	–
	Flexor	Balance	hago	–	–	–	–	–
	Limb	Group	Subscale	–	–	–	–	–
Topic Area-5 Sport Medicine and Science-1	**Topic 20**	**Topic 21**	**Topic 24**	**Topic 30**	**Topic 44**	–	–	–
	Nutrit	Infect	Lockdown	Cardiac	Menstrual	–	–	–
	Intake	Sars	Covid	ecg	Cycle	–	–	–
	Dietari	cov	Period	lv	Breastfeed	–	–	–
	Knowledge	Covid	Pandemic	Ventricular	hc	–	–	–
	Energy	pcr	Confidence	Coronaria	Hold	–	–	–
Topic Area-6 Sport Medicine and Science-2	**Topic 4**	**Topic 6**	**Topic 10**	**Topic 12**	**Topic 22**	**Topic 27**	**Topic 29**	**Topic 34**
	Jump	Supplement	Starter	aerob	ssg	Sleep	Load	Neuromuscular
	Sprint	Vitamin	Season	Test	ssgs	Quality	Train	Response
	Train	Blood	Week	fit	Sprint	Night	srpe	Matur
	Performance	Acid	md	vo	Side	Duate	External	Train
	Group	Metabolism	Load	Oxygen	Train	Insomnias	Session	Post
	Topic 36	**Topic 39**	**Topic 41**	**Topic 42**	**Topic 45**	**Topic 46**	**Topic 49**	**Topic 51**
	Week	Kick	Cortisol	gps	Bone	Goalkeep	Match	Stretch
	Load	Ball	Recovery	Track	bmd	Penalty	Peak	Soleus
	Workload	Foot	Hormone	Reliability	Miner	Kick	Distance	Strength
	Injury	Velocity	ck	Polar	Density	Shot	ft	Squat
	Chronic	Pelvis	cwi	Distance	Age	Kicker	Demand	Square

(Continued)

TABLE 2 (Continued)

Topic Area-7 Sport Medicine-3: Injury	**Topic 1**	**Topic 2**	**Topic 19**	**Topic 25**	**Topic 32**	**Topic 43**	–	–
	Head	Injury	mri	acl	Turf	Program	–	–
	Impact	Incident	Image	Reconstruct	Grass	Injury	–	–
	Exposure	Season	Injury	Injury	Artificial	Prevent	–	–
	Brain	rtp	Patient	Knee	Rubber	Hamstring	–	–
	Concuss	Play	Lesion	Ligament	Nature	Intervention	–	–
Topic Area-8 Sport Science: Performance	**Topic 13**	**Topic 16**	–	–	–	–	–	–
	rae	Anthropometric	–	–	–	–	–	–
	Agent	Age	–	–	–	–	–	–
	Talent	Maturity	–	–	–	–	–	–
	Maturity	Test	–	–	–	–	–	–
	Select	Sprint	–	–	–	–	–	–

of research topics that explored coach leadership, parenting styles, and educational environments as they impact soccer player development. Topic 28 was clustered with keywords representing studies that explored specific causal relationships between mental health issues experienced by soccer players during COVID-19, such as anxiety and depression. Topic 38 was clustered under the keyword "sociological issues in soccer related to sex and gender," including gender roles in men's and women's soccer, LGBTQ fan attitudes and their impact on professional soccer as a whole, and LGBTQ players. Topic 14 was clustered under the keyword "sociological issues in soccer," referring to topics on issues related to discrimination against female athletes in sports from a sociological perspective, using women's soccer as a case study. Topic 11 was clustered under the keywords "social media" and "social communities" and keywords that related to other social activity opportunities for clubs to build and maintain a fanbase, as well as methods and effects of club–fan interactions. Topic 5 was clustered under the keyword "political and social issues," including national branding through soccer, the media's role in image-making, and soccer fans' national identity. Topic 9 was identical to one of the topics in the "Sport Science-3: Visual Skill" Topic Area from the pre-COVID-19 period. This can be attributed to the inclusion of the psychology keyword "cognitive" in this Topic Area, as the "Sport Science-3: Visual Skill" Topic Area was not formed in the COVID-19 period.

Topic Area-3 was renamed to the soccer-related domain "Sport Science & Technology." Topic 15 was clustered under the research topic keywords related to the development and validation of artificial intelligence (AI) algorithms for automatically tracking player movements from soccer videos. Topic 17 shows a similar keyword cluster to Topic 12 in the pre-COVID-19 period and was clustered with topic keywords related to enhancing humanoid functions through machine learning for AI soccer robots.

Topic Area-4 was labeled "Sport Medicine-1: Lower Limb Injury-1," a topic similar to Lower Limb Injury in Topic Area-4 ("Sport Medicine-1: - Injury") from the pre-COVID-19 period. Topic 47 was clustered with keywords of research topics related to athlete thresholds for minimizing lower extremity injuries through hip and hip outcome scores. Topic 26 clustered keywords for topics that explored the relationship between chronic ankle instability, which has various causes such as playing soccer and landing after jumps during training. Topic 7 was clustered with topic keywords that explored the relationship between the level of knee muscle extension and injury in soccer players, applying various subjects and external factors.

Topic Area-5 was labeled "Sport Medicine & Science-1" related to soccer and includes the following Topics. Topic 44 was clustered with keywords that explored the physiological phenomena of female soccer players, such as hormonal contraception, pregnancy, menstruation, and breastfeeding, and factors related to athletic activities, such as performance and injury. Topic 20 was clustered with keywords describing topics related to energy expenditure, nutritional intake, and weight control in soccer players, similar to Topic 26 in the pre-COVID-19 period, as well as performance and injury. Topics 21 and 24 can be seen as clusters of topics that address the impact on various soccer stakeholders arising from the fear of infection due to COVID-19 and the medical issues of lockdown. Topic 30 consists of a cluster of keywords describing topics related to myocardium injuries in soccer players, similar to Topic 16 in the pre-COVID-19 period.

Topic Area-6 is soccer-related, and the domain is named "Sport Medicine & Science-2." Because this Topic Area includes many topics, it was divided into subtopic areas. Topics 6, 12, and 41 have subtopic domains named "Sport Medicine-3: Biology & Nutrition in Performance." Topic 6 was similar to Topic 4 in the pre-COVID-19 period and was clustered with nutrition and performance-related keywords, including nutrition as a factor in athletic performance, the relationship between diet and immunity, and blood measurements for validation. Topic 12 was clustered with research topics that explored the relationship between physiological measures of aerobic fitness levels and performance ability. Topic 41 was clustered under the keyword "measurement and validation," which refers to research on hormones, including cortisol, and serum tests for creatine kinase to explore the effects of cold-water immersion on soccer players' recovery process.

In addition, Topics 27, 39, 42, 46, and 49 include a subtopic domain named "Sport Science-1: Exercise Performance." In the pre-COVID-19 period, these domains were categorized as independent Topic Areas, but during the COVID-19 period, they were included in Topic Area 6. Topic 27 was clustered with research keywords that explored the relationship between sleep quality and training, performance, and injury in soccer players. Topic 39 was similar to Topic 14 in the pre-COVID-19 period; it clustered topic keywords related to factors that contribute to effective kicking, such as kick speed, angular velocity, and the use of the (right or left) foot. Topic 42 was similar to Topic 31 in the pre-COVID-19 period and clustered around keywords such as "GPS" and "Polar," which are used as distance markers and measuring instruments in performance research in athletic and training situations. Topic 46 was clustered with research topics that explore goalkeepers' behavioral characteristics in match situations, either throughout the match or in special situations such as penalty kicks. Topic 49 was similar to Topic 13 in the pre-COVID-19 period and was clustered with keywords that represent the athletic demands of effective performance on the field, such as distance traveled, maximum velocity, and acceleration.

Topics 4, 10, 22, 29, 34, 36, and 51 include a subtopic domain named "Sport Science-2: Performance Training." Topic 4 was similar to Topic 2 in the pre-COVID-19 period and was clustered with research keywords related to jump training interventions for various performance enhancements, including sprinting, which is one of the most important motor skills in soccer. Topic 10 was similar to the pre-COVID-19 period (2018–2020), clustered with keywords that refer to topics related to players' training load and performance in and out of season. Topic 22 was clustered with keywords for research exploring the relationship between small-sided games (SSG), a soccer training method, and player performance. Topic 29 was clustered with keywords for research topics that explore the relationship between external loading and athlete session ratings of perceived exertion during training in an attempt to determine effective training volume and training strategies. Topic 34 was clustered under the topic keywords exploring the relationship between training and various maturation and developmental factors, such as neuromuscular and respiratory factors, in athletes. Topic 51 was clustered with topic keywords that explored stretching methods, intensities, methods (squats, etc.), postures, and areas (soleus) for effective lower extremity training.

Topics 36 and 45 included a subtopic domain named "Sport Medicine-4: Injury-2." Topic 36 was similar to Topic 18 in the pre-COVID-19 period. However, the word "season" was removed and clustered with a slightly different keyword composition, specifically, with topics that explored the relationship between training load and injury, such as "chronic" and "Injury." Topic 45 also appeared to be similar to Topic 36 in the pre-COVID-19 period; it was clustered with keywords representing topics that explored differences in bone mineral content and bone mineral density according to demographic characteristics such as sport and gender, as well as types of injuries.

Topics 1, 2, 19, 25, 32, and 43 were included in the topic domain "Sport Medicine-5: Injury-3." Topic 1 appeared similar to the head and brain injury topics in the pre-COVID-19 period but was implied as a single topic. Topic 1 was clustered with topic keywords covering injuries such as concussions due to impact exposure when heading. Topic 2 was clustered with keywords describing two topics, one related to the performance of athletes returning from injury and the other related to the performance of athletes returning after COVID-19. Topic 19 was clustered with keywords describing topics related to the careful measurement and diagnosis of an athlete's injury using MRI images to verify a precise causal relationship with symptoms. Topic 25 was clustered with keywords describing different research approaches to repetitive injuries to the same and surrounding areas after anterior cruciate ligament reconstruction. Topic 32 had the same number as Topic 32 in the pre-COVID-19 period and was clustered under the keyword "infiltration for safe and effective turf surface stability," with topics comparing injury rates and player fatigue on natural and artificial turf. Topic 43 was clustered under the keyword "research," which refers to topics that validated various interventions for the recovery and prevention of hamstring injuries.

Topic Area-8 was labeled "Sport Science-3: Exercise Performance-2." Topic 13 was clustered under the keyword "relative age effect" (REA), which refers to various research topics approaching REA from a performance perspective. Topic 16 appeared to be similar to Topic 39 in the pre-COVID-19 period and was clustered under the keyword "maturity," which refers to a variety of research topics that explored the relationship between maturity and soccer performance, including anthropometrics, demographic characteristics such as age, and athletic performance such as running. The Topic Areas and Topics from the period during the COVID-19 pandemic (2021–2022) are shown in Table 2.

4.3. Visualization

Visualization was also conducted to ensure that well-defined clusters with interpretable topics were acquired. An intertopic distance map is a visualization technique that shows the similarity between topics represented as the distance between each topic. A topic is a node, and the set between nodes is organized as a topic area. Topics that resulted in similar topic areas overlapped.

Despite the variations in location across the quadrants, the social science topic areas were located close together. The sports science and sports medicine topic areas were also located close to each other, although there was a shift in position in the quadrant. However, during COVID-19, Topic Area-4 was clustered with keywords focusing on movement-related factors associated with lower extremity injuries, which may have distanced it from the sports science and sports medicine areas, including Topic Area-6. While the pre-COVID-19 period is characterized by a clustering of injury-related topics, the period during the COVID-19 pandemic is characterized by an overlap of performance-related topics and a scattering of injury-related topics. Insights into visual changes are derived in the Discussion section.

In addition, we utilized hierarchical clustering, a technique in topic modeling to visualize the hierarchical structure of topics, to analyze the topics between 2018–2020 and 2021–2022. We also used a ward-linkage function to perform hierarchical clustering based on the cosine distance matrix between topic embeddings (Ward, 1963). Figure 2 enables us to gain insights into the relationships between topics and identify clusters of related topics. By examining the clusters and their relationships, we can better understand the underlying themes and patterns present in the data. Overall, Figure 3 shows the effectiveness of hierarchical clustering in topic modeling analysis. These findings provide valuable insights for researchers and practitioners in the field and contribute to the growing body of knowledge around topic modeling.

In addition to the hierarchical clustering, we also utilized a heatmap visualization technique to gain further insights into the similarities between the topics in our paper. A heatmap based on the cosine similarity matrix between topic embeddings was created to show the similarities between topics. Figure 4 provides a clear and intuitive visualization of the relationships between the topics, with darker shades indicating a higher degree of similarity. By examining the heatmap, we were able to identify clusters of similar topics and gain a deeper understanding of the underlying themes and patterns present in the data.

Furthermore, we were able to visually confirm both strong and weak similarities between topics by reviewing and analyzing the heatmap visualization results, which provided valuable insights into the relationships between them. The resulting visualization enabled us to gain a deeper understanding of the underlying patterns and themes present in the data and provided a useful framework for further analysis and interpretation of our results.

5. Discussion

5.1. Social sciences in soccer

The topic clusters and topic areas established in this study demonstrate the close relationship between the social sciences, sports science, and sports medicine in soccer. Topic areas and topics were separated or merged over time, and keywords were changed, too. Nevertheless, we derived insights by keeping the connections between complex and interrelated topics as tight as possible.

5.1.1. Psychology

In terms of general factors, we found that the research on the psychology of soccer exhibited similar prominent thematic keywords both before and during the COVID-19 pandemic. “Self-efficacy,” “coach leadership,” and “relationship with parents” were common in both periods (Teques et al., 2019; Hong and Jeong, 2020; Schatz et al., 2020; Maurice et al., 2021; Eckardt et al., 2022). During the COVID-19 pandemic, the keywords “motivation” and “burnout” became less prominent, suggesting that they became less salient as pandemic-related research became more important.

Interestingly, the process of exploring positive and negative factors related to mental health was also common in both periods but changed between them. In the pre-COVID-19 period, multiple studies were found that investigated soccer players’ mental health or tested its causal relationship with various intervention variables, including the digital environment, and applied soccer interventions for people with mental health problems (Abbott et al., 2019; Kunrath et al., 2020; Thompson et al., 2020). During the COVID-19 pandemic, a large proportion of the research was inductive, exploring the mental health issues experienced by players in the context of the various restrictions imposed as a result of the pandemic (Jordana et al., 2022; Zhao et al., 2022), suggesting a difference in approach to mental health compared to the pre-pandemic period.

Additionally, studies from the pre-COVID-19 period on soccer players’ visual skills were categorized as “performance” (Song et al., 2019; Bekris et al., 2020). However, during the COVID-19 pandemic, the Topic Area “Performance-Visual Skill” disappeared, and cognitive keywords that are important in visual-skill research emerged, which could be interpreted as a topic area in the field of psychology (Casella et al., 2022; Knollner et al., 2022). Soccer players’ psychological state can be attributed to both self-influences and external/environmental factors (Schinke et al., 2018). Therefore, it is expected that researchers will continue to publish results on the psychological issues experienced by soccer players in the current COVID-19 pandemic situation. In addition, the new phase of soccer players’ experience in the post-COVID-19 environment will be an important issue that may continue to be explored in the field of psychology.

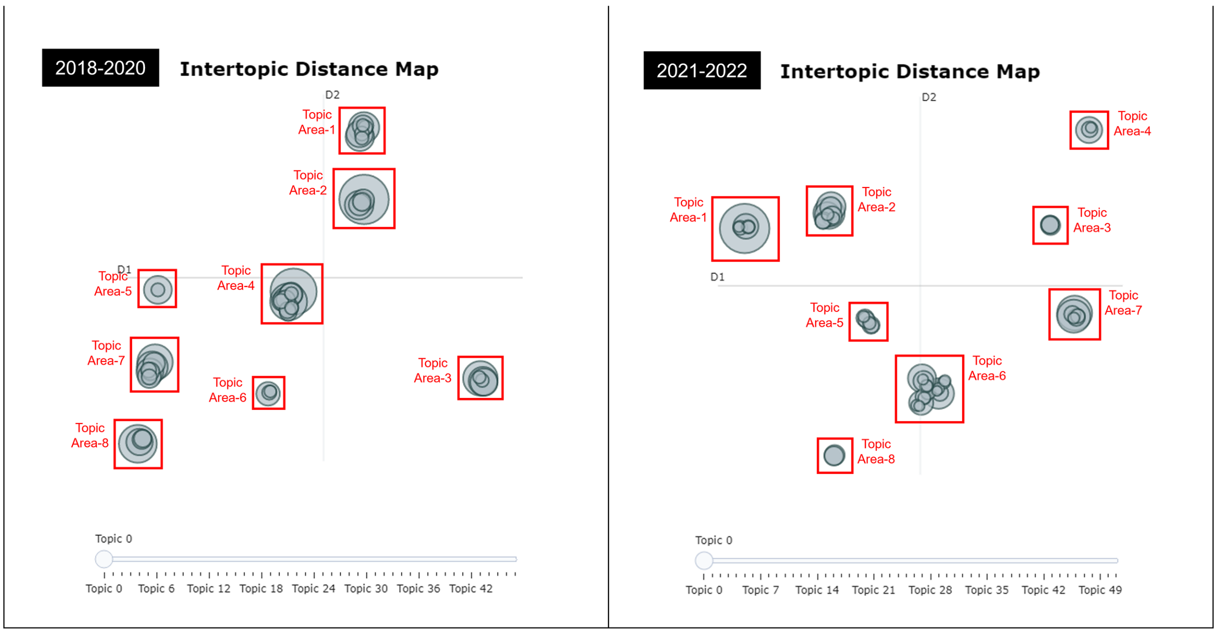

FIGURE 2
Intertopic distance map of soccer research before and during COVID-19.

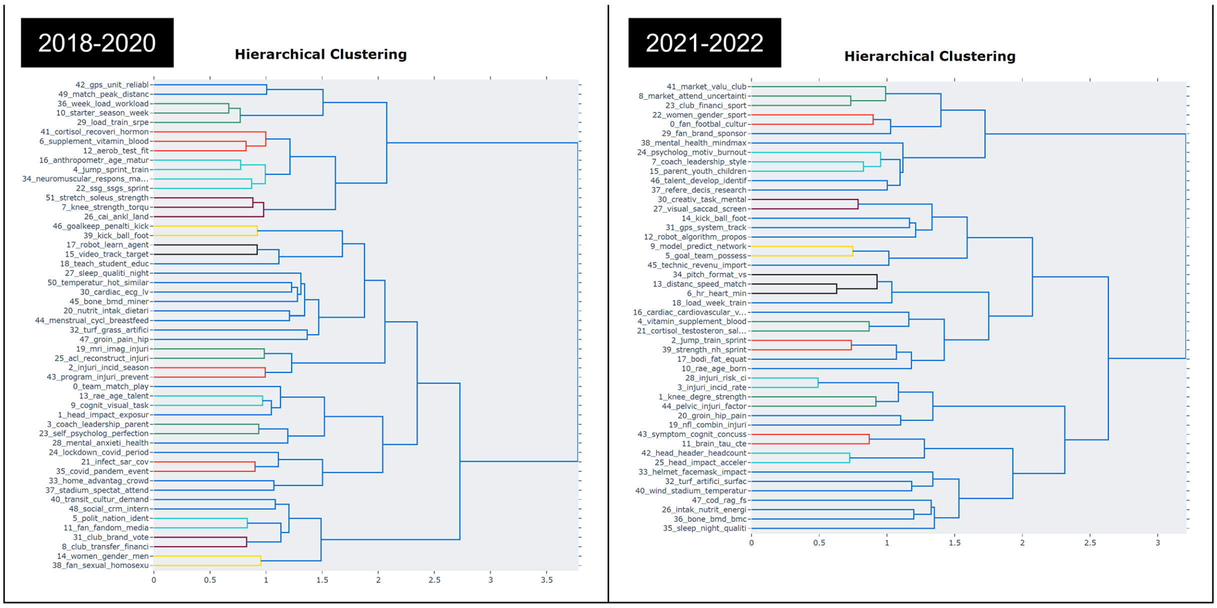

FIGURE 3
Hierarchical clustering of soccer research before and during COVID-19.

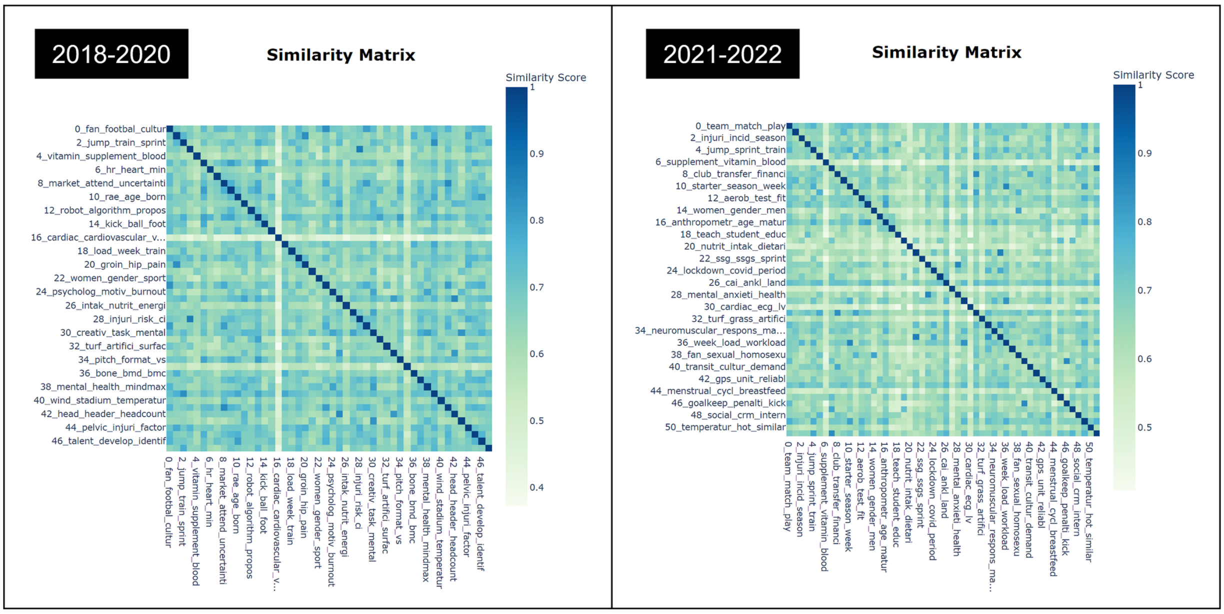

FIGURE 4
Similarity matrix of soccer research before and during COVID-19.

5.1.2. Sociology

The sociological study of soccer was discovered to be more interdisciplinary than general sociological research, with a variety of topic meanings and keywords that were similar in both time periods studied. Nevertheless, soccer studies that addressed sex and gender, such as the perceptions and gender roles of female soccer players and the attitudes and impact of LGBTQ fans, were identified in both periods (Petty and Pope, 2019; Bevan et al., 2021; Kossakowski and Besta, 2022; Mikkonen, 2022). In addition, studies exploring fans' political behaviors, attitudes, projected national identities, and ideologies in relation to soccer were also deeply sociological (Tamir, 2019; Baltas, 2021; Oonk, 2021; Webber, 2022) and have been noted as thematic issues across both periods.

Although the keywords organized in each topic vary by time period, there were many sociological studies centered on fan culture. In the pre-COVID-19 period, keywords such as "ideology" and "politics" were used to identify fans' sociocultural behavioral characteristics (Smith and Lord, 2018; Papadima and Photiadis, 2019). During the COVID-19 pandemic, fan-focused sociological research topics expanded compared to the pre-COVID-19 period.

Indeed, the establishment of club–fan relationships and identities conveyed to fans through social activities and promotions, online interactions, community club activities, etc., can be studied, and such studies can be characterized as sociological research toward the ultimate goal of a viable and successful business approach that includes the branding of football clubs (Calabuig et al., 2021; Mora et al., 2021; Weber et al., 2022; Brand et al., 2023; Fenton et al., 2023). In fact, Calloway et al. (2019) and Radmann and Karlen (2022) reported that the most important aspect to consider in a catastrophic crisis such as lockdowns and reduced league operations due to COVID-19 is the relationship with fans. This need was predicted to be the cause of the fan-centered sociological studies conducted during the pandemic.

On the other hand, research topics emerged that could be approached in the unique context of the COVID-19 pandemic. For example, the scholarly soccer literature explored whether there was still a significant home-advantage effect in soccer matches played away from home during the pandemic (McCarrick et al., 2021; Lee et al., 2022). Through this topic, future research directions can be anticipated as areas where comparative approaches can be made considering the current post-COVID-19 situation. Overall, similar to psychology, future research will continue to focus on the social relationships that clubs need to consider with their fans as they largely return to pre-COVID-19 conditions (Lawrence and Crawford, 2022). In addition, it will be interesting to see how the new context and paradigm of the pandemic generate novel research ideas in the areas of gender, sexuality, and ideology.

5.1.3. Business

Business research in soccer changed significantly during the pandemic compared to before it. Only the topic keyword cluster related to determinants of the market value of professional soccer clubs was similar in both periods (Kalen et al., 2019; Kirschstein and Liebscher, 2019; Wheatcroft, 2020; Gyimesi and Kehl, 2021). We found two related topics in the pre-COVID-19 period and one during the pandemic period. Timely research topic keywords exploring changes in key market value determinants, such as economic issues for clubs due to lockdowns, league reductions, and fan management, were also found in the pre-COVID-19 period (Herold et al., 2021; Quansah et al., 2021). In other words, active research approaches and practices are evident in both periods, as factors affecting market value and strategies to address them must continue to evolve in response to the changing environment.

In the pre-COVID-19 period, several business-focused keywords related to soccer were found in the topics. Research topics inferred from keywords such as "spectator attendance determinants," "brand image," "sponsorship," and "loyalty" are typical of business research and are expected to continue being explored in the post-COVID-19 era, just as they were in the pre-COVID-19 era (Wang et al., 2018; Gyimesi, 2020; Pradhan et al., 2020; Valenti et al., 2020; Skinner and Smith, 2021). During the COVID-19 pandemic, many of the typical business-related keywords that were common in the pre-COVID-19 period disappeared. In addition, there were fewer keywords and topic clusters that can be identified as distinct business research topics compared to before the pandemic. The only business-related topics we found consisted of keywords related to CSR and CRM strategies, which are highly relevant to the socio-business research covered in the Sociology section (Fiadotava, 2021; Radmann and Karlen, 2022).

In fact, it could be inferred from the topic modeling results that soccer business research during the COVID-19 pandemic assumed a relational approach to preventing the loss of fans, which loss was predicted to be catastrophic due to the physical void caused by COVID-19. During the pandemic, soccer businesses tried to maintain and rebuild relationships with fans as potential consumers to prevent catastrophic losses due to physical voids such as lockdowns, unattended games, and shrinking consumption (Brand et al., 2023; Fenton et al., 2023). The topic keywords and clusters suggest that many strategies for fostering social relationships to overcome this crisis have been attempted in the interdisciplinary research of socio-business.

Furthermore, the topic modeling results demonstrate that the keyword clusters generally differ between both periods. The change in keyword clusters does not imply a change in research topics but rather a difference in the amount of research that was actively conducted at different times. The keyword clusters and topics found in both periods are those that have been studied in the soccer business field from the past to the present. Lee et al. (2022) reported that new business paradigms are emerging in the field to cope with the economic crisis of sporting organizations that have experienced fractured player–club and fan relationships and near bankruptcy. These new strategies and efforts to overcome the crisis will have their own set of failures and successes, and the role of football business research in this process needs to be explored specifically.

5.2. Sports science and sports medicine in soccer

5.2.1. Technology

Technology research in soccer was divided into independent Topic Areas in both periods. In the pre-COVID-19 period, various types of research were conducted. Research on soccer match analysis has been ongoing since the late 1990s when the importance of match analysis was raised, for example, regarding the development and application of technology for more sophisticated analysis or proposing analysis results from different perspectives using recorded items utilized for specific match analysis factors (Delibas et al., 2019; Stein et al., 2019; Wu et al., 2019; Sheng et al., 2021). In addition, research related to stadium construction based on construction engineering to overcome environmental factors was a topic that confirms the scope of science and technology in soccer (Llarena et al., 2018; Bonser et al., 2020). During the COVID-19 pandemic, the clusters in the topic area were reduced, and only one topic was clustered with keywords that had different meanings than before the pandemic. The only independent cluster of keywords in the technology topic area during the pandemic was found in the soccer area that discussed advanced AI movement-tracking technology (Jin, 2022; Zou et al., 2022).

Similarly, we found studies from both periods regarding the development of individual technologies such as image processing and humanoids to improve the AI performance of soccer robots (Bai et al., 2020; Hu et al., 2021; Janos et al., 2022). The soccer robot is more of a source technology for maximizing robot and AI technology than a technology applied to the actual soccer field (Park et al., 1997; Samani et al., 2004). However, although the active participation in and performance of technology research may appear somewhat reduced during the COVID-19 period, the level of technology for collecting and analyzing game data (numbers, images, videos, etc.) was actually growing rapidly (Almulla et al., 2020; Kelly et al., 2020). Considering past experiences when humanity has developed science and technology to overcome crises, Garfin (2020) predicted that the pandemic period would also see remarkable changes. Therefore, it is expected that AI, robotics, immersive virtual technology, metaverse, blockchain, and all-encompassing WEB 3.0 technologies will be applied to the field of soccer in the process of turning the current crisis into an opportunity (Hotaran et al., 2022; Lorabi, 2022; Nobari et al., 2022). In this process, soccer technology research will continue to be an independent field of study.

5.2.2. Soccer performance

In soccer, as in all sports disciplines, the search for new processes to improve player performance has been the focus of many experts and researchers. Research on soccer player performance has been actively conducted in soccer research, including exploring various determinants of performance ability and seeking effective interventions (Forcher et al., 2022). In other words, we found soccer performance keywords and topics about improving the measurement and ability of individual physical and athletic performance factors to be the most extensive, forming large and small clusters (Modric et al., 2019; Altmann et al., 2021; Maciejczyk et al., 2021).

For example, soccer performance research in the pre-COVID-19 period explored the relationship between performance-determining factors such as BMI and athletic performance related to sprinting (e.g., distance, speed, and acceleration) and soccer performance in actual matches (Rivilla-Garcia et al., 2019; Maciejczyk et al., 2021; Fernandez-Galvan et al., 2022). In addition to physical factors, performance factors focused on athleticism such as change of direction (COD) and reactive agility were explored (Little and Williams, 2005; Haugen et al., 2014; Carling et al., 2015). Furthermore, performance studies focused on cardiovascular aspects such as heart rate and cardiac output in match and training situations, while psycho-physiological studies measured the association between hormonal and psychological states during athletic performance (Buchheit et al., 2012; Faina et al., 2013). On the other hand, factors directly linked to winning on the field have undeniably been central to soccer performance research, with keyword clusters exploring the relationship between individual performance and the kinesiology expected of soccer performance, including motor behavior (Pain and Harwood, 2007; Abdullah et al., 2016; Williams, 2020).

Regarding the period during the COVID-19 pandemic, we found several similar types of studies to those published before the pandemic. Except for studies exploring goalkeeper behavioral traits and soccer players' sleep quality, habits, and performance, performance studies focusing on kicking and measurements via GPS had mostly similar keyword compositions (Goes et al., 2021; Oliva-Lozano et al., 2021; Pons et al., 2021; Keemss et al., 2022; Vu et al., 2022). However, a more detailed observation suggests that soccer performance studies related to athleticism and physical level, which require direct performance measurement, decreased from the clusters and keyword compositions. It is difficult to conclude that these studies have disappeared by monitoring only the topic composition. However, the environment of changed lockdowns and league schedules, not having spectators, etc., during the COVID-19 pandemic inevitably made it difficult to measure or develop the physical and athletic performance factors that most closely relate to the actual game (Sekulic et al., 2021; Radziminski et al., 2022).

Nevertheless, the relationship between diet and performance and approaches to talent discovery and skill development in elite soccer players has been a consistent theme throughout the years (Braun et al., 2018; Ksiazek et al., 2020; Carter et al., 2021; McGuire et al., 2023). During the COVID-19 pandemic, the relationship between the maturation of basic fitness and athletic performance indices and soccer performance was studied from a variety of perspectives, which could be inferred to be driven by the field and the academic need to identify and develop talented players for team development despite the chaotic environment.

5.2.3. Performance training

Performance training topics that emerged during the COVID-19 pandemic included jump training effectiveness studies validating improvements in various performance components, the link between stretching and performance, and training-induced improvements in muscular and aerobic capacity, as well as several interventions that are specific to improving performance (Bishop et al., 2021a, b; Huang et al., 2022; Nunez et al., 2022; Parpa and Michaelides, 2022). The small-sided game (SSG), the closest simulation to soccer practice, and the concept of session ratings of perceived exertion to reduce the difference between a player's perceived load and physiologically measured load are more direct efforts to create effective training volume and training strategies (Dello Iacono et al., 2021). Research topics on minimizing overload and planning effective training processes for peak performance during the season are similar to those in the area of soccer performance in the pre-COVID-19 period.

All competitive sports require planned, controlled training to achieve high performance and improve team competitiveness (Mujika, 2017). Soccer is no exception, and many studies have proposed and validated proactive training programs (Randers et al., 2010). However, among the pre-COVID-19 topics, it is difficult to find a clear identity for the keyword "training" or a training area, because soccer performance and performance training were not separated into distinct topic areas and clusters. Similarly, in training sessions that require different physical abilities, there is a lot of overlap in concepts as researchers try to review a player's athleticism, tactical understanding, physical development, etc., and compare them to actual competitive matches (Altmann et al., 2021; Teixeira et al., 2021). Therefore, it could be interpreted that the concepts were extracted as the same word in the NLP process, leading to the sharing of keywords between soccer performance and performance training. However, training is strictly differentiated from a match because it is based on a rational and controlled environment intended to uniformly equip a player with various performance factors (Fuller et al., 2006).

The reduced opportunities for actual matches due to lockdowns and the reduction in matches during the pandemic suggest that performance training in soccer has become relatively more prominent as an external factor. During the COVID-19 pandemic, many football organizations had to be adaptable and flexible in the way they trained their players (Bisciotti et al., 2020). In a strange, high-risk environment, players and coaches have had to be proactive in adapting training programs and schedules to changing restrictions and guidelines, and in some cases, switching to training that can deliver maximum impact in a short time (Jukic et al., 2020). In this process, many of the concerns of coaches and athletes would have been inevitably projected onto research, and some of these research attempts have emerged as topic areas.

However, no keywords were found to recognize the application of remote training methods and their underlying technologies, including virtual reality, AI, and wearables, which were used to a large extent during the pandemic. The time required to develop new approaches to respond to extraordinary change, including how long it takes for technologies to be fielded and studied and results to be interpreted, applied, and published, makes us hopeful for creative research trends in the future. In addition, new research topics that can be explored include the comparison of face-to-face training, as identified in this study, with newly published, technology-based training programs and the effectiveness of hybrid training programs that incorporate both elements.

5.2.4. Injury: lower limb

Two injury-related topics emerged in the pre-COVID-19 period, consisting of keywords for specific injury sites in the lower extremities and factors that lead to injury. In soccer research on injuries in general, lower limb injuries have the highest prevalence (Zuke et al., 2018; Al Attar and Alshehri, 2019), but the pre-COVID-19 topics regarding the head, brain, and other body parts were clustered within various topic areas, and the lower limbs are no exception. In this regard, the most common on-field injury for male professional players is a hamstring tear; for female players, it is the knee, which has received considerably less academic attention than other injuries (DeLang et al., 2019; Baroni et al., 2020; Owoeye et al., 2020).

However, during the COVID-19 pandemic, lower-injury research has seen an increase in topics and a more granular focus, including studies of specific injury triggers and interventions for recovery. The injury sites studied were the hip, pelvis, hamstring, ankle, and knee, and the research covered a variety of topics, including injury triggers, repetitive injuries to the same site, injury prevention, and rehabilitation (Fernandez-Baeza et al., 2022; Flore et al., 2022; Mendez-Villanueva et al., 2022; Mohammad and Elsais, 2022; Roughead et al., 2022).

Several reasons have been speculated for the change in research topics related to head and lower extremity injuries during COVID-19 as opposed to pre-COVID-19. Shibukawa and Hoshikawa (2022) limited their study to the Japanese soccer league but demonstrated that heading injuries decreased after the implementation of the revised FIFA rules in 2019. In addition, coaches have been issuing instructions in training to discourage heading (Muller and Zentgraf, 2021; Waring et al., 2022). On the other hand, studies of soccer injuries during the pandemic did not report a change in overall injury rates, but there were reports of an increase in lower limb injuries, including hamstrings, in professional matches that resumed after the lockdown period because players were not ready to play (Orhant et al., 2021; Seshadri et al., 2021; Thron et al., 2021; Mazza et al., 2022; Thron et al., 2022).

It could be assumed that there would inevitably be more training situations than matches during the pandemic and that research based on training environments would be more active. Even in pre-COVID-19 practical match situations, dynamic headers that could cause injury were discouraged to the extent that regulations were implemented to minimize head injuries (Yang and Baugh, 2016; Quintero et al., 2020), and during the lockdowns, more training situations were experienced than games (Bisciotti et al., 2020; Washif et al., 2023). In training, a player rarely makes the same headers as they would in a real game, but they still must work their lower extremities. Small-sided games, one of the soccer training methods, include smaller-than-standard goals, so there are relatively fewer dangerous contacts, especially headers, that often occur in real matches, and some small-sided games even restrict header play (Owen et al., 2014).

These different causes may have contributed to the increased representation of lower limb injury research in the topic modeling results over time. More importantly, however, the problem of functional decline and injury in the lower extremities due to reduced training and playing opportunities has been reported in much of the current research on lower extremity injuries (Rampinini et al., 2021; Paravlic et al., 2022). Demonstrating different interventions to address these injuries might be the most urgent future research direction.

5.2.5. Injury: head and brain

In contrast to the lower limbs, in the pre-COVID-19 era, head injury research was divided into at least two topic areas. One topic area attempted to explore the relationship between impact size and injury by measuring the impact of a header (e.g., physical measurements, survey measurements, etc.) (Campolettano and Rowson, 2021; Miller et al., 2021). The other topic area addressed brain injury in soccer players, with a focus on pathological brain injuries such as encephalopathy, dementia, Alzheimer's, and ADHD (Rutherford et al., 2019; Didehbani et al., 2020; Reyes et al., 2020). In soccer, head injuries cause such serious sequelae that evidence-based rules and policies have been proposed and headers controlled in matches and training (Beaudouin et al., 2021; Chandran et al., 2021; Haarbauer-Krupa et al., 2021; Ye et al., 2022). In addition, some studies have highlighted reports of sequelae focusing on neurocognitive symptoms after brain injury (Sandmo et al., 2020; Wahlquist and Kaminski, 2021). The seriousness of the problem is evidenced by several research approaches that explore the various factors that influence head and neck injuries, as well as policy and institutional limitations to prevent such injuries.

One cluster of topics emerged during the pandemic that addressed brain injuries, including concussions. Because of the reduced number of matches and the lockdowns during the COVID-19 pandemic, the head injury topic might have been underrepresented more dramatically than the overall physical injury topic. While there were many factors contributing to this relative decline in topics, the variables of attrition and decreased frequency of research cannot be overlooked. As previously described, the relative contraction during the coronavirus period could be attributed to a relative reduction in live matches compared to previous periods, resulting in a decrease in exposure to dangerous head injuries, including headers, and an increase in lower limb injuries (Bamac et al., 2011; Rodrigues et al., 2019; Mazza et al., 2022).

However, Shibukawa and Hoshikawa (2022) reported a reduction in head injuries in some professional leagues following FIFA's goal-kicking policy. Coincidentally, the pandemic started not long after this policy. At this point, it is difficult to prove whether this reduction was due to the policy or the pandemic. Currently, it is expected that reports of brain injuries and research to prove exact causations will follow.

5.2.6. Other injury

In addition to the lower limbs and head, injuries in soccer occur in a variety of other areas, and research has been published on these injuries. Although not organized into independent topic areas, discrete clusters of topics identified thematic areas of injury research. Some topics consisted of many of the same keywords, regardless of the time period. First, studies exploring the association between bone density and mineral content and injury were published before and during COVID-19, with various studies focusing on bone composition, including differences in bone density and injury in soccer players according to gender and bone density and injury according to sport (Lozano-Berges et al., 2018; Gomez-Campos et al., 2019; Filippella et al., 2020; Bergamo et al., 2023).

Keyword clusters indicative of cardiac injuries in soccer players were also found in both periods. Soccer research on the heart can be categorized into studies examining soccer players' heart disease and cardiac responses after matches and training (Martin-Sanchez et al., 2011; Unnithan et al., 2022). The topics in this study cover mild and severe heart-related injuries, including coronary artery disease and sudden cardiac death in soccer players. There are specific reports of a long history of cardiac research regarding soccer players from 1955 to the present (Higgins and Andino, 2013). There has also been a long history of exploration into the most potentially fatal of soccer injuries, including in-competition deaths and chronic heart disease in retired players.

In both periods, we also found studies that explored turf type as a factor, as opposed to specific injury sites. Natural and artificial turf comprise two of the many influential external environments in which players play (Nedelec et al., 2013; Ataabadi et al., 2017). Importantly, (Silva et al., 2017) reported that the interaction between a player's style of play and the surface condition of the turf may be a contributing factor to injury. Multiple studies have been published on the relationship between turf type and injury prevalence, as well as literature reviews and meta-analyses, and to date, research continues to be attempted (Calloway et al., 2019)

Dietary habits, energy intake, and metabolism were always clustered as one or more themes in performance studies, but there was also a strong presence of studies demonstrating a link between these themes and injury (Cavarretta et al., 2018; Faltstrom et al., 2022). This cluster could be found in both periods, with the primary approach being the relationship to injury, which can be influenced by behaviors related to diet. Additionally, COVID-19 keywords were found in topics during the pandemic, suggesting that changes in dietary behavior under lockdowns during the pandemic have not been overlooked by researchers (Carter et al., 2021). To date, there are no published studies demonstrating a relationship between problematic dietary behaviors and injury prevalence resulting from lockdowns during COVID-19. However, now that the pandemic has ended and normalcy has returned, there is concern that poor dietary habits from past lockdowns may continue to lead to health problems and injuries (Haan et al., 2021; Rico-Gonzalez et al., 2021). The study of dietary habits is worthy of continued exploration until the effects of the pandemic have had time to dissipate.

In addition, the relationship between the soccer environment and injury, which is bound to have changed through the pandemic, is a timely topic. Topics describing the relationship between training load and performance, which were found in the performance research area during the pre-COVID-19 period, have been partially transformed into keyword clusters linking training load to injury (Bache-Mathiesen et al., 2022). The risk of injury is also inevitable because of the increased training time during the pandemic, and the cluster of topics related to injury experiences and concerns may also reflect the temporal nature of the pandemic (Schuttler et al., 2022). In addition, clusters containing keywords about returning from injury and athletes returning after the pandemic are not conclusions based on experiments or surveys but rather topics that can be expected to be the subject of further research (Ross et al., 2021; Maestro et al., 2022).

On the other hand, the psychosocial and medical issues of soccer players and other practitioners who had to face restrictions not only in matches but also in training and daily life due to league suspensions, curtailments, and lockdowns (Balyan et al., 2021; Karagun et al., 2021; Papagiannis et al., 2022) that were unavoidable during the COVID-19 pandemic period suggest a research approach of qualitative and quantitative exploration to identify these issues in the present and prepare for the threat of recurrence in the future.

6. Limitation

In the present research, we utilized the Web of Science (WOS) database to carry out a topic modeling analysis, encompassing articles indexed in the Science Citation Index Expanded, the Social Sciences Citation Index, and the Arts & Humanities Citation Index. We anticipate that a more integrated approach in data collection and analysis could be achieved by incorporating diverse academic databases such as Scopus and SportDISCUS, alongside WOS. Furthermore, it is pertinent to highlight the potential role of the BERT model, which forms the foundation of BERTopic, in enhancing the quality and depth of analysis. BERT, known for its capability to acquire intensive domain knowledge in diverse fields, can facilitate the extraction of more pertinent keywords and topics when fine-tuned with specialized domain knowledge. Future research endeavors could explore the outcomes of employing a BERT model that has been fine-tuned using sports or soccer-centric documents. Lastly, as the global society transitions into the post-pandemic period, it would be significant to adopt a longitudinal perspective in examining whether the trends in soccer research are reverting to the patterns observed before the advent of the COVID-19 pandemic.

7. Conclusion

The COVID-19 pandemic has had a clear impact on soccer research trends. Topic modeling revealed a context in which the pandemic led to changes in research priorities that reflect changes in soccer participation, training routines, and even the sports business environment. First, the interdisciplinary nature of topics across both time periods emerged, spanning psychology, sociology, business, and technology. This emphasizes that socioeconomic phenomena are emerging from soccer that are relevant to a variety of academic disciplines. On the business side, concerns about the economic impact of the COVID 19 pandemic were reflected in the research. It also emphasized the importance of team-fan and player-fan relationships to overcome this crisis. Second, before and during the pandemic, sports, including soccer, still valued performance. In both periods, there was a strong emphasis on training, an expected theme given soccer players' constant efforts to improve their performance. However, during the COVID-19 pandemic, a shift in themes revealed a focus on developing fast-paced, highly efficient training sessions in response to various constraints. Third, this change in the soccer environment during the pandemic was inferred as the reason for the shift in research focus from head injuries to lower limb injuries. It could be that training routines changed as match play was restricted, which affected the types of injuries players faced, or it could be that the pandemic led to less physical contact during matches, which led to fewer head-related injuries. This shift in focus could be a direct result of the pandemic, but it could also be due to new rules, advances in technology, or a shift in awareness of the issue of injury sites. Furthermore, the relative decline in head and brain injury research during the pandemic does not necessarily mean that the issue has become less important; rather, it may be an opportunity for researchers to explore the long-term effects of these injuries and the potential benefits of reducing exposure to dangerous situations. In conclusion, while the COVID-19 pandemic has clearly impacted soccer research trends, the overall direction of research on player performance, injury prevention, and technology integration remains macroscopically consistent compared to pre-COVID-19. However, as the world adapts to the new normal, soccer research must evolve to optimize athlete health and training methods and continue to advance performance. Future research must bridge these gaps and develop a holistic strategy to meet the ever-evolving challenges of this popular sport.

Data availability statement

The original contributions presented in the study are included in the article/supplementary materials, further inquiries can be directed to the corresponding author.

Author contributions

JL and DH contributed to the conception and design of this study. SS collected the database. YK performed the topic modeling analyses. JL, S-BP, and DH wrote sections of the manuscript, contributed to manuscript revision, read, and approved the submitted version. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Which factors modulate spontaneous motor tempo? A systematic review of the literature

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Intentionally or not, humans produce rhythmic behaviors (e.g., walking, speaking, and clapping). In 1974, Paul Fraisse defined rhythmic behavior as a periodic movement that obeys a temporal program specific to the subject and that depends less on the conditions of the action (p. 47). Among spontaneous rhythms, the spontaneous motor tempo (SMT) corresponds to the tempo at which someone produces movements in the absence of external stimuli, at the most regular, natural, and pleasant rhythm for him/her. However, intra- and inter-individual differences exist in the SMT values. Even if several factors have been suggested to influence the SMT (e.g., the age of participants), we do not yet know which factors actually modulate the value of the SMT. In this context, the objectives of the present systematic review are (1) to characterize the range of SMT values found in the literature in healthy human adults and (2) to identify all the factors modulating the SMT values in humans. Our results highlight that (1) the reference value of SMT is far from being a common value of 600 ms in healthy human adults, but a range of SMT values exists, and (2) many factors modulate the SMT values. We discuss our results in terms of intrinsic factors (in relation to personal characteristics) and extrinsic factors (in relation to environmental characteristics). Recommendations are proposed to assess the SMT in future research and in rehabilitative, educative, and sport interventions involving rhythmic behaviors.

KEYWORDS
SMT, rhythm, intertap interval, intra-individual, inter-individual, variability, frequency

1. Introduction

Rhythm is an essential human component. "Rhythm is defined as the pattern of time intervals in a stimulus sequence" (Grahn, 2012, p. 586), and the tempo is the rate of the stimuli's onset within a regular sequence (Grahn, 2012). Early in life, rhythm is present in a large number of activities of daily life, such as walking, speaking, chewing, doing leisure activities (dancing, swimming, pedaling, playing a musical instrument, singing, clapping, etc.), or school activities (writing and reading). Some activities require producing a rhythm with a spontaneous tempo (e.g., writing, reading, chewing, walking, speaking, etc.), and some others require synchronizing with a rhythm produced by an external event (e.g., playing a musical instrument, singing, clapping, dancing, etc.). Those activities can have different rhythmic components. For example, speech generally shows a non-isochronous rhythmic structure, but other language skills, such as reading, may also show beat-based patterns (i.e., isochronous patterns based on equal time intervals; see Ozernov-Palchik and Patel, 2018). Writing seems to be linked to isochronous rhythmic production (Lê et al., 2020b), even if it is not yet well-known whether writing shows more beat- or non-beat-based processing. Other activities, such as tapping or clapping, are well-known to show isochronous patterns.

Rhythmic abilities are deficient in various populations, and nowadays, rehabilitative interventions based on rhythmic synchronization are used to improve motor control. This is the case for populations with neurological diseases (e.g., Parkinson's disease, stroke, and cerebral palsy; see Braun Janzen et al., 2021), rare diseases or conditions (Launay et al., 2014; Bégel et al., 2017, 2022a; Tranchant and Peretz, 2020), or neurodevelopmental disorders (e.g., dyslexia, developmental coordination disorder, and attention deficit and hyperactivity disorder; Puyjarinet et al., 2017; Bégel et al., 2018, 2022b; Lê et al., 2020a; Blais et al., 2021; Daigmorte et al., 2022). In this context, participants are required to synchronize their movements to an external rhythm, usually with an auditory metronome, to regulate the speed of their gait or manual or verbal responses. The ability to synchronize with an external rhythm is particularly studied during sensorimotor synchronization tasks that consist of the "coordination of a rhythmic movement with an external rhythm" (Repp and Su, 2013, p. 1). The tempo and the sensory modality of the external rhythmic stimuli can modulate the performance of sensorimotor synchronization (see Repp, 2005; Repp and Su, 2013 for extensive reviews of the literature). Sensorimotor synchronization is less accurate and stable when the tempo is slower (Drewing et al., 2006; Repp and Su, 2013) and slower than the spontaneous motor tempo (SMT; Varlet et al., 2012). SMT is the rhythm at which a person produces movements in the absence of stimuli at his/her own most regular, natural, and pleasant rate. Hence, the tempo of the external rhythm has to be adapted to the actual tempo of the participants. Recent studies individualize the parameters of the intervention by adapting the tempo of the metronome to be synchronized (Benoit et al., 2014; Dalla Bella et al., 2017; Cochen De Cock et al., 2021; Frey et al., 2022). This is done by measuring the individual's SMT before an intervention. Rehabilitation is then performed with music at either ±10% of this tempo. Therefore, it seems interesting to evaluate rhythmic abilities, especially spontaneous motor tempo (SMT), to individualize learning and rehabilitation.

It is usually admitted in the pioneering work of Paul Fraisse that the most representative reference value of the spontaneous motor tempo (SMT) is 600 ms in healthy human adults (Fraisse, 1974). However, a growing body of literature about SMT suggests that this value is not universal. Fraisse himself pointed out that, even if the SMT is supposed to be relatively stable in one individual, inter-individual differences are more important and could be related to the instructions, the material of measurement, the body position, the chronological and intellectual development, and the sensory deficits (Fraisse, 1974). Even if these factors have been tested in a few studies, to our knowledge, no updated review of the literature has been made to provide complete and recent knowledge on the range of SMT values in healthy human adults and the factors influencing them. For example, recent studies suggest that age is a major factor modulating the value of SMT. The review by Provasi et al. (2014a) focuses on the spontaneous (and induced) rhythmic behaviors during the perinatal period, with a special emphasis on the spontaneous rhythm of sucking, crying, and arm movements in newborns. The authors indicate that the SMT evolves from newborns to the elderly. Fast rhythmical movements of the arms have been identified in fetuses with a tempo of 3 or 4 movements per second (250–333 ms; Kuno et al., 2001), whereas a tempo of 450 ms has been found during drumming (Drake et al., 2000) or tapping (McAuley et al., 2006) in children around 4 years old and more. The value of the SMT is relatively fixed around 400 ms between 5 and 8 years, even if the variability of the SMT tends to decrease with age (Monier and Droit-Volet, 2019). The SMT is supposed to increase to achieve 600 ms in adulthood (Fraisse, 1974) and to slow down further with age to achieve 700–800 ms in the elderly (Vanneste et al., 2001). In the case of tempo produced with the mouth, the SMT of non-nutritive sucking is around 450 ms in neonates (Bobin-Bègue et al., 2006), whereas the spontaneous crying frequency is between 1,100 and 2,400 ms in newborns (Brennan and Kirkland, 1982). All these results suggest that the relationship between SMT and age is *not* general and linear. The effector producing the SMT could be a potential factor affecting the relationship between SMT and age.

Some studies focus on the SMT produced with the mouth in a quasi-rhythmic pattern during speech production and in an isochronous repetitive pattern during syllable rate production. The review of Poeppel and Assaneo (2020) reports that the temporal structure of speech "is remarkably stable across languages, with a preferred range of rhythmicity of 2–8 Hz" (125–500 ms; Poeppel and Assaneo, 2020, p. 322). One could suggest that this rhythm is faster than the rhythm supposed to be found in rhythmical movements of the arms (600 ms in adulthood, Fraisse, 1974). However, in the broader context of speech production, we cannot neglect the communicative aspect of speech. The audience for the speech could also influence the SMT (Leong et al., 2017). Thus, it is possible that, in addition to the age previously mentioned, not only the effector but also the communicative goal of the activity may influence the SMT.

Moreover, environmental factors are supposed to influence SMT values. In the review of Van Wassenhove (2022), it is suggested that the manipulation of external landmarks, such as the time of day, can modulate the endogenous temporal representation of time and, as a consequence, the SMT (Van Wassenhove, 2022).

In this context, the objectives of the systematic review are (1) to characterize the range of SMT values found in the literature in healthy human adults and (2) to identify all the factors modulating the SMT values in humans.

TABLE 1 Search strategy information.

	PubMed	Science Direct	Web of Science
Search equation	((spontaneous motor tempo) OR ((spontaneous OR self-paced OR internally-driven OR internal OR preferred OR internally-guided) AND (motor NOT locomotion NOT locomotor) AND (tempo OR rhythm OR rhythmic OR tapping OR (intertap interval))))	('human') AND (('spontaneous motor tempo') NOT ('locomotion' OR 'locomotor')	ALL = (human) AND (ALL = ((spontaneous motor tempo) OR ((spontaneous OR self-paced OR internally-driven OR internal OR preferred OR internally-guided) AND (motor NOT locomotion NOT locomotor) AND (tempo OR rhythm OR rhythmic OR tapping OR (intertap interval)))))
Applied filters	"Human" and "All type of documents"	"Review articles" and "Research articles"	"All type of documents"
Search results	1,225	1,141	813

2. Materials and methods

We conducted a systematic review according to PRISMA recommendations (Preferred Reporting Items for Systematic Reviews and Meta-Analyses; Page et al., 2021).

2.1. Information sources and search strategy

Studies were identified by searching in the PubMed, Science Direct, and Web of Science databases. These databases were selected because they represent a broad spectrum of disciplines related to motor behavior. The final search was performed on 4 July 2022. There was no restriction on the year of publication; all articles present in the databases at this time point were searched. The search was first conducted in all languages, and then only English and French studies were selected for screening. As the term "spontaneous motor tempo" is not exclusively used, we searched a broad spectrum of synonyms for this term. Filters were also used to identify relevant research depending on the database (Table 1).

2.2. Selection of studies and eligibility criteria

We only selected articles and reviews before screening by excluding congress papers, chapters, books, and theses. Reviews identified in databases were just used to find missing original articles about SMT, and they have not been included in the systematic review (reviews not included: Provasi et al., 2014a; Poeppel and Assaneo, 2020; Van Wassenhove, 2022).

For greater specificity in the selection of the studies, inclusion criteria were based on the PICO (population, intervention, comparator, and outcome) strategy (Table 2). For this, we selected studies carried out on human samples producing rhythmic tasks. A control factor or control group was identified as a comparator. Spontaneous motor tempo was identified as the Outcome. Moreover, we selected other exclusion criteria: (1) studies that did not present experimental data; (2) studies that did not present a SMT task (i.e., focusing only on sensorimotor synchronization or on perception of rhythmic stimuli); (3) studies that did not report data on SMT (a SMT task is produced by the participants, but variables studied assess, for example, brain data or relative phases); (4) studies that did not focus on intentional SMT (studies on cardiorespiratory rhythms like breath or heart rate); and (5) studies that focus on walking with displacement (locomotion). We excluded studies on locomotion because locomotion involves spatiotemporal regulation; however, we retained studies on walking on a treadmill because walking on a treadmill involves mainly temporal regulation.

TABLE 2 Description of the PICO strategy that was used.

PICO strategy	
Description	Component
Population	Human
Intervention	Rhythmic task
Comparator	Control factor or group
Outcomes	Spontaneous motor tempo

All titles and abstracts were screened by one researcher (AD), and if the articles fit the review criteria, they were read in full. The full-text eligibility assessment was conducted by two independent reviewers (AD and JT). Disagreements were resolved by a discussion according to the PICO strategy with a third researcher (EM).

2.3. Data collection process

For tabulation and extraction of data referring to the selected studies, Excel® software spreadsheets were used. After screening the selected studies, we classified them into two categories, i.e., those measuring the SMT values (in general, as a prerequisite for a subsequent rhythmic sensorimotor synchronization task) and those examining the effect of factor(s) on the SMT values.

For studies measuring the SMT values, we extracted study characteristics, demographic variables, methodological

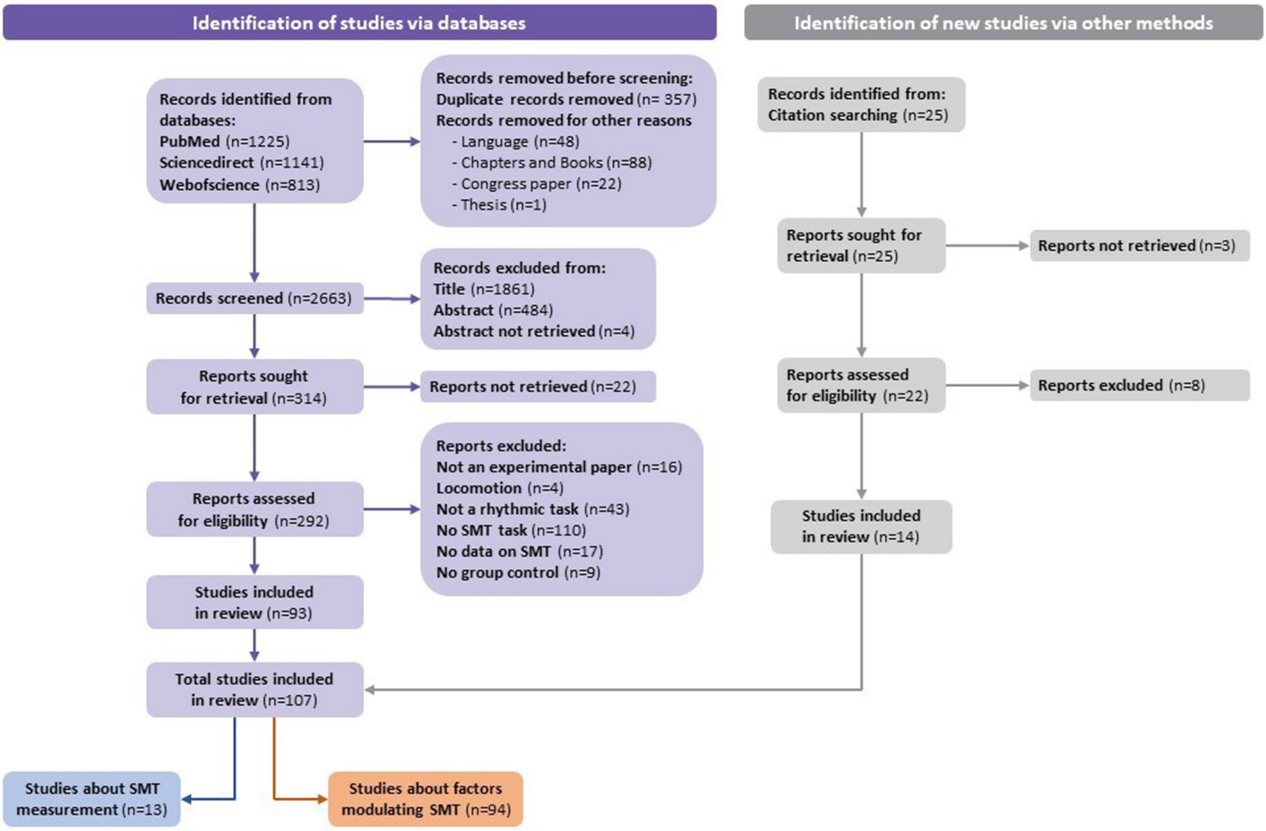

FIGURE 1
Flowchart of the identification of studies via databases.

variables, and outcome indicators from each study. The extracted characteristics included the authors, the year of publication, and the sample size. Demographic variables included sex, age, and laterality. Methodological variables included the instruction, the task, the effector(s), and the measurement recording. Outcome indicators included SMT values and their units. We finally convert all of the SMT values to milliseconds to be comparable and to provide a range of SMT values.

For studies about factor(s) modulating SMT values, we extracted study characteristics (first author and year of publication), methodological variables (task and effector(s)), and outcome indicators (factor(s) effects, their significance, and their direction on SMT values, i.e., on the mean or median and/or the standard deviation or coefficient of variation). Sometimes, we also extracted other information (e.g., subgroups and specific statistical analyses) to understand and interpret the results.

3. Results

A total of 3,179 studies were identified via databases. Before screening, 357 duplicates and 159 studies were removed (e.g., language, chapters and books, congress papers, or theses). According to the exclusion criteria, 2,349 studies were excluded based on the title or the abstract. After verifying the records left in full, according to the pre-established eligibility criteria, 93 studies from databases were included in the systematic review. Moreover, 14 out of 25 studies identified via citation searching were included. Finally, a total of 107 studies were included in the systematic review. Results from the process for selecting the included articles (following the recommendations of Page et al., 2021) are described in the flowchart (Figure 1).

In total, 13 studies provide a SMT value or a range of SMT values in healthy adults (Table 3). Our results reveal that the range of SMT values is from 333 to 3,160 ms. Notably, 94 studies measure the effect of the factor(s) on the SMT values (Table 4). We classified studies according to the type of factors modulating the SMT values: *intrinsic factors*, in relation to personal characteristics, and *extrinsic factors*, in relation to environmental characteristics. Concerning intrinsic factors, we have found studies investigating the effects of a pathology ($N = 27$), age ($N = 16$), the effector or the side ($N = 7$), the expertise or a predisposition ($N = 7$), and the genotype ($N = 2$). Concerning extrinsic factors, we have found studies investigating the effects of physical training ($N = 10$), external constraints ($N = 7$), observation training ($N = 5$), the time of testing ($N = 4$), the internal state ($N = 3$), the type of task ($N = 5$), and a dual task ($N = 2$).

TABLE 3 Summarized results of studies measuring SMT values ($N = 13$).

References	Participants processed		Paradigm					SMT					
	Number of participants	Sex Age ± SD (years old) Laterality	Instruction	Task	Trial(s) (duration or intervals number)	Measurement recording	Effector	SMT values			Converted SMT values (in ms)		Coefficient of variation
								Mean, median or range	SD	Unit	Mean, median, or range	SD	
Hattori et al. (2015)	6	2M 4F 27 ± N.S. Not reported	Not reported	Tapping	1 (30 times)	Intertap intervals	Fingers	333–505	12.6–23	ms	333–505	12.6–23	Not reported
Ruspantini et al. (2012)	11	Not reported Not reported Not reported	To periodically articulate the/pa/syllable, mouthing silently, at a self-paced, comfortable rate	Producing a syllable	Not reported	Syllable rate	Mouth/lips	2.1	0.5	Hz	476	200	Not reported
McPherson et al. (2018)	20	5M 15F 18–26 19 right-handed 1 left-handed	To hit the drum, sustaining a constant pulse at their own, naturally comfortable tempo	Drumming	10 (15 s each)	Beats per minute	Hand	62–122 (one at 189)	Not reported	bpm	492–968 (one at 317)	Not reported	Not reported
Rousanoglou and Boudolos (2006)	11	5M 6F 21.2 ± 0.5 (M) 21.3 ± 0.5 (F) Not reported	To perform two-legged hopping in place at their preferred hopping frequency	Hopping	2 (15 s each)	Duration of the hopping cycle	Legs	0.555	0.083	s	555	83	Not reported

(Continued)

TABLE 3 (Continued)

References	Participants processed		Paradigm					SMT					
	Number of participants	Sex Age ± SD (years old) Laterality	Instruction	Task	Trial(s) (duration or intervals number)	Measurement recording	Effector	SMT values			Converted SMT values (in ms)		Coefficient of variation
								Mean, median or range	SD	Unit	Mean, median, or range	SD	
Michaelis et al. (2014)	14	7M 7F 18–35 Right-handed	To tap a response key at whichever rate felt "most comfortable," to keep a steady pace, and make the spaces between taps as even as possible	Tapping	4 (30 intertap intervals)	Intertap intervals	Finger	0.68	0.32	s	680	320	Not reported
Sidhu and Lauber (2020)	11	8M 3F 25.9 ± 3.8 Not reported	To cycle at a freely chosen cadence	Cycling on a cycle ergometer	1 (5 min)	Cadence	Legs	71.6	8.1	rpm	838	95	Not reported
Zhao et al. (2020)	21	13M 8F 26.2 ± 5.4 19 right-handed 2 left-handed	To perform rhythmic oscillatory movements at their preferred frequency (if he or she can do it all day long) with the amplitude of the participant's shoulder	Performing rhythmic oscillatory movements with a stick	1 (30 s)	Number of movement cycles	Hand	17–33	Not reported	no unit	909–1,765	Not reported	Not reported
De Pretto et al. (2018)	14	7M 7F 27.7 ± 3.1 Right-handed	To tap at their most natural pace, at a frequency they could maintain without mental effort, and for a long period of time	Tapping	3 (40 intertap intervals)	Intertap intervals	Finger	931	204	ms	931	204	5.6 ± 1.3%

(Continued)

TABLE 3 (Continued)

References	Participants processed		Paradigm					SMT					
	Number of participants	Sex Age ± SD (years old) Laterality	Instruction	Task	Trial(s) (duration or intervals number)	Measurement recording	Effector	SMT values			Converted SMT values (in ms)		Coefficient of variation
								Mean, median or range	SD	Unit	Mean, median, or range	SD	
Eriksson et al. (2000)	12	5M 7F 25–45 Not reported	Not reported	Opening and closing the jaw Chewing	2 (12 s each) 2 (12 s each)	Cycle time Cycle time	Jaw Jaw	2.43 0.86	0.86 0.16	s s	2,430 860	860 160	Not reported
Sotirakis et al. (2020)	20	Not reported 27.1 ± 9.15 Not reported	To perform voluntary postural sway cycles at their own self-selected amplitude and pace	Swaying	1 (20 cycles)	Cycle duration	Whole body	3,160	530	ms	3,160	530	Not reported
Malcolm et al. (2018)	16	11M 5F 25.6 ± 4.5 Right-handed	Not reported	Walking on a treadmill	Not reported	Speed walking	Legs	3.2–4.5	Not reported	km/h	Not convertible	Not reported	Not reported
LaGasse (2013)	12	Not reported 18–35 Not reported	To repeat the syllable/pa/at a comfortable and steady pace	Producing a syllable	7 (8 sequential repetitions)	Inter-responses interval	Mouth/lips	Not reported	Not reported	Not reported	Not reported	Not reported	Not reported
Zhao et al. (2017)	22	12M 10F 26.9 ± 6.6 Not reported	To tap at a constant and comfortable tempo	Tapping	6 (30 s each)	Not reported	Finger	Not reported	Not reported	Not reported	Not reported	Not reported	Not reported

The original SMT values reported were converted to milliseconds by the authors (A.D., E.M., and J.T.) to provide a range of SMT values in milliseconds: [333–3,160 ms].

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TABLE 4 Summarized results of studies investigating the effects of factors on the SMT values (*N* = 94).

References	Factors modulating the SMT										
	I. Intrinsic factors										
	1. Pathology	Significance	Direction of the effect (on mean or median of SMT)	Direction of the effect (on the SD or coefficient of variation of SMT)	Other factor(s)	Direction of the effect (on mean or median of SMT)	Direction of the effect (on the SD or coefficient of variation of SMT)	Interaction	Task(s)	Effector(s)	Other information
Amrani and Golumbic (2020)	ADHD vs. Healthy adults	Yes	ADHD faster than Healthy adults	ADHD less stable than Healthy adults (within trial and across sessions)	/	/	/	/	Tapping on an electro-optic sensor	Finger	/
Byblow et al. (2002)	Parkinson's vs. Healthy elderly	Yes	Parkinson's is slower than Healthy elderly	Not found	Mode of coordination Side	Inphase faster than antiphase Not found	Not found Not found	No interaction	Producing pronation and supination movements	Forearm	/
Delevoye-Turrell et al. (2012)	Schizophrenia vs. Healthy adults	Yes	• Schizophrenia is slower than Healthy adults	• Schizophrenia is less stable than Healthy adults	/	/	/	/	Producing finger down and up rhythmic movements	Finger	/
	Ultra-High Risk vs. Healthy Younger adults	Yes	• Ultra-High Risk = Healthy Younger adults	• Ultra-High Risk less stable than Healthy young adults • Ultra-High Risk = Schizophrenia							
Flasskamp et al. (2012)	Parkinson's vs. Healthy elderly	Yes	Parkinson's faster than Healthy elderly	Parkinson's less stable than Healthy elderly	/	/	/	/	Producing a syllable	Mouth/lips	Subgroups of Parkinson's (Left-sided vs. Right-sided symptoms)
Frankford et al. (2021)	Stammerers vs. Healthy adults	No	Stammerers = Healthy adults	Stammerers = Healthy adults	/	/	/	/	Reading sentences	Mouth/lips	/

(Continued)

TABLE 4 (Continued)

References	Factors modulating the SMT									
	I. Intrinsic factors									
	1. Pathology	Significance	Direction of the effect (on mean or median of SMT)	Direction of the effect (on the SD or coefficient of variation of SMT)	Other factor(s)	Direction of the effect (on mean or median of SMT)	Direction of the effect (on the SD or coefficient of variation of SMT)	Interaction	Task(s)	Effector(s)	Other information
Häggman-Henrikson et al. (2002)	Whiplash-associated disorders vs. Healthy adults	Yes	Whiplash-associated disorders slower than Healthy adults	Not found	/	/	/	/	Chewing	Jaw	/
Horin et al. (2021)	Parkinson's vs. Healthy elderly	Yes	Parkinson's faster than Healthy elderly	Parkinson's = Healthy elderly	Effector	• Finger faster than Gait • Foot faster than Gait	• Finger = Gait • Foot = Gait	Interaction Pathology × Effector: Parkinson's faster than Healthy elderly for foot tapping	• Tapping on a keyboard key • Tapping on a pedal	• Finger • Foot	Other 5 m walking task
Keil et al. (1998)	Schizophrenia vs. Healthy adults	No	Schizophrenia = Healthy adults	Not found	Movement direction	Vertical faster than Horizontal	Not found	Not found	Bimanual coordination task	Fingers	Horizontal and vertical movements
Konczak et al. (1997)	Parkinson's vs. Healthy elderly	Yes	• Producing a syllable: Significant effect (no other information) • Tapping: Significant effect (no other information)	• Producing a syllable: Not found • Tapping: Not found	Task (Dual vs. Single)	• Producing a syllable: Significant effect (no other information) • Tapping: Not found	• Producing a syllable: Not found • Tapping: Not found	Not found	• Producing a syllable • Tapping on a table	• Mouth/lips • Finger	Subgroups of Parkinson's (With vs. Without hastening)
Kumai (1999)	2–3.5 vs. 3.6–4.5 vs. 4.6–5.5 vs. 5.6–6.11 vs. 7+ years of mental ages	No	2–3.5 =3.6–4.5 = 4.6–5.5 = 5.6–6.11 = 7+ years of mental ages	Not found	/	/	/	/	Drumming with a stick	Hand/Forearm	Biological age: 13–23 years old

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TABLE 4 (Continued)

References	Factors modulating the SMT										
	I. Intrinsic factors										
	1. Pathology	Significance	Direction of the effect (on mean or median of SMT)	Direction of the effect (on the SD or coefficient of variation of SMT)	Other factor(s)	Direction of the effect (on mean or median of SMT)	Direction of the effect (on the SD or coefficient of variation of SMT)	Interaction	Task(s)	Effector(s)	Other information
McCombe Waller and Whitall (2004)	Chronic hemiparesis vs. Healthy adults	No	• Paretic limb: Not found • Non-paretic limb: Chronic hemiparesis = Healthy adults	• Paretic limb: Not found • Non-paretic limb: Chronic hemiparesis = Healthy adults	Sensorimotor synchronization training in the non-paretic limb (in hemiparesis patients)	Pre faster than Post	Pre = Post sensorimotor synchronization training	Not found	Tapping on keys	Fingers	/
Martin et al. (2017)	Alzheimer's vs. Healthy elderly	No	Alzheimer's = Healthy elderly	Not found	/	/	/	/	Tapping on a keyboard key	Finger	/
Martínez Pueyo et al. (2016)	Huntington vs. Healthy adults	Yes	Huntington is slower than Healthy adults	Huntington is less stable than Healthy adults	/	/	/	/	Tapping on a keyboard key	Finger	/
Palmer et al. (2014)	2 Beat-deaf vs. Healthy adults	No	2 Beat-deaf = Healthy adults	2 Beat-deaf = Healthy adults	/	/	/	/	Tapping on a silent piano key	Finger	/
Phillips-Silver et al. (2011)	1 Beat-deaf (congenital amusia) vs. Healthy adults	Not found (case report)	Not found (case report)	Not found	/	/	/	/	Bouncing	Whole body	/

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TABLE 4 (Continued)

References	Factors modulating the SMT									
	I. Intrinsic factors									
	1. Pathology	Significance	Direction of the effect (on mean or median of SMT)	Direction of the effect (on the SD or coefficient of variation of SMT)	Other factor(s)	Direction of the effect (on mean or median of SMT)	Direction of the effect (on the SD or coefficient of variation of SMT)	Interaction	Task(s)	Effector(s)	Other information
Provasi et al. (2014b)	Cerebellar medulloblastoma vs. Healthy children	Yes	Cerebellar medulloblastoma is slower than Healthy children	Cerebellar medulloblastoma is less stable than Healthy children	Sensorimotor synchronization task Sex	Pre faster than Post Male = Female	Pre = Post sensorimotor synchronization task Female = Male	• Interaction Pathology × Sensorimotor synchronization task: effect of Sensorimotor synchronization on SMT value and its stability is higher in Cerebellar medulloblastoma than in Healthy children. • No interaction Sex × Pathology × Sensorimotor synchronization task	Tapping on a keyboard key	Finger	/
Roche et al. (2011)	DCD vs. Healthy children	Yes	DCD = Healthy children	DCD is less stable than Healthy children	Sensory feedback	Vision+ Audition = No vision + Audition = Vision + No audition = No vision + No audition	Vision+ audition = No vision + Audition = Vision + No audition = No vision + No audition	No interaction Pathology × Sensory feedback	Anti-phase tapping on a table	Fingers	/
Roerdink et al. (2009)	Stroke vs. Healthy adults	Yes	Stroke is slower than Healthy adults	Not found	/	/	/	/	Walking on treadmill	Legs	/

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TABLE 4 (Continued)

References	Factors modulating the SMT										
	I. Intrinsic factors										
	1. Pathology	Significance	Direction of the effect (on mean or median of SMT)	Direction of the effect (on the SD or coefficient of variation of SMT)	Other factor(s)	Direction of the effect (on mean or median of SMT)	Direction of the effect (on the SD or coefficient of variation of SMT)	Interaction	Task(s)	Effector(s)	Other information
Rose et al. (2020)	Parkinson's vs. Healthy elderly vs. Younger healthy adults	Yes (in all tasks)	• Finger tapping: Parkinson's = Healthy elderly// Parkinson's faster than Younger healthy adults// Healthy elderly (515 ms) faster than Younger healthy adults • Toe tapping: Parkinson's faster Healthy elderly = Younger healthy adults • Stepping: Parkinson's faster than Younger healthy adults// Parkinson's = Heatlthy elderly// Healthy elederly = Younger healthy adults	• Finger tapping: Parkinson's = Younger healthy adults// Parkinson's less stable than Healthy elderly// Younger healthy adults less stable than Healthy elderly • Toe tapping: Parkinson's = Younger healthy adults = Healthy elderly • Stepping: Parkinson's = Younger healthy adults = Healthy elderly	/	/	/	/	• Tapping on a stomp box • Tapping on a stomp box • Stepping on the spot	• Finger • Toe • Feet	
Rubia et al. (1999)	ADHD vs. Healthy children	Yes	ADHD = Healthy children	ADHD less stable than Healthy children	/	/	/	/	Tapping on a button	Finger	/

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TABLE 4 (Continued)

References	Factors modulating the SMT									
	I. Intrinsic factors									
	1. Pathology	Significance	Direction of the effect (on mean or median of SMT)	Direction of the effect (on the SD or coefficient of variation of SMT)	Other factor(s)	Direction of the effect (on mean or median of SMT)	Direction of the effect (on the SD or coefficient of variation of SMT)	Interaction	Task(s)	Effector(s)	Other information
Schwartze et al. (2011)	Stroke (Basal ganglia lesions) vs. Healthy adults	Yes	Not found	Stroke less stable than Healthy adults	Sensorimotor synchronization task	Not found	Pre less stable than Post	No interaction Pathology × Sensorimotor synchronization task	Tapping on a copper plate	Hand	/
Schwartze et al. (2016)	Cerebellar lesion vs. Healthy adults	Yes	Cerebellar lesion = Healthy adults	Cerebellar lesion less stable than Healthy adults	Sensorimotor synchronization task	Pre = Post	Not found	No interaction Pathology × Sensorimotor synchronization task	Tapping on a pad	Finger	/
Schellekens et al. (1983)	Minor neurological dysfunction vs. Healthy children	Yes	Minor neurological dysfunction slower than Healthy children	Minor neurological dysfunction less stable than Healthy children	/	/	/	/	Pressing buttons	Hand/Arm	/
Volman et al. (2006)	DCD vs. Healthy children	Yes (in both tapping modes)	• In-phase: DCD slower than Healthy • Anti-phase: DCD slower than Healthy	Not found	Limb combination	• In-phase: Hand-foot ipsilateral = Hand-foot controlateral slower than Hand-hand • Anti-phase: Hand-foot ipsilateral = Hand-foot controlatéral slower than Hand-hand	• In-phase: Not found • Anti- phase: Not found	No interaction Pathology × Limb combination (for In-phase and Anti-phase)	In-phase and Anti-phase bi-effectors tapping on a pad	Hand and foot	Limb combinations: - Hand–hand coordination (homologous); - Hand–foot coordination same body side (ipsilateral) - Hand-foot coordination different body side (contralateral)

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TABLE 4 (Continued)

References	Factors modulating the SMT									
	I. Intrinsic factors									
	1. Pathology	Significance	Direction of the effect (on mean or median of SMT)	Direction of the effect (on the SD or coefficient of variation of SMT)	Other factor(s)	Direction of the effect (on mean or median of SMT)	Direction of the effect (on the SD or coefficient of variation of SMT)	Interaction	Task(s)	Effector(s)	Other information
Wittmann et al. (2001)	Adults with Brain subcortical injury left hemisphere without aphasia (LHsub) vs. Brain cortical injury left hemisphere with aphasia (LH) vs. Brain cortical injury right hemisphere (RH) vs. Controls (orthopedic but not brain injury; CTrl)	Yes	LH slower than CTrl LHsub faster than CTrl RH = CTrl	LH = LHsub = RH = CTrl	Side (in controls)	Left = Right	/	/	Tapping on a keyboard key	Finger	/
Wurdeman et al. (2013)	Transtibial amputee vs. Healthy adults	No	Transtibial amputee = Healthy adults	Not found	/	/	/	/	Walking on a treadmill	Legs	/

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TABLE 4 (Continued)

References	Factors modulating the SMT										
	I. Intrinsic factors										
	1. Pathology	Significance	Direction of the effect (on mean or median of SMT)	Direction of the effect (on the SD or coefficient of variation of SMT)	Other factor(s)	Direction of the effect (on mean or median of SMT)	Direction of the effect (on the SD or coefficient of variation of SMT)	Interaction	Task(s)	Effector(s)	Other information
Yahalom et al. (2004)	Parkinson's vs. Healthy elderly	No	Parkinson's = Healthy elderly	Parkinson's = Healthy elderly	/	/	/	/	Tapping on a board	Fingers	Subgroups of Parkinson's (Tremor predominant vs. Freezing predominant vs. Akinetic rigid vs. Unclassified) Freezing predominant Parkinson's vs. Unclassified Parkinson's adults significantly different
	2. Age	Significance	Direction of the effect (on mean or median of SMT)	Direction of the effect (on the SD or Coefficient of variation of SMT)	Other factor(s)	Direction of the effect (on mean or median of SMT)	Direction of the effect (on the SD or Coefficient of variation of SMT)	Interaction	Task(s)	Effector(s)	Other information
Baudouin et al. (2004)	21–35 vs. 66–80 vs. 81–94 years old	Yes	21–35 faster than 66–80 = 81–94 years old	Not found	/	/	/	/	Tapping on a plastic block	Finger	/
Drake et al. (2000)	4 vs. 6 vs. 8 vs. 10 years old children vs. Adults	Yes	Younger faster than Older	Younger more stable than Older	Trial measurement Musical expertise	Trial 1 slower than Trial 5 Non-musicians faster than Musicians	Not found Non-musicians less stable Musicians	No interaction Age × Trial measurement × Musical expertise	Drumming with a stick	Hand/forearm	/

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TABLE 4 (Continued)

References	Factors modulating the SMT										
	I. Intrinsic factors										
	2. Age	Significance	Direction of the effect (on mean or median of SMT)	Direction of the effect (on the SD or Coefficient of variation of SMT)	Other factor(s)	Direction of the effect (on mean or median of SMT)	Direction of the effect (on the SD or Coefficient of variation of SMT)	Interaction	Task(s)	Effector(s)	Other information
Droit et al. (1996)	31–35 vs. 37–39 weeks of postmenstrual age in brain-damaged and low risks preterm infants	No	31–35 = 37–39 weeks of postmenstrual age	Not found	/	/	/	/	Kicking	Legs	/
Ejiri (1998)	Before vs. After onset of canonical babbling (CB)	Yes	Onset CB faster than Before and After CB	Not found	Audibility of rattles Weight of rattles Sex Side	Audible faster than Inaudible Not found Not found Not found	Not found Not found Not found Not found	Interaction Onset CB × Audibility of rattle: after onset CB, Audible rattle is faster than Inaudible.	Shaking a rattle	Arm	/
Fitzpatrick et al. (1996)	3 vs. 4 vs. 5 vs. 7 years old children	No	3 = 4 = 5 = 7 years old	Not found	Side Loading	Left = Right Not found	Not found Not found	Interaction Side × Loading: the right limb loaded oscillates faster than the left limb loaded.	Clapping with and without inertial loading limbs	Hands	/
Gabbard and Hart (1993)	4 vs. 5 vs. 6 years old children	Yes	Older faster than Younger	Not found	Sex Laterality	Male = Female Right = Mixed = Left	Not found Not found	No interaction Age × Sex × Laterality	Tapping on a pedal	Foot	/

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TABLE 4 (Continued)

References	Factors modulating the SMT										
	I. Intrinsic factors										
	2. Age	Significance	Direction of the effect (on mean or median of SMT)	Direction of the effect (on the SD or Coefficient of variation of SMT)	Other factor(s)	Direction of the effect (on mean or median of SMT)	Direction of the effect (on the SD or Coefficient of variation of SMT)	Interaction	Task(s)	Effector(s)	Other information
Getchell (2006)	4 vs. 6 vs. 8 vs. 10 years old children vs. Adults	Yes	4 faster than 6 = 8 =10 years old = Adults	4 = 6 = 8 = 10 years old less stable than Adults	Dual task	Single faster than Dual	Dual less stable than Single	No interaction Age × Dual task	Striking cymbals	Hands/forearms	Other walking task (GAITRite)
Hammerschmidt et al. (2021)	7–49 years old	Yes	Younger faster than Older	Not found	Time of day	Earlier slower than Later	Not found	Not found	Tapping on a keyboard key, or a mouse key, or a touchscreen of a tablet or a smartphone	Finger	Clusters analysis-based on SMT values
					Arousal	Very calm = Rather calm = Neutral = Rather excited = Very excited	Not found				
					Long-term stress	Low stress = Moderate stress = High stress	Not found				
					Musical expertise	Non-musicians slower than Musicians	Not found				
James et al. (2009)	6 vs. 10 years old children vs. Adults	Yes	6 years old faster than Adults	Younger less stable than Older	Support for rocking	Supported = Unsupported	Significant effect (no other information)	Interaction Age × Supported rocking on SMT and its stability: - When the feet were unsupported, only 6 year old were faster than Adults - Only 6 and 10 years old children are more stable with unsupported rocking.	Body rocking	Whole body	/

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TABLE 4 (Continued)

References	Factors modulating the SMT										
	I. Intrinsic factors										
	2. Age	Significance	Direction of the effect (on mean or median of SMT)	Direction of the effect (on the SD or Coefficient of variation of SMT)	Other factor(s)	Direction of the effect (on mean or median of SMT)	Direction of the effect (on the SD or Coefficient of variation of SMT)	Interaction	Task(s)	Effector(s)	Other information
McAuley et al. (2006)	4–5 vs. 6–7 vs. 8–9 vs. 10–12 years old children vs. 18–38 vs. 39–59 vs. 60–74 vs. 75+ years old adults	Yes	Younger faster than Older	Not found	/	/	/	/	Tapping on a copper plate	Hand	Correlation analysis
Monier and Droit-Volet (2018)	3 vs. 5 vs. 8 years old children vs. Adults	Yes	• In non-emotional context: 3 = 5 = 8 years old faster than Adults • In emotional context: 3 = 5 = 8 years old faster than Adults	• In non-emotional context: 3 less stable than 5 less stable than 8 years old = Adults • In emotional context: 3 less stable than 5 less stable than 8 years old less stable than Adults	Emotional context Sex	High-Arousal faster than Low-Arousal = Neutral Male = Female	High-Arousal more stable than Low-Arousal = Neutral Male = Female	No interaction Age × Emotional context	Tapping on a keyboard key	Finger	/

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TABLE 4 (Continued)

References	Factors modulating the SMT									
	I. Intrinsic factors									
	2. Age	Significance	Direction of the effect (on mean or median of SMT)	Direction of the effect (on the SD or Coefficient of variation of SMT)	Other factor(s)	Direction of the effect (on mean or median of SMT)	Direction of the effect (on the SD or Coefficient of variation of SMT)	Interaction	Task(s)	Effector(s)	Other information
Monier and Droit-Volet (2019)	5 vs. 6 vs. 7 years old children	Yes	5 = 6 = 7 years old	5 less stable than 6 less stable than 7 years old	Trial measurement	Trial 1 = Trial 2 = Trial 3	Trial 1 = Trial 2 = Trial 3	/	Tapping on a keyboard key	Finger	Linear regression analysis for age
Provasi and Bobin-Bègue (2003)	2½ vs. 4 years old children vs. Adults	Yes	Younger faster than Adults	Younger less stable than Older	Sensorimotor synchronization task	Pre faster than Post	Pre = Post	Not found	Tapping on a computer screen	Hand	/
Rocha et al. (2020)	4–37 months old infants	Yes	Younger slower than Older	Younger less stable than Older	/	/	/	/	Drumming	Hand	Correlation analysis
Vanneste et al. (2001)	24–29 years old adults vs. 60–76 years old elderly	Yes	24–29 faster than 60–76 years old	26 = 69 years old	Session measurement	Significant effect (no other information)	Session 1 = Session 2 = Session 3 = Session 4 = Session 5	Interaction Age × Session measurement: - Session 1 slower than Session 2 = Session 3 = Session 4 = Session 5 in Younger. - Session 1 slower than Session 2 slower than Session 3 = Session 4 = Session 5 in Oldest.	Tapping on a plastic block	Hand	/
Yu and Myowa (2021)	18 vs. 30 vs. 42 months old children	No	18 = 30 = 42 years old	Not found	/	/	/	/	Drumming with a stick	Hand/forearm	/

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TABLE 4 (Continued)

References	Factors modulating the SMT									
	I. Intrinsic factors									
	3. Effector/ side	Significance	Direction of the effect (on mean or median of SMT)	Direction of the effect (on the SD or Coefficient of variation of SMT)	Other factor(s)	Direction of the effect (on mean or median of SMT)	Direction of the effect (on the SD or Coefficient of variation of SMT)	Interaction	Task(s)	Effector(s)	Other information
Byblow and Goodman (1994)	Left vs. Right	No (in both coordination modes)	• Single rhythmic 1:1 coordination: Left = Right • Polyrhythmic 2:1 coordination: Left = Right	• Single rhythmic 1:1 coordination: Left = Right • Polyrhythmic 2:1 coordination: Left = Right	Session measurement	• Single rhythmic 1:1 coordination: Session 1 = Session 2 = Session 3 • Polyrhythmic 2:1 coordination: Not found	• Single rhythmic 1:1 coordination: Session 1 = Session 2 = Session 3 • Polyrhythmic 2:1 coordination: Not found	Not found (for single and polyrhythmic coordination)	• Single rhythmic 1:1 coordination • Polyrhythmic 2:1 coordination	• Forearm • Forearm	No comparison between the 2 modes of coordination
Getchell et al. (2001)	Right finger tapping in-phase; right finger tapping antiphase; arms clapping alone; lead leg galloping alone; lead leg galloping with clapping; arms clapping with galloping; right leg crawling	Tasks not compared	Not found (tasks not compared)	Not found (tasks not compared)	/	/	/	/	• Tapping on a key • Clapping • Galloping	• Finger • Arms • Legs	Correlation analyses between tasks

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TABLE 4 (Continued)

References	Factors modulating the SMT										
	I. Intrinsic factors										
	3. Effector/ side	Significance	Direction of the effect (on mean or median of SMT)	Direction of the effect (on the SD or Coefficient of variation of SMT)	Other factor(s)	Direction of the effect (on mean or median of SMT)	Direction of the effect (on the SD or Coefficient of variation of SMT)	Interaction	Task(s)	Effector(s)	Other information
Kay et al. (1987)	Left vs. Right	No	• Single: Left = Right • Bimanual: Left = Right in Mirror and Parallel	• Single: Left = Right • Bimanual: Left = Right	Mode of production Session measurement	Single = Mirror faster than Parallel Session 1 = Session 2	Single = Mirror = Parallel Session 1 = Session 2	Not found	• Producing single flexion and extension • Producing bimanual flexion and extension	• Wrist • Wrist	/
Rose et al. (2021)	Finger vs. Foot vs. Whole body	No	Finger = Foot = Whole body	Not found	Age	Younger = Older	Not found	No interaction Effector × Age	• Tapping on a stomp box • Tapping on a stomp box • Stepping on the spot	• Finger • Foot • Whole body	/
Sakamoto et al. (2007)	Arm vs. Leg	Yes	Arms slower than Legs	Not found	/	/	/	/	• Pedaling • Pedaling	• Arms • Legs	/
Tomyta and Seki (2020)	1 Finger vs. 4 Fingers vs. Hand/Forearm	No	Not found	1 Finger = 4 Fingers = Hand/Forearm	/	/	/	/	• Tapping on (a) keyboard key(s) • Drumming with a stick	• Finger(s) • Hand/ Forearm	/
Whitall et al. (1999)	Left vs. Right	No	Left = Right	Not found	Mode of tapping	In-phase faster than Anti-phase	In-phase less stable than Anti-phase	Not found	Tapping on keyboard keys	Fingers	/

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TABLE 4 (Continued)

References	Factors modulating the SMT									
	I. Intrinsic factors									
	4. Expertise/ pre disposition	Significance	Direction of the effect (on mean or median of SMT)	Direction of the effect (on the SD or Coefficient of variation of SMT)	Other factor(s)	Direction of the effect (on mean or median of SMT)	Direction of the effect (on the SD or Coefficient of variation of SMT)	Interaction	Task(s)	Effector(s)	Other information
Assaneo et al. (2021)	High vs. Low synchronization skill	Yes	High faster than Low	Not found	/	/	/	/	Producing a syllable	Mouth/lips	/
Bégel et al. (2022c)	Musicians vs. Non- musicians	Yes	Musicians = Non-musicians	Musicians more stable than Non-musicians	/	/	/	/	Tapping on a pad	Finger	/
Loehr and Palmer (2011)	Musicians vs. Non- musicians	No	Musicians = Non- musicians	Not found	/	/	/	/	Playing (one hand) a melody on a piano	Fingers	/
Scheurich et al. (2018)	Musicians vs. Non-musicians	Yes	Musicians slower than Non- musicians	Musicians more stable than Non-musicians	Trial measurement	Trial 1 slower than Trial 2 and Trial 3	Trial 1 = Trial 2 = Trial 3	No interaction Musical expertise × Trial measurement	Tapping a melody on one piano key	Finger	/
Scheurich et al. (2020)	Musicians vs. Non- musicians (experiment 2)	No	Musicians = Non-musicians	Not found	Trial measurement	Trial 1 slower than Trial 2 slower than Trial 3	Not found	No interaction Musical expertise × Trial measurement	Tapping on a force sensitive resistor	Finger	Percussionists excluded
Slater et al. (2018)	Musicians vs. Non- musicians	Yes	Not found	Musicians more stable than Non-musicians	/	/	/	/	Drumming	Hand	Percussionists
Tranchant et al. (2016)	High vs. Low synchronization skill	Yes	• Bouncing: High = Low synchronization skill • Clapping: High = Low synchronization skill	• Bouncing: High more stable than Low synchronization skill • Clapping: High = Low synchronization skill	Type of task	• In High synchronization skill: Clapping faster than Bouncing • In Low synchronization skill: Not found	• In High synchronization skill: Clapping more stable than Bouncing • In Low synchronization skill: Not found	/	• Bouncing • Clapping	• Whole body • Hands	/

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TABLE 4 (Continued)

References	Factors modulating the SMT										
	I. Intrinsic factors										
	5. Genotype	Significance	Direction of the effect (on mean or median of SMT)	Direction of the effect (on the SD or Coefficient of variation of SMT)	Other factor(s)	Direction of the effect (on mean or median of SMT)	Direction of the effect (on the SD or Coefficient of variation of SMT)	Interaction	Task(s)	Effector(s)	Other information
Suzuki and Ando (2018)	Monozygotic vs. Dizygotic twins	No	Monozygotic = Dizygotic	Monozygotic = Dizygotic	Sex	Male = Female	Male = Female	Not found	Striking cymbals	Forearms/ Hands	Significant correlation between the tempo level of each Monozygotic twin but not between each Dizygotic twins
Wiener et al. (2011)	A1+ vs. A1- polymorphism Val/Val vs. Met+ polymorphism	• Yes • No	A1+ slower than A1 - Val/Val = Met+	A1+ = A1 - Val/Val = Met+	/	/	/	/	Tapping on a keyboard key	Not found	Subgroups of polymorphism [DRD2/ANKK1-Taq1a (A1–, A1+); COMT Val158Met (Val/Val, Met+); BDNF Val66Met (Val/Val, Met+)]

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TABLE 4 (Continued)

References	II. Extrinsic factors									
	1. Physical training	Significance	Direction of the effect (on mean or median of SMT)	Direction of the effect (on the SD or Coefficient of variation of SMT)	Other factor(s)	Direction of the effect (on mean or median of SMT)	Direction of the effect (on the SD or Coefficient of variation of SMT)	Interaction	Task(s)	Effector(s)	Other information
Byblow et al. (1994)	Pre vs. Post sensorimotor synchronization	Yes	Pre slower than Post	Not found	Mode of coordination Side	Not found Not found	Not found Not found	Not found	Producing pronation and supination coordination	Forearms	/
Carson et al. (1999)	Pre vs. Post sensorimotor synchronization	Yes	Pre slower than Post	Pre = Post	Weighted coordination Side Mode of coordination	Heavy weight slower than No weight = Light weight Right slower than Left In-phase slower than Anti-phase	Heavy = No weight = Light weight Right = Left In-phase = Anti-phase	Not found	Coordinating flexing and extending elbow and wrist joints	Arm	/
Collyer et al. (1994)	Pre vs. Post sensorimotor synchronization	No	Pre = Post	Not found	Trial measurement Session	Pre: Trial 1 slower than Trial 2 = Trial 3 Post: Trial 1 slower than Trial 2 = Trial 3 Session 1 = Session 2 = Session 3 = Session 4 = Session 5 = Session 6 = Session 7 = Session 8	Not found Not found	Not found	Tapping on a plastic box	Finger	/

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TABLE 4 (Continued)

References	II. Extrinsic factors										
	1. Physical training	Significance	Direction of the effect (on mean or median of SMT)	Direction of the effect (on the SD or Coefficient of variation of SMT)	Other factor(s)	Direction of the effect (on mean or median of SMT)	Direction of the effect (on the SD or Coefficient of variation of SMT)	Interaction	Task(s)	Effector(s)	Other information
Dosseville et al. (2002)	Pre vs. Post physical exercise of pedaling	Yes	Pre slower than Post	Not found	Trial measurement Time of day	Pre: Trial 1 = Trial 2 = Trial 3 = Trial 4 Post: Trial 1 = Trial 3 6 pm faster than 6 am, 10 am and 10 pm//6 am slower than 2 pm	Not found Not found	Not found	Tapping on a table	Finger	/
Hansen et al. (2021)	Cadence of physical training: 50 rpm vs. 90 rpm vs. Freely chosen	Yes	50 rpm slower than Freely chosen 90 rpm faster than Freely chosen	Not found	/	/	/	/	Pedaling	Legs	/
Robles-García et al. (2016)	Pre vs. Post vs. 2 weeks Post imitation and motor practice vs. Motor practice alone in elderly with Parkinson's disease	No	Pre = Post = 2 weeks Post	Pre = Post = 2 weeks Post	Type of physical training Laterality	Imitation and motor practice = Motor practice alone Not found	Imitation and motor practice = Motor practice alone In Pre physical training: Dominant more stable than Non-dominant hand	No interaction Training × Type of physical training	Tapping	Finger	/

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TABLE 4 (Continued)

References	II. Extrinsic factors										
	1. Physical training	Significance	Direction of the effect (on mean or median of SMT)	Direction of the effect (on the SD or Coefficient of variation of SMT)	Other factor(s)	Direction of the effect (on mean or median of SMT)	Direction of the effect (on the SD or Coefficient of variation of SMT)	Interaction	Task(s)	Effector(s)	Other information
Rocha et al. (2021)	Pre vs. Post passive walking in non-walking infants	Yes	Pre = Post	Not found	Passive walking frequency	Fast = Slow	Not found	Interaction Training × Passive walking frequency: - Infant SMT in the Fast walking frequency became faster from pre to post training. - Infant SMT in the Slow condition became slower from pre to post training.	Drumming	Hands	/
Sardroodian et al. (2014)	Pre vs. Post 4 weeks of heavy strength training	No	Pre = Post	Not found	/	/	/	/	Pedaling	Legs	/
Turgeon and Wing (2012)	Pre vs. Post sensorimotor synchronization and continuation	No	Pre = Post	Pre = Post	Age	Younger faster than Older	Younger more stable than Older	Not found	Tapping on a mouse key	Finger	Linear regression analysis for age
Zamm et al. (2018)	Pre vs. Post faster or slower sensorimotor synchronization	No	Pre = Post	Not found	Time of day Age Sex	Earlier = Later Younger = Older Not found	Not found Not found Not found	Not found Not found Not found	Playing a melody on a piano	Fingers	Pianists Correlation analysis for age

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TABLE 4 (Continued)

References	II. Extrinsic factors										
	1. Physical training	Significance	Direction of the effect (on mean or median of SMT)	Direction of the effect (on the SD or Coefficient of variation of SMT)	Other factor(s)	Direction of the effect (on mean or median of SMT)	Direction of the effect (on the SD or Coefficient of variation of SMT)	Interaction	Task(s)	Effector(s)	Other information
Bouvet et al. (2019)	Ascending vs. Descending rhythmic stimuli (listening while trying not to synchronize) vs. Without rhythmic stimuli	Yes	Ascending faster than Descending rhythmic stimuli and Without rhythmic stimuli	Ascending stimulus less stable than Descending and Without rhythmic stimuli	Time of testing	Significant effect (no other information)	Significant effect (no other information)	Interaction Value modulation of stimuli time intervals × Time of testing: - Ascending more stable than Without rhythmic stimuli at the beginning of testing. - Ascending and Descending more stable than Without rhythmic stimuli at the end of testing.	Air tapping task (flexion and extension)	Finger	/
	2. External constraints	Significance	Direction of the effect (on mean or median of SMT)	Direction of the effect (on the SD or Coefficient of variation of SMT)	Other factor(s)	Direction of the effect (on mean or median of SMT)	Direction of the effect (on the SD or Coefficient of variation of SMT)	Interaction	Task(s)	Effector(s)	Other information
Bouvet et al. (2020)	One vs. Two vs. Three times the spontaneous motor tempo value as time intervals between stimuli (listening while trying not to synchronize)	Yes	One faster than Two and Three times the spontaneous motor value	One = Two = Three times the spontaneous motor value	Accentuation pattern Session Trial measurement	Unaccented = Binary accented = Ternary accented Session 1 = Session 2 Trial 1 = Trial 2 = Trial 3	Unaccented = Binary accented = Ternary accented Session 1 = Session 2 Trial 1 = Trial 2 = Trial 3	• No interaction Value of stimuli time intervals × Accentuation pattern • No interaction Session × Trial measurement	Air tapping task (flexion and extension)	Finger	/

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TABLE 4 (Continued)

References	II. Extrinsic factors										
	2. External constraints	Significance	Direction of the effect (on mean or median of SMT)	Direction of the effect (on the SD or Coefficient of variation of SMT)	Other factor(s)	Direction of the effect (on mean or median of SMT)	Direction of the effect (on the SD or Coefficient of variation of SMT)	Interaction	Task(s)	Effector(s)	Other information
Hansen and Ohnstad (2008)	200 m real vs. 3,000 m simulated altitude with loading on the cardiopulmonary system (experiment 1)	No	173 W at 200 m real = 173 W at 3,000 m simulated = 224 W at 200 m real	Not found	/	/	/	/	Pedaling	Legs	/
Hatsopoulos and Warren (1996)	0 kg vs. 2.27 kg vs. 4.55 kg external added mass	Yes	0 kg faster than 2.27 kg faster than 4.55 kg	Not found	Session External spring stiffness	Session 1 = Session 2 0 N/m slower than 47.34 N/m slower than 94.68 N/m slower than 142.02 N/m	Not found Not found	Interaction External added mass × External spring stiffness (no more information)	Arms swinging	Arms	/
Sofianidis et al. (2012)	No contact vs. Fingertip contact	Yes	No contact slower than Fingertip contact	Not found	Dance expertise	Expert dancers = Novice dancers	Not found	No interaction Contact interaction × Dance expertise	Body rocking	Whole body	/
Verzini de Romera (1989)	Quiet vs. Noisy environment	Yes	Noisy environment faster than Quiet	Not found	/	/	/	/	Not found	Not found	/
Wagener and Colebatch (1997)	0.35 Nm vs. 0.18 Nm vs. 0.26 Nm extension vs. 0.09 Nm vs. 0.18 Nm flexion torque load vs. without external load	No	0.35 Nm = 0.18 Nm = 0.26 Nm extension = 0.09 Nm = 0.18 Nm flexion = Without external load	Not found	/	/	/	/	Flexion and extension	Wrist	/

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TABLE 4 (Continued)

References	II. Extrinsic factors									
	3. Observation training	Significance	Direction of the effect (on mean or median of SMT)	Direction of the effect (on the SD or Coefficient of variation of SMT)	Other factor(s)	Direction of the effect (on mean or median of SMT)	Direction of the effect (on the SD or Coefficient of variation of SMT)	Interaction	Task(s)	Effector(s)	Other information
Aridan and Mukamel (2016)	Pre vs. Post passive observation of a rhythmic action	Yes	Pre slower than Post (only in subjects with “slower” spontaneous motor tempo at Pre training)	Not found	/	/	/	/	Tapping on keys	Fingers	Subgroups of spontaneous motor tempo profile in Pre training: Slow (slowest spontaneous motor tempo) vs. Fast (fastest spontaneous motor tempo)
Avanzino et al. (2015)	Pre vs. Post passive observation combined with Transcranial Magnetic Stimulation	Not found	Not found	Not found	Type of observation training (Passive observation of a rhythmic action vs. Passive observation of a landscape)	Not found	Not found	Interaction Passive observation training × Type of observation: Pre slower than Post only for Passive observation of a rhythmic action.	Performing an opposition sequence	Fingers	/

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TABLE 4 (Continued)

References	II. Extrinsic factors										
	3. Observation training	Significance	Direction of the effect (on mean or median of SMT)	Direction of the effect (on the SD or Coefficient of variation of SMT)	Other factor(s)	Direction of the effect (on mean or median of SMT)	Direction of the effect (on the SD or Coefficient of variation of SMT)	Interaction	Task(s)	Effector(s)	Other information
Bisio et al. (2015)	Pre vs. Post passive observation of a rhythmic action	Not found	Not found	Not found	Type of observation training (Passive observation of a rhythmic action vs. Passive observation of a rhythmic action combined with peripherical nerve stimulation vs. Peripherical nerve stimulation vs. Passive observation of a landscape)	Not found	Not found	Interaction Passive observation training × Type of observation: Pre slower than Post only for Passive observation of a rhythmic action combined with peripherical nerve stimulation.	Performing an opposition sequence	Fingers	/

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TABLE 4 (Continued)

References	II. Extrinsic factors										
	3. Observation training	Significance	Direction of the effect (on mean or median of SMT)	Direction of the effect (on the SD or Coefficient of variation of SMT)	Other factor(s)	Direction of the effect (on mean or median of SMT)	Direction of the effect (on the SD or Coefficient of variation of SMT)	Interaction	Task(s)	Effector(s)	Other information
Bove et al. (2009)	Pre vs. Post passive observation of a rhythmic action (after 45 min and 2 days)	No	Pre = Post 45 min = Post 2 days	Not found	Instruction Type of passive observation	Not found Not found	Not found 1 Hz more stable than 3 Hz rhythmic action and Landscape	• Interaction Type of Passive observation × Instruction: With instruction faster than without instruction only for passive observation of a 3 Hz rhythmic action. • Interaction Pre-Post × Type of observation: Pre less stable than Post only for passive observation of a 3 Hz rhythmic action	Performing an opposition sequence	Fingers	/
Lagravinese et al. (2017)	Type of passive observation: Passive observation of a rhythmic action vs. Passive observation of a metronome	Not found	Not found	Not found	Session	In Pre training: Session 1 slower than Session 2 slower than Session 3 = Session 4 = Session 5	Significant effect (no other information)	Interaction Type of passive observation × Session: - Day 5 faster than Day 1 only for Passive observation of a rhythmic action. - Day 5 more stable than Day 1 only for Passive observation of a metronome.	Performing an opposition sequence	Fingers	/

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TABLE 4 (Continued)

References	II. Extrinsic factors										
	4. Time of testing	Significance	Direction of the effect (on mean or median of SMT)	Direction of the effect (on the SD or Coefficient of variation of SMT)	Other factor(s)	Direction of the effect (on mean or median of SMT)	Direction of the effect (on the SD or Coefficient of variation of SMT)	Interaction	Task(s)	Effector(s)	Other information
Hansen and Ohnstad (2008)	Week 1 from Week 12 (experiment 2)	No	• Pedaling: No change across Weeks • Tapping: No change across Weeks	• Pedaling: Not found • Tapping: Not found	/	/	/	/	• Pedaling • Tapping on a pad	• Legs • Finger	/
Moussay et al. (2002)	6 am vs. 10 am vs. 2 pm vs. 6 pm vs. 10 pm	Yes	• Tapping: 6 am slower than 6 pm//6 pm faster than 10 pm • Pedaling: 6 am slower than 10 am, 2 pm, 6 pm, and 10 pm	• Tapping: Not found • Pedaling: Not found	/	/	/	/	• Tapping on a table • Pedaling	• Finger • Legs	Cyclists
Oléron et al. (1970)	Wake-up vs. Morning vs. Midday vs. Early afternoon after nap vs. Middle afternoon vs. Evening vs. Bed time	Yes	Wake-up slower than Morning	Not found	Staying in a cave	Beginning of staying in a cave slower than Ending of staying in a cave (linked to circadian rhythm modification)	Not found	Not found	Tapping on a Morse key	Finger	Significant effect only reported between Wake up and Morning
Schwartze and Kotz (2015)	Time 1 (Target) vs. Time 2 (Control)	Yes	Time 1 (Target) = Time 2 (Control)	Time 1 (Target) more stable than Time 2 (Control)	Age	Younger = Older	Younger = Older	Not found	Tapping on a pad	Finger	Correlation analysis for age
Wright and Palmer (2020)	9 am vs. 1 pm vs. 5 pm vs. 9 pm	Yes	9 am slower than 1 pm, 5 pm and 9 pm//1 pm slower than 9 pm	9 am less stable than 5 pm and 9 pm//1 am less stable than 9 pm	Familiar melody	Familiar slower than Unfamiliar	Familiar more stable than Unfamiliar	No interaction Time of testing × Familial melody	Playing (one hand) a melody on a piano	Fingers	Pianists

(Continued)

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TABLE 4 (Continued)

References	II. Extrinsic factors										
	5. Internal state	Significance	Direction of the effect (on mean or median of SMT)	Direction of the effect (on the SD or Coefficient of variation of SMT)	Other factor(s)	Direction of the effect (on mean or median of SMT)	Direction of the effect (on the SD or Coefficient of variation of SMT)	Interaction	Task(s)	Effector(s)	Other information
Boulanger et al. (2020)	Increasing vs. Decreasing gravity	Yes (but descriptive data)	Larger linear relationship with gravity in Increasing gravity than in Decreasing gravity (higher energetic cost in high gravity for a given change in frequency)	Not found	Session	Session 1 = Session 2	Not found	Not found	Performing upper arm movements	Arm	Mathematical data representing spontaneous motor tempo
Dosseville and LaRue (2002)	Apnea vs. No apnea	Yes	Apnea slower than No apnea	Not found	/	/	/	/	Tapping on a metal plate	Finger	/
Murata et al. (1999)	Mental stress vs. No mental stress	Yes	Mental stress faster than No mental stress	Mental stress less stable than No mental stress	Trial measurement (3 Trials with Mental stress)	Not found	Not found	Not found	Tapping a key	Finger	/
	6. Type of task	**Significance**	**Direction of the effect (on mean or median of SMT)**	**Direction of the effect (on the SD or Coefficient of variation of SMT)**	**Other factor(s)**	**Direction of the effect (on mean or median of SMT)**	**Direction of the effect (on the SD or Coefficient of variation of SMT)**	**Interaction**	**Task(s)**	**Effector(s)**	**Other information**
Forrester and Whitall (2000)	In-phase vs. Anti-phase	Yes	In-phase faster than Anti-phase	In-phase = Anti-phase	Fingers pairing	Index only slower than Middle only	Index only = Middle only = Index + Middle	No interaction Type of task × Fingers pairing	Bimanual tapping on keys	Fingers	/

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TABLE 4 (Continued)

References	II. Extrinsic factors										
	6. Type of task	Significance	Direction of the effect (on mean or median of SMT)	Direction of the effect (on the SD or Coefficient of variation of SMT)	Other factor(s)	Direction of the effect (on mean or median of SMT)	Direction of the effect (on the SD or Coefficient of variation of SMT)	Interaction	Task(s)	Effector(s)	Other information
Pfordresher et al. (2021)	Finger tapping vs. Playing a melody vs. Reciting a sentence (experiment 1)	Yes	Finger tapping slower than Playing a melody slower than Reciting a sentence (experiment 1)	Reciting a sentence more stable than Playing a melody and Finger tapping (experiment 1)	/	/	/	/	• Playing (one hand) a melody on a piano • Tapping on a piano key • Reciting a sentence	• Fingers • Finger • Mouth/lips	Correlations analyses on consistency across trials
	Playing a melody vs. Reciting a sentence (experiment 2)	Yes	Playing a melody slower than Reciting a sentence (experiment 2)	Reciting a sentence more stable than Playing a melody (experiment 2)							
Scheurich et al. (2018)	Tapping a melody vs. Playing a melody (experiment 1)	No	Tapping a melody = Playing a melody	Not found	Trial measurement	Trial 1 slower than Trial 2 slower than Trial 3	Not found	No interaction Type of task × Trial measurement	• Tapping a melody on one piano key • Playing (one hand) a melody on a piano	• Finger • Fingers	Correlations analyses on consistency across melodies
Tajima and Choshi (1999)	Polyrhythmic vs. Single rhythmic task	Yes	• Left hand: Polyrhythmic slower than Single rhythmic task (Trial 1, 2 and 3) • Right hand: Polyrhythmic slower than Single rhythmic task (Trial 1 and 2)	• Left hand: Polyrhythmic less stable than Single rhythmic task (Trial 1 and 2) • Right hand: Polyrhythmic less stable slower than Single rhythmic task (Trial 1, 2 and 3)	Sex	Male = Female	Male = Female	Not found	Tapping on Morse keys	Fingers	Differences reported separately for the right and the left hands and across trials

(Continued)

TABLE 4 (Continued)

References	II. Extrinsic factors										
	6. Type of task	Significance	Direction of the effect (on mean or median of SMT)	Direction of the effect (on the SD or Coefficient of variation of SMT)	Other factor(s)	Direction of the effect (on mean or median of SMT)	Direction of the effect (on the SD or Coefficient of variation of SMT)	Interaction	Task(s)	Effector(s)	Other information
Zelaznik et al. (2000)	Tapping vs. Drawing	Yes	Tapping faster than Drawing	Drawing more stable than Tapping	/	/	/	/	• Tapping on a desk • Drawing a circle on a paper	• Finger • Fingers/Wrist	/
	7. Dual task	Significance	Direction of the effect (on mean or median of SMT)	Direction of the effect (on the SD or Coefficient of variation of SMT)	Other factor(s)	Direction of the effect (on mean or median of SMT)	Direction of the effect (on the SD or Coefficient of variation of SMT)	Interaction	Task(s)	Effector(s)	Other information
Aubin et al. (2021)	Selective vs. Divided vs. Sustained attentional conditions	No	Selective = Divided = Sustained	Selective = Divided = Sustained	/	/	/	/	Legs swinging	Legs	Dual task
Serrien (2009)	Single motor task vs. Dual motor and verbal counting task	Not found	Not found	Not found	Side (Left vs. Right vs. Bimanual)	Not found	Not found	Interaction Dual task × Side: In Bimanual mode, Dual slower than Single	Tapping on a keyboard	Finger(s)	/

Factors are classified as intrinsic and extrinsic. Significance is reported as YES if one of the dependent variables (mean, median, standard deviation, or coefficient of variation of SMT) is significantly different between modalities of the main factor studied. The effectors used to perform the task are reported. Other information is reported if mentioned in the studies, particularly the effects of other secondary factors or interactions. The directions of effects of the main and other factors on the dependent variable(s) are reported. The directions of effects are reported as Not found when no statistics were performed on the dependent variable, when the dependent variable was not studied, or when the direction of the effect or the interaction was not explicitly reported.

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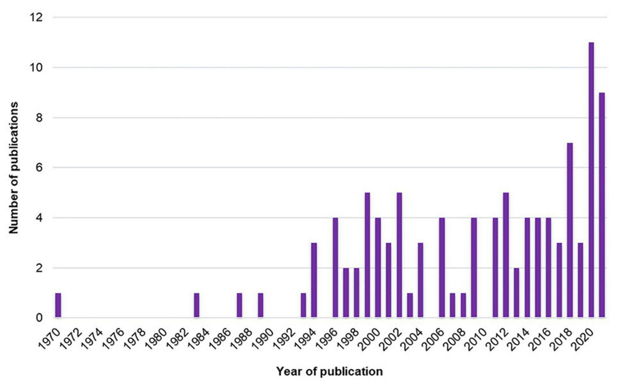

FIGURE 2
Number of studies exploring the SMT across years.

The number of studies exploring the SMT across years is presented in Figure 2.

4. Discussion

The present systematic review aimed to (1) characterize the range of SMT values found in the literature in healthy human adults and (2) identify all the factors modulating the SMT values in humans.

First, it is interesting to note that the global number of studies has grown since the early 1970's (Figure 2). The increase in studies about SMT actually started in the mid-1990's and has grown non-linearly to reach a peak in 2020. Thus, interest in SMT is old but has recently increased.

Second, our results highlight that (1) the reference value of SMT is far from being a common value of 600 ms in healthy human adults, but a range of SMT values exists and (2) many factors modulate the SMT values. We discuss these factors according to a classification as *intrinsic factors*, in relation to personal characteristics, and *extrinsic factors*, in relation to environmental characteristics. We also provide recommendations to measure, report, and use the SMT values for future studies on rhythmic production and perception.

4.1. Range of SMT values in healthy human adults

Regarding the range of SMT values, we have selected the studies that propose an SMT task as a baseline, followed by a second task that is usually a sensorimotor synchronization task, without comparison between factors or conditions (Table 3). However, no value of SMT is reported in some studies ($N = 2/13$). Hence, it is important to measure the SMT as a baseline before any rhythmic task and to report the SMT values in order to interpret the results with regard to this baseline.

The number of studies measuring the SMT as a baseline for a rhythmic task (to adjust the tempo of the rhythmic task) is rather low (Table 3), compared to those testing the effects of variables on the SMT values (Table 4). This may be due to the fact that the terminology used to designate the spontaneous motor tempo is heterogeneous. Although the SMT was clearly defined by Fraisse (1974) as the speed that the subject considers most natural and pleasant (p. 50), this terminology is not unanimous. Although some authors use the term "spontaneous motor tempo" (Drake et al., 2000; McPherson et al., 2018; Amrani and Golumbic, 2020), others use different terms, such as "preferred motor tempo" (Michaelis et al., 2014), "preferred rate" (McCombe Waller and Whitall, 2004), "preferred frequency" (Volman et al., 2006; Bouvet et al., 2020), "internal clock" (Yahalom et al., 2004), "spontaneous production rate" (Wright and Palmer, 2020), "motor spontaneous tempo" (Dosseville and LaRue, 2002; Moussay et al., 2002), "spontaneous movement tempo" (Avanzino et al., 2015; Bisio et al., 2015), "freely chosen cadence" (Sidhu and Lauber, 2020; Hansen et al., 2021), or "personal tempo" (Tajima and Choshi, 1999). In the same vein, the term "self-paced" is not used with a consensual definition. Sometimes, this term relates to an intentional spontaneous motor behavior without a rhythmic component, even if authors use the term "self-paced tapping" (e.g., Bichsel et al., 2018, not included in the present review), and sometimes it relates to an intentional spontaneous rhythmic motor behavior when "self-paced" is followed by "tempo" (Serrien, 2009; Hattori et al., 2015). For future studies measuring the SMT, we recommend using the terminology "spontaneous motor tempo" when the participant is invited to produce a rhythmic motor task not induced by external stimuli specifying a required tempo. The term "spontaneous motor tempo" should be preferred to the term "self-paced" to define the task. To increase the visibility of studies implying SMT, the term "spontaneous motor tempo" and its acronym "SMT" should appear in the title or keywords of the articles.

The tasks used to measure the SMT are also very heterogeneous. Even if Fraisse (1974) declared that SMT is commonly measured during a manual task (Fraisse, 1974), our results reveal that studies exploring SMT also measure other effectors apart from manual ones. Some studies use self-paced tapping with one or two effectors; others use drumming, hopping, pointing, cycling, swaying, and producing syllables; and another uses jaw opening-closing and chewing (Table 3). Regarding the SMT values, participants seem to be slower when the whole body or the jaw is required, compared to manual responses. Thus, the heterogeneity of effectors (finger, arm, leg, whole body, mouth/lips, and jaw) used to produce the SMT could explain the heterogeneity of results. This hypothesis could be in accordance with the results of Sakamoto et al. (2007), highlighting that the SMT is effector-dependent (Sakamoto et al., 2007), but we recommend to carry out further studies to test the impact of effectors on SMT.

The range of SMT values (from 333 to 3,160 ms) is far from being a common value of 600 ms, as first reported by Fraisse (1974). More specifically, it is important to note that studies reporting the slowest SMT values involve cyclical movements compared to the discrete isochronous movements of tapping or clapping. Regarding finger tapping, SMT appears to be faster (from 333 to 931 ms). Bouvet et al. (2020), who investigate the effect of accents and subdivisions in synchronization, performed a measurement of SMT during finger-tapping with a large number of taps in several trials.

They also find a faster value around 650 ms. The heterogeneity of results can be explained by the heterogeneity in the paradigm applied to measure the SMT in the studies. We provide such examples in the following paragraphs.

First, the characteristics of participants are not homogeneously reported, particularly their level of musical experience. In some studies listed in Table 3, authors report that participants have no musical training. Note that some studies mix musicians and non-musicians in their samples (e.g., Michaelis et al., 2014; De Pretto et al., 2018). However, three studies reported in Table 4 show an effect of music expertise (Drake et al., 2000; Slater et al., 2018; Hammerschmidt et al., 2021). Information about musical expertise is particularly important, including the expertise of listening to music, given that it is possible that participants could present amusia or a deficit in rhythm production or perception (Stewart et al., 2006; Clark et al., 2015; Peretz, 2016; Sarasso et al., 2022). To have a better overview of the range of SMT values in healthy adults without musical expertise, we recommend reporting a general level of musical experience, that is, both the level of expertise in music/rhythm production and music/rhythm exposure.

Second, the characteristics of participants are also heterogeneous across studies in terms of age, sex, and laterality. Regarding the age, participants are from 18 to 45 years old (Table 1). Despite the fact that the age range is representative of healthy young adults, the range of SMT values varies in five studies about manual responses from 333 to 1,100 ms (Michaelis et al., 2014; De Pretto et al., 2018; McPherson et al., 2018; Zhao et al., 2020). Regarding the sex repartition, only two studies recruit an equal number of women and men (Michaelis et al., 2014; De Pretto et al., 2018); the others recruit either more women or more men. As reported in Table 4, the effect of sex on SMT has not been extensively studied, given that only one study addresses this question and reports no significant results (Suzuki and Ando, 2018). Regarding the laterality, the majority of studies do not report the laterality of participants (Table 3, $N = 8/13$). The other studies generally recruit right-handed participants (Table 3, $N = 3/5$). Some studies include one or two left-handed participants (Table 3, $N = 2/5$). In Table 4, no study investigates the effect of laterality on the SMT values. In the absence of clear results about laterality, we recommend specifying the laterality of the participants by means of a laterality questionnaire (e.g., Oldfield, 1971) in the case of a SMT task performed with a lateralized effector (hand or leg). More globally, to have a better overview of the range of SMT values in healthy adults, we recommend reporting the age, sex, and laterality of participants and specifying, if possible, whether the SMT differs according to these variables.

Third, how the SMT is *measured* is not consistent across studies (Table 3). As specified in Table 3, SMT paradigms differ according to the number of trials and their duration, as well as to the instructions provided to the participants. The number and duration of trials vary across studies. Globally, the number of trials is from 1 to 10, and the duration of each trial can be expressed as a range of time (seconds or minutes), a number of responses, or a number of inter-response intervals (Table 3). Two studies do not report any information about trials (Ruspantini et al., 2012; Malcolm et al., 2018). Regarding the instructions, it is important to note that the instructions are *not* reported in three out of 13 studies (Eriksson et al., 2000; Hattori et al., 2015; Malcolm et al., 2018). When reported, the instructions contain the terms "natural," "comfortable," "most comfortable," "naturally comfortable," "preferred," "steady," "freely chosen," "own self-selected," "spontaneously," "without mental effort," "do not require much awareness," "without fatigue," and "could be performed all day if necessary," to characterize the manner to produce the SMT (Table 3). Moreover, the tempo itself is characterized as "tempo," "pace," "cadence," "speed," "rate," and "frequency." Even if these terms are supposed to represent the same instruction, we would like to emphasize that the semantics is not a detail. The instruction can modify the participant's behavior depending on the interpretation he/she makes of it. For example, the term "speed" can be interpreted by participants as an instruction to go fast. Thus, to have a better overview of the range of SMT values in healthy adults, we recommend reporting exactly and exhaustively the standardized instructions given to participants. More precisely, we recommend giving priority to the notions of "preferred," "spontaneous," and "comfortable tempo," in the instructions given to the participant. It seems important to avoid the notion of "speed" in order not to induce the idea of performing the task as quickly as possible.

Fourth, how SMT is *recorded and computed* is not consistent. Regarding the measurement recordings, authors report the inter-response interval, frequency, number of movement cycles during the total duration of the trial, rate, cycle time, speed, or cadence. If reported, the values also have different units (milliseconds, seconds, beats per minute, Hertz, repetitions per minute, or kilometers per hour). Furthermore, the authors usually report the range of SMT values, the SMT mean and/or median, its standard deviation, and/or the coefficient of variation (Table 3). These discrepancies are probably due to the type of task used. Only two studies recording SMT do not report any value for SMT (LaGasse, 2013; Zhao et al., 2017). On this basis, we recommend reporting the SMT values when recorded and homogenizing the measurement recording, the variables, and their units (in milliseconds or Hz). It is, therefore, necessary to report, at least, the SMT values with the median and the range of SMT values with a box plot representing individual values to get access to the distribution of data with the minimal and maximal values. It is also important to specify the methodology to compute the SMT, in particular to report excluded data, for example, the first responses that were performed by the participants, which can be considered warm-up.

4.2. Intrinsic and extrinsic factors modulating SMT values

Table 4 summarizes the results of studies about factors that could modulate the SMT values. We classified these factors as intrinsic and extrinsic ones, i.e., factors that could explain inter- and intra-individual variability in SMT values. Figure 3 presents the repartition of studies about the factors modulating the SMT values according to the intrinsic factors ($N = 59$) and the extrinsic factors ($N = 36$).

Regarding the intrinsic factors, our results reveal that the SMT is affected by several factors such as pathology, age, effector,

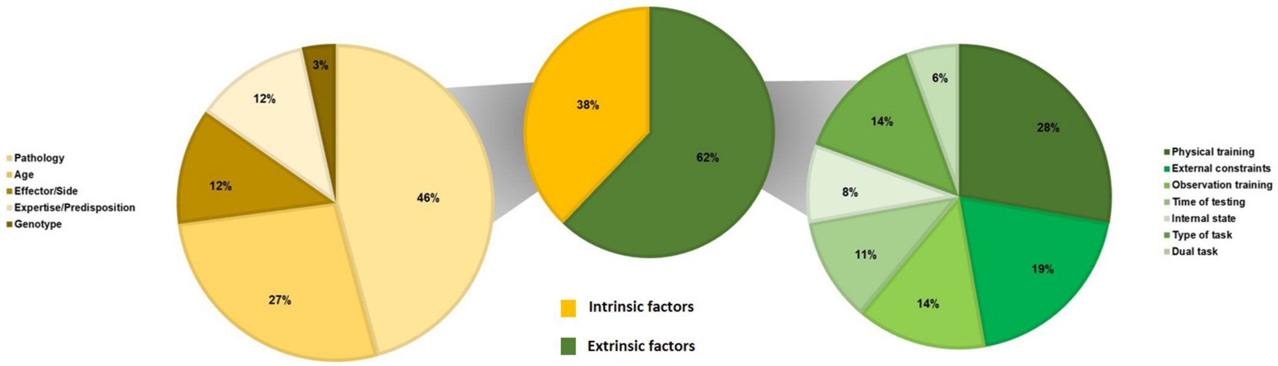

FIGURE 3
Repartition of studies on the factors modulating the SMT values ($N = 94$) according to intrinsic factors ($N = 59$) and extrinsic factors ($N = 36$).

expertise, or genotype (see Table 4). First, our results reveal that several pathologies modify the SMT values. Studies investigate brain lesions (six on Parkinson's, four on stroke, one on Huntington disease, one on Alzheimer's disease, one on Whiplash, and two on cerebellar lesions), neurodevelopmental disorders (two on attention deficit and hyperactivity disorder, two on developmental coordination disorder, one on developmental intellectual deficit, one on stuttering, and one on minor neurological dysfunction), and mental disorders (two on schizophrenia). Two studies test the effects of a deficit in music perception (beat deafness, i.e., difficulties in tracking or moving to a beat), and only one study examines the effect of an amputation. Globally, our results show that the most studied pathologies are brain lesions. Results indicate quasi-unanimously that SMT is affected by brain lesions (Table 4, $N = 12/15$). Studies report that either the frequency or the stability of the SMT differs in brain-injured patients compared to controls. In brain lesions, neurodegenerative disorders are the most studied, such as Parkinson's and Huntington's diseases (both implying a lesion of the basal ganglia) or Alzheimer's disease. Studies on Parkinson's disease report quasi-consistently that SMT is significantly affected in patients compared to healthy elderly individuals (Table 4, $N = 5/6$), and the study on Huntington's disease reports the same effect (Martínez Pueyo et al., 2016). The only study on Alzheimer's disease does not report any difference between patients and healthy elderly individuals (Martin et al., 2017). Moreover, most of the studies report that SMT is significantly affected in patients with stroke compared to healthy adults (Table 4, $N = 3/4$). In contrast, results are less consistent for neurodevelopmental and mental disorders. Attention deficit and hyperactivity disorder seems to affect the SMT (Table 4, $N = 2/2$), as does developmental coordination disorder (Table 4, $N = 2/2$). Only two studies report the effects of beat deafness with no consistent results (Phillips-Silver et al., 2011; Palmer et al., 2014). Based on these results, it is interesting to note that the SMT is affected regardless of the location of the lesion (motor cortex, language areas, basal ganglia, or cerebellum) and regardless of the physiopathology (neurodegenerative vs. neurological vs. neurodevelopmental). Although it seems more likely that focal lesions affect the SMT, future studies are required to better understand if and how the SMT is affected by neurodevelopmental, mental, and sensory disorders.

A second factor modulating the SMT is age. Studies investigate mostly infants (Table 4, $N = 14/16$). Only three studies investigate the elderly (Vanneste et al., 2001; Baudouin et al., 2004; McAuley et al., 2006). Our results reveal that age modifies the value of the SMT in the majority of studies (Table 4, $N = 11/14$). In fact, only three out of 14 studies do not find an effect of age in infants or children (Droit et al., 1996; Fitzpatrick et al., 1996; Yu and Myowa, 2021). It is interesting to note that only two studies test the possible effects of age on the SMT in individuals between 18 and 60 years old (McAuley et al., 2006; Hammerschmidt et al., 2021). Anyway, our results suggest that future studies about the SMT should take into account the effect of age bands or include the age of participants as a covariate, especially if participants are infants or elderly individuals.

A third intrinsic factor modulating the SMT is the effector/side used to produce the task. Results are very contradictory, with one study revealing an effect of the effector (Sakamoto et al., 2007) and two studies failing to reveal this effect (Tomyta and Seki, 2020; Rose et al., 2021). It seems that there is no effect of the side of the hand producing the SMT (Kay et al., 1987; Byblow and Goodman, 1994; Whitall et al., 1999). Moreover, it is also possible that SMT differs when it is produced with arms and legs (Sakamoto et al., 2007). Finally, the study of Getchell et al. (2001) reveals a correlation between SMT produced by different effectors. This result suggests that individuals have a general ability to produce their own SMT regardless of the type and number of effectors used (Getchell et al., 2001). Given that only one study reports this finding, further studies are required to confirm this effect.

As previously discussed above, expertise in music seems to modify the SMT. Musicians seem to have a more stable SMT than non-musicians (Scheurich et al., 2018; Slater et al., 2018; Bégel et al., 2022c). Moreover, two studies suggest that a predisposition to high or low synchronization (i.e., good or poor synchronization skills in rhythmic synchronization tasks) alters the SMT (Tranchant et al., 2016; Assaneo et al., 2021). Even if long-lasting intensive training could modify the SMT in certain conditions, it seems that intrinsic predispositions could be important. This result is in accordance with the last intrinsic factor identified in the current literature review, namely, the genotype. Two studies focus on this factor (Wiener et al., 2011; Suzuki and Ando, 2018). The first study finds a significant correlation between the tempo level in monozygotic twins but not in dizygotic twins, thereby suggesting that the genetic code could have a role in the SMT values (Suzuki and Ando, 2018). However, no difference between women and men is found, thereby preventing the possible role of sex on the SMT values (Suzuki and Ando, 2018). The second study reveals a significant effect of a polymorphism (Wiener et al., 2011). If we consider that one polymorphism (A1+) seems implied in the regulation of the density of receptors in the striatum (see Wiener et al., 2011), this result is in accordance with the results of studies showing an effect of Parkinson's disease, which affects the striatum, on the SMT (Konczak et al., 1997; Byblow et al., 2002; Flasskamp et al., 2012; Rose et al., 2020; Horin et al., 2021). Even if further studies are required to confirm this hypothesis, there is evidence that the genotype plays a role in the SMT values.

Regarding the extrinsic factors, our results highlight that the SMT is affected by several factors such as physical training, external constraints, observation training, time of testing, type of task, or dual tasking (see Table 4).

In total, 10 studies report results about the effects of physical training on the SMT. Six studies reveal a significant effect of cycling, strength training, synchronization, or physical exercise on the SMT values measured before and after training (Table 4). This result suggests that all studies about SMT should report the activity preceding the measurement of the SMT, especially physical activity.

In the same vein, all the studies ($N = 5$) testing the effects of the observation of a rhythmic action on the SMT found a significant effect (see Table 4). This result indicates that observing a rhythmic action without moving or synchronizing with it induces a spontaneous change in the SMT. This result is in accordance with the results of studies about the effects of physical training with rhythmic stimuli (Byblow et al., 1994; Carson et al., 1999; Hansen et al., 2021; Rocha et al., 2021). They are also in accordance with results about the effect of external constraints that show a significant effect of producing SMT while listening to a rhythmic metronome without synchronizing (Bouvet et al., 2019). The effect of observation or listening could be related to the implication of the Mirror System that is activated during observation, listening, and action (Kohler et al., 2002; Rizzolatti and Craighero, 2004). More precisely, it is possible that observing/listening a rhythm activates the same cerebral areas (i.e., the fronto-parietal system) as synchronizing to rhythmic stimuli (Konoike and Nakamura, 2020), hence modifying the SMT values according to the observed/listened tempo.

Regarding the effect of a dual task on the SMT, only one of the two studies reports a significant difference in the SMT during a single vs. dual task (Serrien, 2009). In the other study (Aubin et al., 2021), participants were instructed to swing their legs at their preferred frequency while performing a secondary task (reaction times), but no significant effect of the dual task was found. The discrepancy of results between the two studies could be explained by the fact that the secondary task is not rhythmic in Aubin et al. (2021), whereas the secondary task implies a rhythmic component in Serrien (2009). This hypothesis is in accordance with the results of studies examining the effects of rhythmic external constraints (Bouvet et al., 2019, 2020). We could deduce that the SMT is robust to a general cognitive load but can be impacted by external rhythmic stimulation. Hence, we can recommend not to perform a rhythmic task before or during the production of a task assessing SMT because it can change the SMT values.

Regarding the external constraints, most studies ($N = 5/7$) report consistent results about the significant effects of external constraints, such as a noisy environment, the presence of fingertip contacts, or a varying spring constraint on the SMT values (Table 4). However, the effect of loading is not consistent (Hatsopoulos and Warren, 1996; Wagener and Colebatch, 1997; Hansen and Ohnstad, 2008).

The type of task seems to quasi-consistently modulate the SMT values in four out of five studies (Table 4). Specifically, results indicate that the SMT is affected by in-phase or anti-phase bimanual tapping, polyrhythmic or single rhythmic tapping, and by tapping, drawing, playing a melody, or reciting a sentence (Tajima and Choshi, 1999; Forrester and Whitall, 2000; Zelaznik et al., 2000; Pfordresher et al., 2021).

The internal state seems to modulate the SMT values as well (Table 4). Three out of 3 studies report an effect of the internal state, such as apnea, mental stress, and gravity on the SMT values (Murata et al., 1999; Dosseville and LaRue, 2002; Boulanger et al., 2020). Once again, these results indicate that the SMT is not robust and that intra-individual variability exists. In the same vein, the time of testing seems to have an effect on the SMT values (Table 4). More precisely, studies unanimously report an effect of the time of day on the SMT values (Oléron et al., 1970; Dosseville et al., 2002; Moussay et al., 2002; Wright and Palmer, 2020). It seems that the SMT values vary in the course of the day, being slower in the morning than in the evening (Moussay et al., 2002; Wright and Palmer, 2020). As for the effect of internal state mentioned above, this effect may be related to the circadian variations of internal physiological and psychological factors, such as hormones or fatigue. Anyway, it is important to interpret this result in relation to the results of many studies that have shown an effect of trial measurement (Collyer et al., 1994; Drake et al., 2000; Scheurich et al., 2018, 2020; Bouvet et al., 2019).

5. Conclusion and perspectives

All in all, our systematic review highlights large intra- and inter-individual variability in the SMT values. According to the internal clock model (Treisman, 1963), individuals have an internal clock that is a reference generating time information, used to perceive information, and to produce and reproduce behaviors. Each individual has his/her own internal clock, leading to strong intra-individual consistency, but individual preferences exist in the production and perception of rhythms. Moreover, the internal clock can be affected by many intrinsic and extrinsic factors. We hope that the current review will lead to a better choice of reference values for SMT. We have proposed specific recommendations and points of vigilance to assess the SMT in future research.

Our results could also be transferred to applied contexts related to rehabilitative, educative, and sport interventions involving rhythmic sensorimotor synchronization. For example, dance can be viewed as a rhythmic activity in which individuals have to learn a choreography in synchrony with rhythmic stimuli provided by music and partners. Irrespective of the context (e.g., rehabilitation, education, and sport), current studies recommend individualizing music-based rhythmic cueing to induce motor improvement (Dalla Bella et al., 2018). Given that performance in synchronization-continuation tasks is improved when the tempo of stimuli is closest to the SMT (Delevoye-Turrell et al., 2014) and that the SMT seems to predict performance in externally paced tasks such as sensorimotor synchronization (McPherson et al., 2018), the choice of the tempo of the music should be carefully determined to correspond to the SMT. However, our systematic review highlights that the SMT is not a fixed and universal value but rather a range of values, so it should be measured just before intervention to provide a reference at the time of the intervention, considering the effectors used to produce the task and the current conditions. Accordingly, the measurement of SMT should be explicitly and exhaustively described to interpret the value obtained (including the instructions provided to measure the SMT). To consider the large intra-individual variability of the SMT, we advise performing more than a single trial per participant to measure the SMT. In line with the recommendation of Amrani and Golumbic (2020), SMT consistency should be measured within a trial, within a session, and across sessions (Amrani and Golumbic, 2020). Finally, it could be interesting to conduct a similar systematic review on the preferred perceived tempo (PPT), which can be measured either as the chosen tempo among several tempi (Baruch et al., 2004; Bauer et al., 2015) or from a dynamic tempo adjustment (speed up or slow down) of a rhythmic metronome until individuals reach their preferred tempo (e.g., Amrani and Golumbic, 2020; Hine et al., 2022). Given the possible relationship between the SMT and the preferred music tempo (e.g., Hine et al., 2022), it is possible that a common tempo for motor and perceived preferences exists. In the case of a common internal clock, we could expect that similar factors affect the SMT and the PPT.

Interdisciplinary implications extend to the field of rehabilitative, educative, and sport interventions involving rhythmic sensorimotor synchronization. Indeed, studies have highlighted the strong role of rhythm in engagement, motivation, and pleasure in performing physical activities. In the context of sport performance, music—through its intrinsic qualities, such as rhythm and particularly its tempo—is known to promote engagement and involvement in a physical activity or sport (Karageorghis et al., 2021). For example, synchronization with music during endurance-based activities (treadmill running tasks) allows for increased time spent practicing (Terry et al., 2012). More globally, results from a meta-analytic review support "the use of music listening across a range of physical activities to promote more positive affective valence, enhance physical performance (i.e., ergogenic effect), reduce perceived exertion, and improve physiological efficiency" (Terry et al., 2020, p. 91).

As a conclusion, the present review provides new elements to understand the inter- and intra-variability of the SMT, and we hope that our recommendations will be taken into account in future studies investigating performance in rhythmic production and perception tasks.

Author contributions

AD and JT primarily conducted this systematic review and wrote the first draft of the manuscript. EM provided expertise on the methodology for conducting a systematic review and participated in the discussions for the selection of articles. AD, EM, and JT collected all the information from the selected articles, provided feedback, and revised the manuscript. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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Classical singers are also proficient in non-classical singing

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Classical singers train intensively for many years to achieve a high level of vocal control and specific sound characteristics. However, the actual span of singers' activities often includes venues other than opera halls and requires performing in styles outside their strict training (e.g., singing pop songs at weddings). We examine classical singers' ability to adjust their vocal productions to other styles, in relation with their formal training. Twenty-two highly trained female classical singers (aged from 22 to 45 years old; vocal training ranging from 4.5 to 27 years) performed six different melody excerpts a cappella in contrasting ways: as an opera aria, as a pop song and as a lullaby. All melodies were sung both with lyrics and with a /lu/ sound. All productions were acoustically analyzed in terms of seven common acoustic descriptors of voice/singing performances and perceptually evaluated by a total of 50 lay listeners (aged from 21 to 73 years old) who were asked to identify the intended singing style in a forced-choice lab experiment. Acoustic analyses of the 792 performances suggest distinct acoustic profiles, implying that singers were able to produce contrasting sounding performances. Furthermore, the high overall style recognition rate (78.5% Correct Responses, hence CR) confirmed singers' proficiency in performing in operatic style (86% CR) and their versatility when it comes to lullaby (80% CR) and pop performances (69% CR), albeit with occasional confusion between the latter two. Interestingly, different levels of competence among singers appeared, with versatility (as estimated based on correct recognition in pop/lullaby styles) ranging from 62 to 83% depending on the singer. Importantly, this variability was not linked to formal training *per se*. Our results indicate that classical singers are versatile, and prompt the need for further investigations to clarify the role of singers' broader professional and personal experiences in the development of this valuable ability.

KEYWORDS
music, performance, acoustics, versatility, singing styles

1. Introduction

Classical singers invest years in training to acquire and master a very specific technique. However, the reality of their professional lives often leads them to look for opportunities outside their strict field of training – for instance, performing at weddings or other social events, taking requests to sing pop songs, or even crossing over to musical theater, often without ever properly learning a technique to perform contemporary commercial music (CCM). LeBorgne and Rosenberg (2021) refer to the "hybrid singer" as a highly skilled vocal athlete, able to perform in multiple vocal styles, possessing a solid vocal technique that is "responsive, adaptable, and agile in order to meet demands of current and ever-evolving vocal music industry genres" (p. XV). Nevertheless, they note that the assumption that traditional classical pedagogy can support any style of singing is inconsistent with scientific findings about physiologic differences between classical and CCM styles of singing. Indeed, the growing number of books (Spivey et al., 2018; LeBorgne and Rosenberg, 2021) and dissertations (e.g., Hall, 2006; Willis-Lynam, 2015; Wilson, 2019) about how to teach classical singers to also (healthily) perform musical theater indicates the high demand for singers to (learn to) be versatile. In this study, we investigate the versatility of a cohort of classical singers by examining the acoustic characteristics of singers' performances in contrasting styles, as well as the perception of these performances by lay listeners. We also explore the relationship between singers' versatility and their music training.

According to Edith Bers, Chair of the Julliard Voice Department, it takes about ten years for a classical singer to be ready to begin a career (Kennedy Center, n.d.). Over the years, singers learn to master the mechanisms of vocal production. Following the source-filter theory of voice production (Fant, 1960), the acoustical properties of the voice result from the combination of voice source and vocal tract resonances. Concretely, the subglottal pressure, as well as the tensing and stretching of the vocal folds, and the glottal adduction, collectively modulate the frequency of the airflow going through the vocal folds, which in turn determines the fundamental frequency (f_o). This airflow is then filtered by the vocal tract, which selectively enhances the amplitude of certain partials of the voice source spectrum, via changes in the position of articulators (lips, tongue, lower jaw, velum, pharyngeal walls, and larynx). These alterations in the configuration of the vocal tract lead to formants, that is, bands of enhanced power in the resulting sound (ANSI, 2004; Titze et al., 2015). Specifically, changes in the vocal tract resonance frequencies f_{R1} and f_{R2} (and resulting formants F1 and F2) play a central role in determining vowel quality. Beyond being involved in speech production, this complex machinery allows for the specific acoustic characteristics of classical singing, as summarized by Sundberg (2013). One example is the so-called singer's formant cluster, most clearly described for male voices. Trained male classical singers can produce voice spectra in which the partials falling in the frequency region around 2,5–3 kHz are greatly enhanced, leading to a peak in the spectral envelope. This phenomenon is explained as the acoustic consequence of clustering of the resonances f_{R3}, f_{R4} and f_{R5} (Sundberg, 1974). Another example, mostly concerning female singers, is the resonance tuning strategy in high-pitched singing, which consists of widening the jaw opening so that f_{R1} is shifted to a frequency near f_o, resulting in considerable gain in amplitude of a specific frequency zone (Sundberg, 1975; Joliveau et al., 2004; Garnier et al., 2010). Importantly, both the resonance tuning strategy in high-pitched singing and the singer's formant cluster are resonatory phenomena that increase singers' audibility in the presence of orchestral accompaniment without additional vocal effort (i.e., they allow for vocal economy). This contrasts with contexts like pop singing, where singers typically use a microphone, or lullaby singing, where the intimate setting of close proximity to an infant requires very soft singing. Also noteworthy are nonlinear source-filter interactions, which may make vocal fold vibration unstable when f_o approaches f_{R1} (Titze, 2008; Titze et al., 2008; Kaburagi et al., 2019). These interactions are especially relevant and frequent for female high-pitched singers, who must skillfully mitigate them to avoid qualitative changes in timbre and volume.

Another important feature of classical singing is the extensive use of vibrato, that is, a periodic oscillation in the f_o that develops automatically with training (Bjørklund, 1961; Sundberg, 1994). Voice pedagogues tend to agree that a healthy, well-trained voice will naturally have vibrato (e.g., Miller, 1986). According to Sundberg (2013), the use of vocal vibrato may eliminate beats with the sound of a vibrato-free accompaniment, providing classical singers with some freedom in intonation and allowing thus for greater emotional expression in singing. Likewise, the ability to sing with a "straight tone" – i.e., healthy, unconstrained singing, that is perceived as singing without vibrato, even though there might be oscillations in the acoustic signal – may be seen as a sign of versatility, showing that singers can skillfully control their vibrato to fit any style (Katok, 2021).

In addition to having a wide vibrato, the operatic singing style has been described as more irregular and chaotic than other styles: based on archetypical singing voice samples from different styles (opera, country, soul, jazz, musical theater, and pop), Butte et al. (2009) used nonlinear dynamic analysis of the correlational dimension (the D_2 measure), as well as usual voice perturbation measures, to compare styles. They found higher shimmer and D_2 values for operatic than other singing styles, as well as higher jitter for operatic, pop and soul than other styles. Similarly, Larrouy-Maestri et al. (2014) compared singing performances of the same melodies with and without use of the classical singing technique and described higher jitter and shimmer and lower signal-to-noise ratio (as well as wider vibrato extent and slower tempo) in operatic singing, supporting the (somewhat counterintuitive) idea that the waveform resulting from classical singing is more irregular than that from other singing styles.

A different approach to describe different singing styles focuses on production mechanisms and the voice source. Thalen and Sundberg (2001) recorded performances by one singer proficient in classical, pop, jazz and blues styles, and analyzed perceived phonatory pressedness in relation to markers of vocal production function (inverse filtering and glottogram data). They proposed characterizing singing styles based on modes of phonation (which are related to different degrees of airflow and vocal fold adduction force: breathy, flow, neutral and pressed phonation modes of phonation have been described – Sundberg, 1987). Thalen and Sundberg (2001) suggested that classical singing is usually close to flow phonation, pop and jazz singing have values closer to flow than pressed phonation, and blues singing lies close to pressed phonation. For comparison, the pop style is typically represented by performers like Randy Crawford and Whitney Houston; the jazz style, by performers like Billie Holiday and Sarah Vaughan; and the blues style by performers like Bessie Smith and Janis Joplin (examples given by Sundberg et al., 2004).

Singing expertise demands highly developed motor control, which relies on auditory and kinesthetic feedback (Wyke, 1974). Both aural and kinesthetic awareness are thus encouraged by voice pedagogues (e.g., Ohrenstein, 2003). Such training leads to a particular role of kinesthetic control in classical singers compared both to non-singer musicians and to non-musicians, as indicated by the effect of masking noise in intonation accuracy (Mürbe et al., 2004; Jones and Keough, 2008; Erdemir and Rieser, 2016). This ability is also demonstrated in brain imaging studies showing that classical singing expertise coincides with the development of enhanced somatosensory processing, representing proprioceptive feedback from the articulators and the larynx (Kleber et al., 2010). Classical singing expertise is also related to increased involvement of the cerebellum and implicit motor memory areas at the subcortical level, and to a fronto-parietal network associated with action monitoring and sensory guidance of motor activity (Kleber et al., 2010).

While classical singing training results in specific acoustic patterns and systematic bodily changes, it is not clear how it affects a singer's ability to produce diverse sound qualities when singing in other styles. That is to say, to convincingly perform in other styles, singers may need to suppress or adapt muscular programs acquired during their intense training. To the best of our knowledge, empirical investigations about the proficiency of classical singers in other styles have not yet been conducted.

Here, we examine this ability by focusing on a cohort of classical singers performing the same melodies in three contrasting ways: singers were instructed to sing as if they wanted to make a baby sleep; as if they were singing a pop song with a microphone; and as if they were singing an opera aria on stage. We use the term "style" operationally, with the meaning of contrasting functions and resulting sound qualities. For pragmatic reasons, we chose styles that classical singers could perform without having to learn a further specific singing technique (such as belting). Since we did not provide singers with any definition of "pop," and given the broad use of this term, the pop singing we report here is directly related to the stylistic conceptions and abilities of our particular cohort of (Brazilian) classical singers. Regarding the lullaby singing, we refer to the typical singing used to soothe an infant. Lullabies are usually simple, repetitive melodies, with simple rhythm and a preponderance of small melodic steps, and are typically performed a cappella, with soft and quiet singing by a caregiver (Unyk et al., 1992; Trehub and Trainor, 1998; Mehr et al., 2019). Such typical features allow lullabies to be cross-culturally recognized when compared to matched adult-directed songs (Trehub et al., 1993) or as "music to soothe an infant" (relative to dance, healing or love uses of songs) (Mehr et al., 2018; Yurdum et al., 2023).

Apart from investigating and comparing acoustic characteristics of contrasting singing performances, we also examine singers' versatility through the listener perspective, in a lab experiment where lay listeners performed a style recognition task.

2. Part I: acoustic characteristics of singing performances

2.1. Method

2.1.1. Singer participants

Twenty-two highly trained Brazilian female classical singers (16 sopranos, 6 mezzo-sopranos, aged from 22 to 51 years old, $M = 32.5$, $SD = 7.1$) were recruited *via* personal contact. They had between 4.5 and 27 years of training in classical singing ($M = 12.9$ years, $SD = 6$). All of them also declared having experience performing in other styles: 14 in pop, 13 in MPB (Música Popular Brasileira, a genre of popular Brazilian Music), five in jazz, three in gospel, one in musical theater (multiple responses possible for each singer). They reported spending between one and 40 h per week performing ($M = 15.9$ h, $SD = 9.9$) at the time of the recording (including the time spent practicing). Five singers reported singing exclusively as soloists, five indicated singing about 75% of the time as soloists (and 25% of the time in a choir), five indicated singing about half the time as soloists, and seven indicated singing about 25% of the time as a soloist (and 75% in a choir). Singers also reported having started voice lessons between ages of six and 25 years old ($M = 17.7$ years, $SD = 5.7$), having between four and 30 years of music training ($M = 15.7$, $SD = 7.3$) and playing an instrument between zero and 15 years ($M = 4.5$ years, $SD = 3.9$). They also reported having had on average between zero and eight performances per month in the last 12 months ($M = 2.9$, $SD = 2.4$), including online versions of events due to the COVID-19 pandemic. Singers' characteristics are summarized in Supplementary Table S1.[1]

2.1.2. Material

The melody excerpts correspond to the first phrase of six different Brazilian songs: the lullabies Nana Nenê and Boi da Cara Preta; the play songs Alecrim and Nesta Rua (all very well known, traditional and anonymous Brazilian songs); the MPB song (Música Popular Brasileira, or popular Brazilian music) Chove Chuva by Brazilian artist Jorge Ben Jor (1939–); and the art song Melodia Sentimental, part of the symphonic poem A Floresta do Amazonas by Brazilian classical composer Heitor Villa-Lobos (1887–1959), with text by Dora Vasconcellos (1910–1973). Singers were provided with sheet music well in advance of their scheduled recording session to ensure thorough preparation. Most singers received sheet music between three and four weeks beforehand, together with their invitation to participate in the recording. However, four singers were brought in as last-minute substitutes due to others canceling participation, in which case they received sheet music at least two days before their recording session. The starting note of each melody was played on a keyboard by the researcher before each performance. Please see Supplementary Figure S1 for sheet music and Supporting Text 1 for translations of the texts from the melody excerpts. Performances in operatic singing were recorded with higher pitch than pop and lullaby performances, with the aim of producing naturalistic performances and keeping singers comfortable.[2] This means that for all but one of the melodies, operatic singing was recorded one fifth higher than pop and lullaby singing. The exception was the melody Melodia Sentimental, which was recorded one fourth higher. This was done because of the melody's extensive range, which would otherwise include a G5, potentially challenging for the mezzo-sopranos in the sample.

2.1.3. Procedure

2.1.3.1. Recordings

Singers were invited to a recording session of approximately one hour, in a professional music recording studio in São Paulo,

1 A note about singers' vocal health: we did not explicitly ask for information about vocal health, but two singers declared having acute voice issues in the recording day: singer S14 reported having an acute allergy crisis. Singer S19 only mentioned her voice was "tired"; as the recording session progressed her voice became breathier and she had many voice cracks. Both singers insisted on completing the recording session, so we proceeded. We chose to include their recordings since they added variability. We repeated all analyses without the data from these two singers and found similar results – except that the proportion of correct recognition of operatic performances increased slightly from 86.4 to 89.3% (the difference for the other styles was of less than 0.5%).

2 We considered that operatic singing typically has higher pitch than pop and lullaby singing. We address the implications of this choice in all comparisons across styles made throughout the study.

Brazil, in March 2022. Recordings were made using an AKG C-414 B-ULS microphone in cardioid pattern, and using the Mac standard for lossless audio (Audio Interchange Format, AIFF), with 24 bits per sample and 44.1 kHz sampling rate. The recording procedure was consistent throughout all recording sessions. Singers were instructed to stand on fixed marks on the floor (though some movement during singing is unavoidable). The distance between singers' mouths and the microphone was set to around 10 cm for the lullaby performances; around 30–40 cm for pop performances; and around 60 com for operatic performances.[3] Singers were asked to perform each melody excerpt as a lullaby, as a pop song, and as an opera aria, and to additionally speak the corresponding lyrics as if speaking to an adult and as if speaking to an infant. Note that the speech performances are not analyzed in the current study.[4] Singers received the following instructions:

- for lullaby singing: imagine you have a baby on your chest and you want to make it sleep;
- for pop singing: imagine you are performing a pop song using a microphone;
- for operatic singing: imagine you are on stage performing an opera aria.

Performances with a /lu/ sound were recorded directly after the corresponding performance with lyrics. The vowel /u/ was chosen based on the first author's experience as a voice teacher and the observation that it is a comfortable vowel for Brazilian female singers to produce a homogenous sound. Each singer was thus recorded in 36 different singing conditions (six melodies, in three styles of singing and two types of production), for a total of 792 performances in this stimulus set (that is, resulting from 36 conditions performed by 22 singers).[5] For each of the 36 conditions, at least three takes were recorded. At request of the recording technician and/or of the singers, one or two additional takes were occasionally recorded (in rare cases, between three and four extra takes were recorded for the same condition).

2.1.3.2. Audio processing and take selection

Individual takes of recorded performances (lasting between 5 and 12 s) were cut using Audacity software (version 3.1.3). For each singer, one take for each of the 36 conditions was selected by the first author for further analysis, based on the following (admittedly arbitrary) criteria to exclude takes: (a) occasional ambient noise (e.g., coming from singers' movements); (b) low vocal quality; (c) low expressiveness; (d) low authenticity.

2.1.3.3. Loudness normalization

The final set of 792 stimuli was normalized to ensure a similar level of loudness within style, while keeping variability between styles (i.e., contrastive softness of lullabies compared to the higher intensity associated with operatic technique). Using the software To Audio Converter (version 1.0.16–1059), all opera stimuli were loudness normalized following the EBU R 128 standard (without any dynamic range compression) to −14 Loudness Units relative to Full Scale (LUFS); all pop singing stimuli to −18 LUFS; and all lullaby stimuli to −25 LUFS. Examples of the stimuli used in the present study are currently available at https://osf.io/6eyuc/.

2.1.4. Acoustic analyses

Each of the 792 singing performances was segmented into individual notes using Tony (Mauch et al., 2015). After note corrections (made manually upon visual inspection of individual files), data about duration of each individual note were exported and used to extract individual notes of the melodies using a sox bash script. Consonants were kept at the beginning of each note. This procedure produced 9,108 chunks of individual notes. The average length of individual notes was 0.596 s (SD = 0.445, range: 0.081–3.240 s). For each note, we used Praat (Boersma, 2001; Version 6.0.46) with the settings pitch floor = 75 Hz and pitch ceiling = 800 Hz, to extract the measures: f_o; f_o max; f_o min; standard deviation of the f_o; shimmer_local (perturbation in the amplitude of f_o); and jitter_local (perturbation in the periodicity of f_o). Note that for jitter and shimmer, we observed measurement imprecision (aberrant values for very short notes), so we trimmed values higher than two standard deviations above the mean value before calculating average values per performance. As a consequence, we excluded 4% of individual note measurements for jitter and 2.6% for shimmer. Using VoiceSauce (Shue et al., 2011),[6] with the same settings as in Praat mentioned earlier (and also based on individual notes), we also extracted the following measures – (a) Harmonics-to-noise ratio in the 0–3.5 kHz band (HNR35): the ratio between periodic and nonperiodic components of the signal, based on the algorithm described by Krom (1993). The HNR measurements are found by liftering the pitch component of the cepstrum and comparing the energy of the harmonics with the noise floor. (b) Cepstral peak prominence (CPP): a different voice quality measure of the relative levels of harmonic and inharmonic energy in the voice, based on the algorithm described by Hillenbrand et al. (1994). CPP is the dB difference between the cepstral peak and a linear regression line measured at the corresponding quefrency – where lower values have been perceptually associated to breathiness and dysphonia (Murton et al., 2020). (c) Energy (specifically, the Root Mean Square Energy): generally used to

3 A recording technician additionally adjusted the gain of the microphone for performances in different styles to maintain good signal rates and avoid clipping, since performances varied greatly in terms of sound intensity level.

4 The complete stimulus set, including the speech vocalizations, will be made available via open access in a separate publication. We limit ourselves here to the singing performances, which will also serve as material of the perceptual experiment described in Part II.

5 Unfortunately, nine performances were missing due to technical issues during the recording sessions (S01_NR_pop_U, S01_BO_pop_U, S05_AL_cl_L, S05_AL_cl_U, S07_NR_pop_L, S07_NR_pop_U, S09_NR_pop_L, S09_NR_pop_U; S11_NN_cl_U) but were replaced by additional recordings of good quality sent afterward by the cooperative singers, who recorded themselves a cappella in private settings. Note that 788 of them (395 with lyrics and 393 with /lu/) were used in Part II (i.e., in the perceptual experiment) since four additional recordings were received after data collection.

6 http://www.phonetics.ucla.edu/voicesauce/documentation/parameters.html

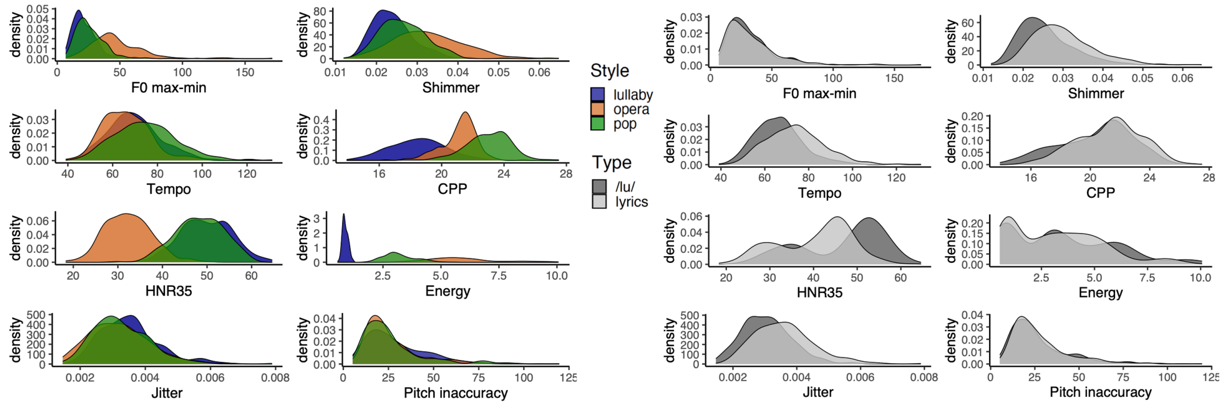

FIGURE 1
Density distribution of acoustic features by style (left) or type of performance (right).

evaluate the amplitude of the audio signal.[7] The extracted features were then averaged per take. We also computed pitch accuracy: we first converted f_o values from Herz to cents (100 cents corresponds to one semitone, the reference lowest note used was 261.626 Hz), then calculated the absolute difference between these values and reference notes (i.e., "correct" notes, according to sheet music), also in cents; then averaged the pitch (in)accuracy per take. In addition, we used f_o max-min as an approximation of vibrato extent based on Praat's output of f_o max and f_o min (in Herz) of a selected long note from each performance (we used the same frequency whenever possible, whatever its position in the melodies; see the notes framed in blue in the respective sheet note in Supplementary Figure S1).

2.1.5. Statistical analyses

All analyses were performed using R Statistical Software (version 4.1.2; R Core Team, 2021) and R Studio (version 2022.7.1.554; RStudio Team, 2022). To test whether acoustic features vary across styles, we ran a two-ways mixed design analysis of variance (ANOVA; with the aov function and default settings in R) for each acoustic feature, with factors Style (within participants) and Type of production (between participants). We also performed a principal component analysis (PCA, with the prcomp function in R) to explore the dimensionality of the acoustic space of the singing performances.

2.2. Results and discussion

A total of 792 performances, consisting of six melody excerpts performed by 22 singers, in three styles of singing and two types of production (with lyrics or a /lu/ sound) were analyzed. Each performance was around nine seconds long. The acoustic analysis reveals clear acoustic profiles for the different singing styles, supporting that singers' productions are contrasted, as illustrated in Figures 1, 2. Please see Supplementary Tables S2, S3 for summary statistics of these measures, and Supplementary Figure S2 for a correlation matrix.

As shown in Figure 2, the ANOVAs showed differences between styles for all acoustic features (all $ps < 0.001$) and between types of performance for all features (all $ps < 0.001$), except for pitch accuracy and f_o max-min. Also, there was a significant interaction between the main effects of style and type of performance in the case of shimmer, CPP, Energy and HNR35 (all $ps < 0.05$).

Comparing the acoustic profiles of the three styles of singing, we found that pop performances had faster tempo and higher CPP values than both other styles. The interpretation of CPP values for the singing voice is still unclear. Considering that Baker et al. (2022) report an interaction between f_o and CPP levels, one could only directly compare CPP levels of pop and lullaby singing of our framework, in which case the lower values of CPP in lullaby singing seem to indicate a breathier voice quality (e.g., Murton et al., 2020). Lullabies also had smaller values of f_o max-min (none or limited vibrato), higher jitter values, and lower pitch accuracy and shimmer. The higher values of jitter in lullabies may be linked to their soft phonation level: for spoken voices, a dramatic increase in jitter has been described below a critical threshold of 80 dB (Brockmann et al., 2008). The worse pitch accuracy might also be related to worse intonation control in soft phonation. Lullabies were also slower than pop performances. These features combined seem to represent the typical soft, slow and intimate singing used to soothe an infant. Turning to operatic performances, they were slower, had lower values of HNR35 and higher values of shimmer and f_o max-min (indicating more extensive use of vibrato) than both other styles. This is in line with the general description of operatic singing by Larrouy-Maestri et al. (2014), with the exception that in that study the authors also reported higher jitter for performances in operatic (than non-operatic) style; and with the description of higher shimmer in operatic singing by Butte et al. (2009). The intermediary values of CPP for operatic singing (lower than in pop singing) are somewhat surprising: CPP values have been described to increase with sound pressure level and f_o (Brockmann-Bauser et al., 2021; Baker et al.,

7 Note the RMS energy values reported here are a direct consequence of our loudness normalization of stimuli to different levels. At production, operatic singing was a lot louder than both others styles, and pop singing was louder than lullabies. Our manipulation kept the general loudness characteristics of stimuli to arbitrary loudness levels that sounded natural to the present authors, but since we varied distance to microphone and microphone gain during recording, we do not report any objective measure of intensity here.

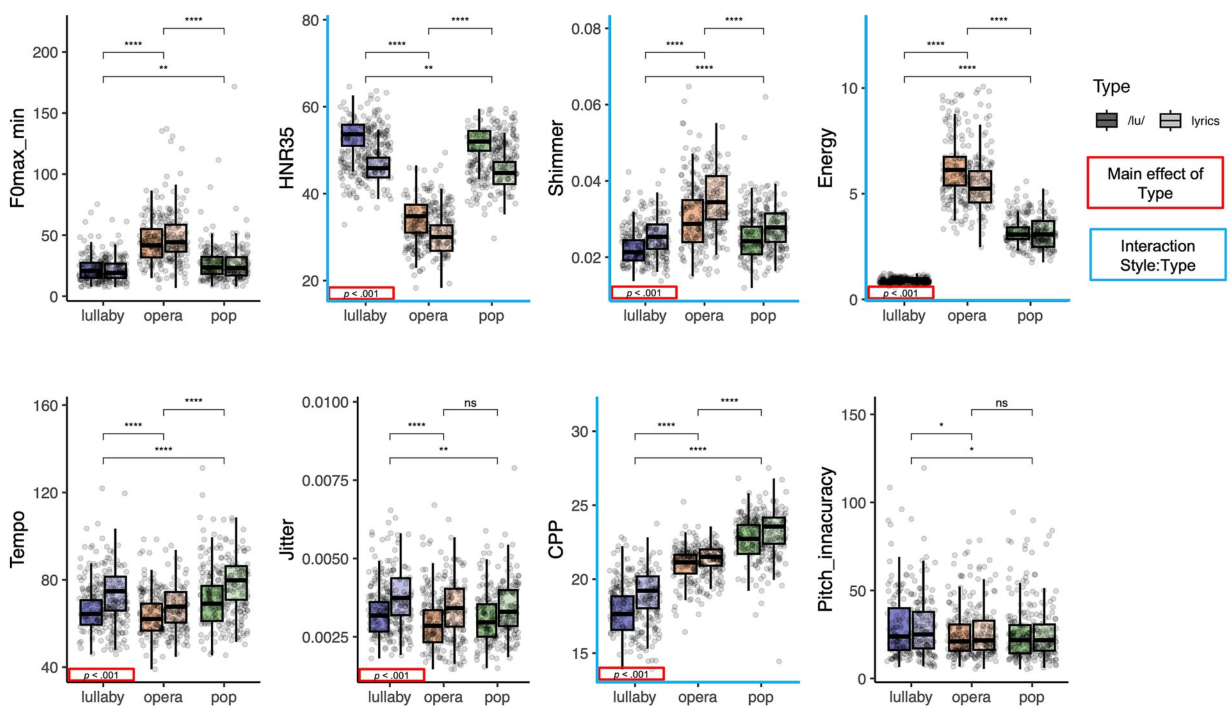

FIGURE 2
Boxplots displaying the distribution of the selected acoustic features for each of the three singing styles (lullaby, opera, pop), by type of production (with /lu/, illustrated with darker colors, and with lyrics, illustrated with lighter colors). Significance of the main effect Style of singing is depicted with stars and significance of the main effect Type of production is presented with red frames in the bottom-left corner of each plot. The blue axes indicate significant interaction between Style and Type of production. The Energy measure is depicted here for transparency (see Footnote 7).

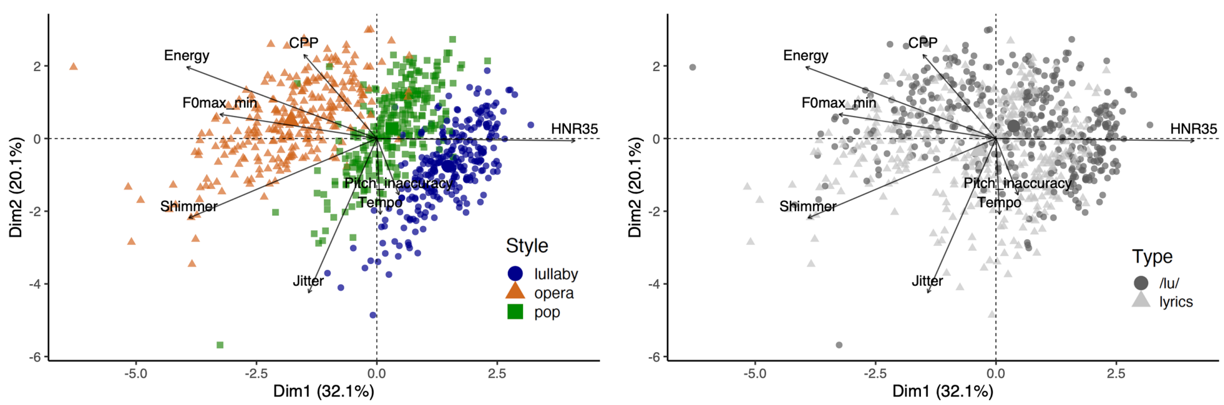

FIGURE 3
Biplots of principal component analysis showing singing performances as dots and loadings of acoustic features as arrowed vectors. Dots' colors correspond to singing styles (left) or type of performance (right).

2022), so considering that operatic performances had higher pitch and sound pressure level than both other styles, it would make sense for them to also have higher CPP values. The use of vibrato may help explain this finding, but this is only speculatory at the moment.

Results of the PCA based on the eight acoustic features are in line with the ANOVAs. Figure 3 presents visualizations of the singing performances along the first and second dimensions of the PCA (which explained 52.2% of the variance): very clear clusters are seen for performances in different styles of singing (Figure 3, left), but not for performances with different types of production (Figure 3, right). Please see the Supplementary Information for a scree plot (Supplementary Figure S3, top) and the contribution of each variable to the first, second and third dimensions of the PCA (Supplementary Figure S3, bottom). Note that we chose to include the Energy measure in this analysis because it is likely an important descriptor of the audio signal, but one can still recognize clear clusters of performances in different styles if one repeats the same analysis without the Energy measure (see Supplementary Figure S4).

The acoustic analysis presented here had the primary goal – and was able to – describe contrasting styles of singing performances.

However, we acknowledge some important limitations: When recording stimuli, we aimed at obtaining naturalistic singing performances of high quality, and to focus on the acoustic signal itself. Our methodology did not follow practices customary in the field of voice science (e.g., Švec and Granqvist, 2010, 2018), where the primary interest is on voice production mechanisms. For instance, we adjusted microphone gain during recording to ensure good signal levels, while avoiding clipping. Further, we performed loudness normalization of stimuli of each style to different loudness levels, in line with the expected sound pressure level at production, that is, quiet for lullabies; intermediary for pop; and a lot louder for operatic performances. Whereas our choices aimed at ensuring recordings of good (artistic) quality, they also brought confounds to the interpretation of our acoustic measurements. More specifically, controlling sound pressure level is important to understand vocal function: increases in voice sound pressure level correlate with decreased jitter and shimmer, and increased HNR (Brockmann et al., 2008; Brockmann-Bauser et al., 2018) and CPP (Brockmann-Bauser et al., 2021). One further limitation is that operatic performances were recorded with higher pitch, which complicates comparisons with the other two styles because of influences of f_o over other acoustic measures (e.g., Brockmann et al., 2011; Sampaio et al., 2020; Brockmann-Bauser et al., 2021; Baker et al., 2022). The use of vibrato (more pronounced in operatic singing) could also be associated with perturbation measures like jitter, shimmer and HNR (Larrouy-Maestri et al., 2014). Further, comparing naturalistic performances, which vary simultaneously in many dimensions, is obviously challenging. Approaches like ours should be complemented with other research designs, like case studies (e.g., Sundberg et al., 1993; Thalen and Sundberg, 2001; Stone et al., 2003) and studies using synthesized stimuli (e.g., Sundberg, 2006; Baker et al., 2022) where variables are changed (as much as possible) in isolation. One additional limitation is that, due to the large number of recorded takes, analysis was conducted on only about one third of all recorded singing material. Selection for analysis followed clear criteria (exclusion of performances with ambient noise, low vocal quality, low expressiveness and/or low authenticity), but despite efforts to maintain objectivity, some subjectivity is inherent in this selection process.

Despite these shortcomings, we indicate possible (functional) meanings of our measures and, more importantly, we report large differences between styles, suggesting singers' proficiency in producing contrasting singing performances. On the other hand, different acoustic profiles do not necessarily mean that the performances will be perceived as intended. To clarify this point, we further investigated singers' versatility in Part II, by looking at the perceptual experience of listeners when listening to these performances.

3. Part II: perception of singing performances

We conducted a behavioral experiment to examine whether the singing performances sounded as intended to naïve listeners. Recognition accuracy is thus used as a proxy to singers' versatility – the rationale behind this is that versatile singers should be able to produce contrasting and characteristic-enough performances for participants to accurately recognize. By recruiting lay listeners, that is, participants without specific musical training, we aimed to examine participants with a large range of expertise, which is meant to be representative of a general population. Note that studies indicate that lay listeners are able to judge perceptual features of voices if adequate scales are used (Bänziger et al., 2014; Merrill, 2022). We assessed participants on a forced-choice task in which they had to indicate whether a given performance sounded like a lullaby, a pop song, or an opera aria.

3.1. Method

3.1.1. Participants

Fifty participants (30 self-reported as female, 20 as male, $M = 46.6$ years old, $SD = 17.2$, 45 with German as mother tongue, from which 5 bilinguals, none of them with Portuguese as mother tongue) were recruited from the participant database of the Max Planck Institute for Empirical Aesthetics, in Frankfurt, Germany. They did not have hearing impairment and were mostly lay listeners. Participants were randomly assigned to one of two groups, which differed only in terms of which stimuli they were presented with (i.e., performances with lyrics for Group 1 and performances with a /lu/ sound for Group 2; see details in the Procedure section). According to an 18-items adapted version[8] of the scale of music sophistication of Gold-MSI (Müllensiefen et al., 2014), the average music sophistication score was 81.4 ($SD = 19.6$) for Group 1 and 75.7 ($SD = 13.7$) for Group 2 (these values are not statistically different, two-samples $t(42.9) = 1.2$, $p = 0.239$). Participants were compensated at the rate of 14€ per hour of participation.

3.1.2. Material

The stimulus set consisted of the 788 performances, that is, six melody excerpts performed by 22 singers, in three styles, with lyrics or a /lu/ sound, as described in Part I.

3.1.3. Procedure

The experiment was implemented in Labvanced (Finger et al., 2017). The experimental procedure was ethically approved by the Ethics Council of the Max Planck Society, and was undertaken with written informed consent of each participant.

The session began with oral and written instructions, followed by four practice trials with example stimuli which were not part of the final stimulus set, presented through headphones (Beyerdynamic DT 770 PRO 80 Ohm), at a volume adjusted to a comfortable level. In each trial, participants were instructed to indicate if the stimulus presented sounded like a lullaby, a pop song, or an opera aria, by clicking on the respective answer. One group of participants (Group 1, $N = 25$) was presented only with performances with lyrics

8 We included the following items: AE_01, AE_02, AE_05, AE_07, EM_04, MT_03, MT_07, PA_01, PA_04, PA_06, PA_07, PA_08, SA_01, SA_02, SA_03, SA_04, SA_05, SA_06. These correspond to 15 items from the general sophistication scale, plus three items corresponding to a short scale of perceptual abilities.

(395 trials) and one group of participants (Group 2, $N = 25$) only with performances with /lu/ (393 trials). For each group, stimuli from different melodies and styles were presented intermixed and in random order. The visual display of response alternatives ("as a lullaby," "as a pop song," "as an opera aria") was presented in all possible orders but the order was fixed for each participant across the whole session. The experiment was divided into six blocks of 66 trials [except for the last block, which was slightly shorter due to a few missing stimuli (see Footnote 5)], and participants could take a break between blocks. The testing session lasted between 85 and 120 min. Each stimulus was presented once, except for 20 repetitions of a random subset of stimuli in the end of the experiment (different for each participant), which were used to estimate the test–retest intrarater agreement. At the end of the session, participants completed the adapted version of the general music sophistication scale of the Goldsmiths Music Sophistication Index (Müllensiefen et al., 2014).

3.1.4. Statistical analyses

3.1.4.1. Accuracy of style recognition

To test if singing styles were recognized, we compared the proportion of correct responses (across all participants) in each style against chance level (33%), with *Z*-tests for proportions (one-tailed; with the R function prop.test; separately for performances with lyrics and with /lu/). The reported *p*-values have been adjusted with the R function p.adjust to control the family-wise error rate (FWER) of these 6 comparisons with the Holm method (Holm, 1979). To test if accuracy was similar for performances with lyrics (Group 1) and /lu/ (Group 2), we used a two-tailed *Z*-test for proportions. Additionally, for each group, we also compared styles pairwise with *Z*-tests for proportions (two-tailed; also here, reported *p*-values have been adjusted with the Holm method).

3.1.4.2. Accuracy by singer and versatility in pop and lullaby singing

We calculated the proportion of accurate responses for each singer, both across all styles and by style. Since these were productions of classical singers, the proportion of accurate recognition of operatic performances was expected to be high. The proportion of correct recognition of pop and lullaby performances, on the other hand, was taken as indicative of singers' versatility: the more versatile the singer, the more competent she would be in producing non-operatic performances.

3.1.4.3. Versatility and musical training

We also explored the relationship between singers' versatility (as measured by the proportion of correct recognition for each singer in the pop and lullaby styles) and singers' characteristics such as age, years of voice training, years of instrument training, general music training (years formally studying music, that is, enrolled in an institution such as conservatory/university), proportion of time singing as a soloist versus in a choir, and average number of hours spent performing per week (including practicing). To do so, we fit one multiple linear regression model (with the lm function) for each style, predicting the proportion of correct recognition from singers' characteristics.

3.1.4.4. Intrarater agreement analysis

To assess the consistency of participants' responses, we calculated the test–retest intrarater agreement. Based on a subset of 20 repeated trials at the end of the experiment, we calculated Cohens' Kappa, using the kappa2 function from the irr package in R (Gamer et al., 2019). According to Landis and Koch (1977), Kappa values between 0 and 0.2 indicate slight agreement; between 0.21 and 0.40, fair agreement; between 0.41 and 0.60, moderate agreement; between 0.61 and 0.80, substantial agreement; and between 0.81 and 1, perfect agreement. We also report the simple percentage agreement (agree function from the same package). These values were computed separately for Groups 1 (performances with lyrics) and 2 (performances with /lu/). Note that due to a mistake in the coding of the experiment, for a subset of 10 participants of Group 2, the planned repeated trials were not in fact repeated trials, but stimuli with lyrics instead of /lu/. Because of this, computation of Kappa for Group 2 is based only on the 15 participants that were correctly presented with repeated trials.

3.2. Results and discussion

3.2.1. High accuracy of style recognition

The overall proportion of accurate responses was higher for performances with lyrics than for performances with /lu/ [81.2 and 75.8% respectively, $\chi^2(1) = 82.9$, $p < 0.001$], indicating that even though participants did not understand the lyrics of the melodies (performed in Brazilian Portuguese), they could still benefit from the phonetic content of performances when recognizing the style of singing. Note that, at the end of the experiment, participants of Group 1 (performances with lyrics) were asked if they recognized the language of the performances and about one fourth did. Five of them identified Portuguese, two Brazilian Portuguese, and one mentioned Eastern European language. Figure 4 illustrates the accuracy of recognition by style. Participants could recognize singing styles above chance level for all three styles: the proportion of accurate responses from Group 1 (performances with lyrics) was 88.3% for operatic performances [different from chance level, $\chi^2(1) = 4456.2$, $p < 0.001$], 81.6% for lullabies [$\chi^2(1) = 3466.9$, $p < 0.001$], and 73.7% for pop performances [$\chi^2(1) = 2424.6$, $p < 0.001$]. These values were different from each other: the proportion of accurate responses for operatic performances was higher than for lullaby [$\chi^2(1) = 57.1$, $p < 0.001$] and pop performances [$\chi^2(1) = 226.6$, $p < 0.001$], and it was higher for lullaby than for pop performances [$\chi^2(1) = 59.5$, $p < 0.001$]. The same pattern was found for Group 2 (performances with /lu/): the proportion of accurate responses was 84.4% for operatic performances [different from chance-level performance, $\chi^2(1) = 3854.3$, $p < 0.001$], 78.5% for lullabies [$\chi^2(1) = 3033.4$, $p < 0.001$], and 64.5% for pop [$\chi^2(1) = 1426.5$, $p < 0.001$] performances. Again, these values were different from each other: the proportion of accurate responses for operatic performances was higher than for lullaby [$\chi^2(1) = 38.4$, $p < 0.001$] and pop [$\chi^2(1) = 340.3$, $p < 0.001$] performances, and it was higher for lullaby than for pop performances [$\chi^2(1) = 156.8$, $p < 0.001$].

3.2.2. Accuracy by singer and versatility

Figure 5 displays the proportion of correct recognition of performances produced by each singer. The overall proportion of

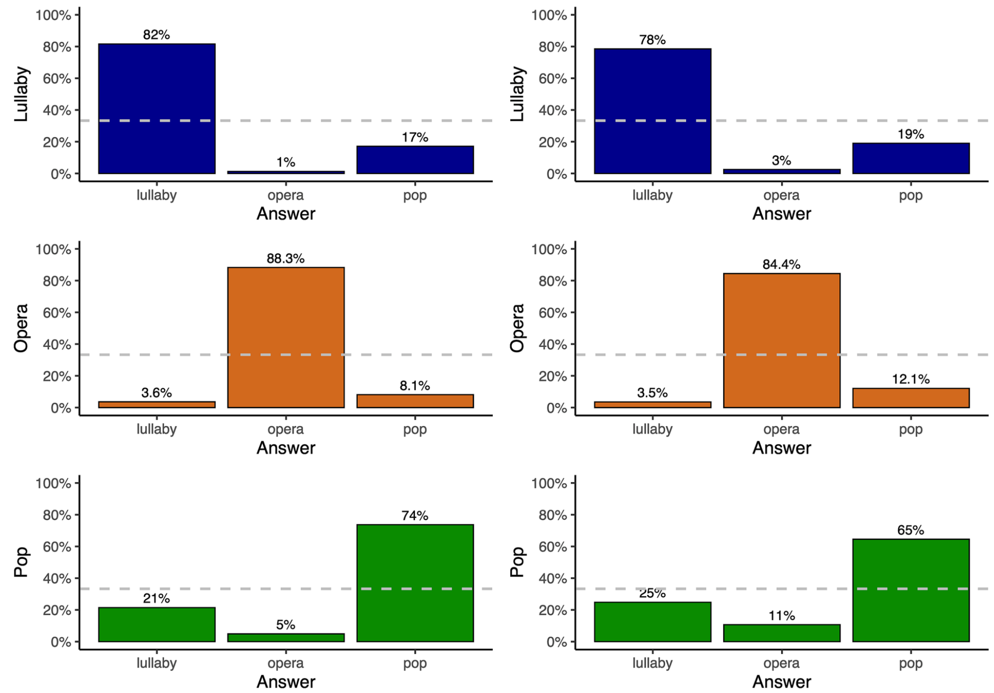

FIGURE 4
Classification of styles by participants in the perceptual experiment for performances with lyrics (left) and /lu/ (right), in trials where presented stimuli were lullaby (top), operatic (middle) or pop performances (bottom). In both panels, the dashed gray horizontal line represents chance-level performance.

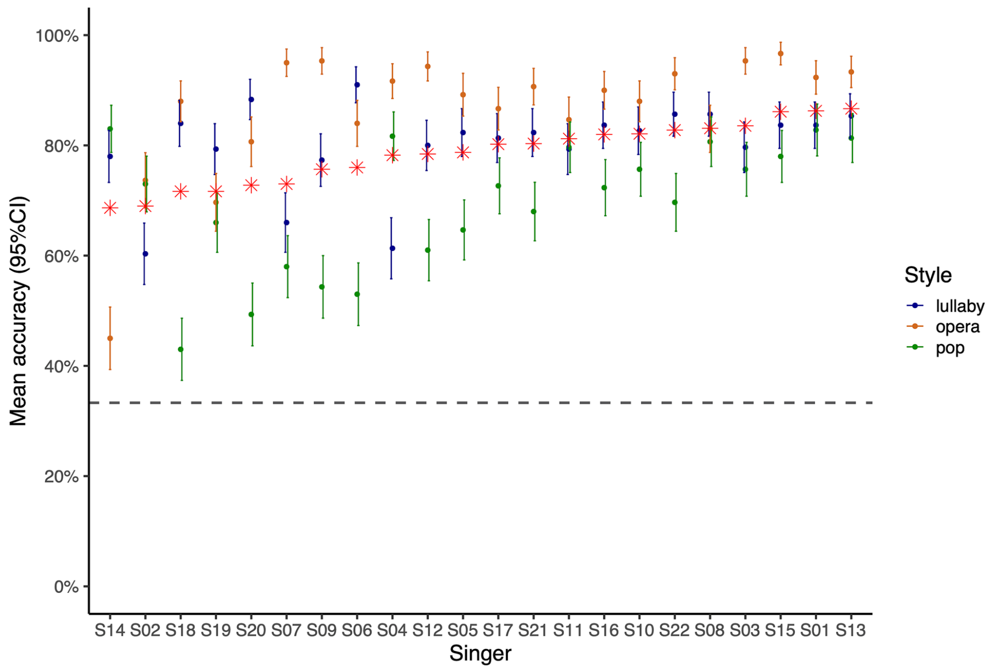

FIGURE 5
Proportion of correct style recognition across all 50 participants in the perceptual experiment for performances by each individual singer, as a proxy of singers' versatility. Colors indicate singing styles. Red stars indicate the proportion of accurate recognition across the three singing styles. Error bars indicate 95% confidence intervals, and the horizontal gray dashed line corresponds to chance-level performance.

correct recognition for performances by each singer was between 69 and 87%. In the case of operatic performances, accuracy ranged from 45 to 97% (or from 73.7 to 97% excluding singers S14 and S19, with declared vocal problems). Importantly, the productions of all singers in the lullaby and pop styles were recognized well above chance-level, showing singers' versatility outside their strict field of classical training. For lullaby performances, the proportion of correct recognition was between 60 and 91%, and for pop performances, between 43 and 83%. Note the most common mistake made by participants was to answer that pop performances were lullabies (or *vice-versa*, to a slightly smaller extent).

3.2.3. Versatility and musical training

Using the proportion of correct recognition of pop and lullaby performances as a proxy of singers' versatility, we explored its relationship with singers' characteristics such as years of voice and instrument training, formal music training (years enrolled in a conservatory or a music university), proportion of solo (to choir) singing, and average number of hours spent performing per week, *via* statistical modeling. Surprisingly, none of the mentioned variables predicted the proportion of correct recognition. In other words, classical singers' ability to adjust or adapt (highly trained) motor schemas to perform in other styles was not affected by the extent of their musical training. Please see the Supplementary Information for a correlation matrix with all these predictors and the proportion of correct recognition by style (Supplementary Figure S5), as well as the coefficients of (non-significant) linear regression models predicting the proportion of correct recognition for each style from singer characteristics (Supplementary Figure S6). More detailed information about singers' professional and private lives would be helpful for qualitative exploration of the impact of singers' experiences on their versatility.

Interestingly, the ability to sound operatic (i.e., estimated by the proportion of correct recognition of operatic performances) was correlated with singers' age ($r_{20} = 0.44$, $t = 2.2$, $p < 0.05$), suggesting that this typicality in operatic sounding might come with gathered experience rather than formal training itself. However, the lack of relationship between the proportion of recognition of operatic performances and singers' (classical) music training might reflect a ceiling effect, since we purposely recruited highly trained singers, who presumably already had sufficient training to perform in this specific style.

3.2.4. Intrarater agreement

Analysis of repeated trials showed participants were consistent in their responses: For Group 1 (performances with lyrics), analysis of test–retest intrarater agreement showed a simple percentage agreement of 82% (i.e., participants gave the same response at both the first and the second presentation of a given stimulus in 82% of the 20 trials), and a Kappa value of 0.73 ($z = 22.9$, $p < .001$), indicating substantial agreement. For Group 2 (performances with /lu/), the simple percentage of agreement was 73%, and Kappa was 0.59 ($z = 14.5$, $p < 0.001$), indicating moderate agreement. Additionally, Supplementary Figure S7 (left) shows the proportion of correct recognition by each participant of this experiment. It ranged from 49.1 to 93.2%, indicating that, while there were individual differences in how well participants could do the task, all of them could do it above chance level, and the majority did it with good accuracy.

3.3. Control experiment

Our approach of normalizing stimuli of different styles to different loudness levels raised the question of how much participants' high style recognition could be linked to differences in loudness between styles. To better understand the role of stimulus loudness in participants' perception and evaluation of our stimuli, we conducted a control experiment in which all stimuli were normalized to the same loudness level.

3.3.1. Participants

Ten additional participants (6 self-reported as female, 3 as male, 1 undisclosed, $M = 49.8$ years old, $SD = 19.2$, 9 with German as mother tongue, from which 3 bilinguals, none of them with Portuguese as mother tongue) were recruited from the participant database of the Max Planck Institute for Empirical Aesthetics, in Frankfurt, Germany. After completing the experiment, four participants answered they recognized the language used, but only one correctly responded Portuguese (one wrote "a fantasy language with elements of Portuguese," one Spanish, one Italian). They did not have hearing impairment and were lay listeners, with an average music sophistication score of 88.5 ($SD = 10.6$) according to the same 18-items adapted version of the scale of music sophistication of Gold-MSI (Müllensiefen et al., 2014). Participants were compensated at the rate of 14€ per hour of participation.

3.3.2. Material

We used half of the stimulus material of the main experiment, that is, a subset of 396 performances corresponding to three melodies (Nana Nenê, Chove Chuva, and Melodia Sentimental). Using the software To Audio Converter (version 1.0.16–1,059), all stimuli were loudness normalized (following the EBU-R128 standard) to −23 LUFS.

3.3.3. Procedure

The only difference in procedure in relation to the original experiment was that all participants dealt with performances both with lyrics and with /lu/, though in different blocks of trials (in counterbalanced order). As before, stimuli from different styles were presented intermixed and in random order, and participants had to indicate if singing performances sounded like a lullaby, a pop song, or an opera aria in a forced-choice design. We also included 20 repeated trials at the end of respective blocks (10 trials for stimuli with lyrics and 10 for stimuli with /lu/) in order to conduct a test–retest intrarater agreement analysis.

3.3.4. Statistical analyses

We repeated the analyses described for the first experiment: we compared the proportion of accurate responses for each style (across all participants) against chance-level performance (33% correct recognition) with Z-tests for proportions (one-tailed; separately for performances with lyrics and with /lu/; adjusting p-values to control the FWER with the Holm method). We also compared recognition between styles with pairwise Z-tests for proportions (two-tailed; separately for performances with lyrics and with /lu/; and adjusting p-values to control the FWER of 6 comparisons with the Holm method). Once again, to test if accuracy was similar for performances with lyrics and /lu/, we used a two-tailed Z-test for proportions. Finally, to compare results across experiments, we performed Z-tests for proportions for each style (two-tailed; separately for performances with /lu/ and lyrics; adjusting p-values to control the FWER of 6 comparisons with the Holm method).

Additionally, we computed a Pearson correlation score between the overall proportion of correct recognition by stimulus item in both experiments. We also conducted analysis of test–retest intrarater agreement based on repeated stimuli.

3.4. Results and discussion

Analysis of repeated trials showed that participants of the control experiment were also consistent in their responses, with a simple percentage agreement of 81.5% and a Kappa value of 0.72 ($z = 14.5$, $p < .001$), indicating substantial intrarater agreement. The proportion of correct recognition by each participant ranged from 43.9 to 88.4% (see Supplementary Figure S7, right), confirming that, as observed in the main experiment, recognition was above chance level for all participants (and the majority did the task with good accuracy).

Both for performances with /lu/ and with lyrics, recognition was above chance level for all styles (all ps < 0.001). For performances with /lu/, we found the same pattern as in the main experiment: higher recognition for operatic (81% CR) than lullaby singing [73% CR; $\chi^2(1) = 13.92$, $p < 0.001$] and pop singing [61% CR; $\chi^2(1) = 64.59$, $p < 0.001$] and higher for lullaby than pop singing [$\chi^2(1) = 19.29$, $p < 0.001$]. For performances with lyrics, the recognition of operatic performances (82% CR) was higher than that of lullabies [68.6% CR; $\chi^2(1) = 30.77$, $p < 0.001$] and pop [67.6% CR; $\chi^2(1) = 35.42$, $p < 0.001$], but there was no difference between recognition rates for pop and lullaby performances [$\chi^2(1) = 0.17$, $p = 0.679$]. Also, in this experiment there was no difference between overall recognition rates for performances with lyrics (72.7% CR) and /lu/ [71.8% CR; $\chi^2(1) = 0.36$, $p = 0.546$]. Please see Supplementary Figure S8 for the proportion of correct recognition by style, and Supplementary Figure S9 for a display of the proportion of correct recognition of performances by each singer in the control experiment.

When comparing recognition rates between experiments, we found that, for performances with lyrics, recognition was higher for all styles in the main experiment [lullaby: $\chi^2(1) = 56.65$, $p < 0.001$; opera: $\chi^2(1) = 20.5$, $p < 0.001$; pop: $\chi^2(1) = 10.4$, $p < 0.01$]. For performances with /lu/, recognition rates seemed higher in the main experiment for all styles, but this difference only reached significance for lullabies [$\chi^2(1) = 10.46$, $p < 0.01$; opera: $\chi^2(1) = 3.82$, $p = 0.1$; pop: $\chi^2(1) = 2.38$, $p = 0.12$]. The illustration of the overall proportion of correct recognition by stimulus item in both experiments can be found in Supplementary Figure S10. Values were highly correlated between experiments [$r_{(396)} = 0.79$, $p < 0.001$], suggesting consistency in how recognizable a given item was across experiments, that is, items that were well recognized in the main experiment were likely to be well recognized in the control experiment.

Overall, the slightly higher proportion of correct recognition in the main experiment suggests that the difference in loudness levels between styles might have aided style recognition in that experiment. However, the high proportion of recognition in the control experiment suggests that the difference in loudness levels was not essential for correct style recognition. In other words, singing performances in different styles were contrasting enough, so that other perceptual features could inform participants' style recognition. Readers interested in the role of acoustic features in the perceptual categorization of different singing styles are invited to read the Supporting Text 2 in the Supplementary materials, where we describe an additional exploratory analysis on this subject (illustrated in Supplementary Figures S11, S12).

4. General discussion

The contrasting acoustic profiles of melodies performed as a lullaby, as a pop song, or as an opera aria, aligned with the high recognition of their intended styles by lay listeners, indicate that classical singers were highly versatile. They not only performed as expected in the style in which they were trained, but managed to refrain from using this specific technique (or arguably, to adapt it) to sing in contrasting styles.

The acoustic analysis showed different acoustic profiles for the three described singing styles, but, as mentioned before, has limitations that may hinder insights about differential mechanisms of production. The acoustic profile of operatic singing included slower tempo, extensive use of vibrato, higher shimmer, lower harmonics-to-noise ratio, and intermediary CPP values. Lullabies had reduced use of vibrato, higher jitter (possibly related to their soft phonation level – e.g., Brockmann et al., 2008, 2011) and lower CPP (likely related to a breathy voice quality – e.g., Murton et al., 2020), as well as worse pitch accuracy. Lullabies were also slower than pop performances. These measures combined suggest that singers did prioritize producing intimate, soft singing, over their usual classical voice production pattern. In the case of pop, performances were faster and had higher CPP values than both other styles.

The versatility of our cohort of classically trained singers was confirmed by the results of the perceptual experiment (replicated in the control experiment). Given their intensive training, it is not surprising that classical singers could provide "operatic sounding" recordings that were recognized as such (86.4% correct recognition). Their versatility is best expressed in the high recognition accuracy of lullaby (80%) and pop (69.1%) performances. Such high recognition rates might be enhanced by the choice of the task (forced-choice) and should be confirmed with a less constrained task (e.g., free label, see Fink et al., 2023). Note that the lower recognition accuracy for pop performances might reflect singers' reduced experience in that style, but also uncertainty about what type of sound to produce, given the lack of a clear definition for pop singing. The majority of mistakes corresponded to participants answering that pop performances were lullabies (or *vice-versa* to a slightly smaller extent). In our study, these two styles were performed with the same pitch, so discriminating between them was indeed more difficult. Nevertheless, participants were able to correctly recognize these performances well above chance level. This was also the case in the control experiment, in which all performances were presented in the same loudness level. The fact that recognition rates were slightly lower in this experiment suggests that the difference in loudness levels probably assisted participants in recognizing styles in the first experiment. However, other perceptual aspects of the singing performances were salient and contrasted enough to inform participants' decisions, allowing them to still recognize styles with high accuracy.

An interesting finding was that the proportion of correct recognition of operatic performances correlated positively with singers' age ($r = 0.44$), but not with their musical training, suggesting that maturity and general experience as a classical singer influenced the recognition of their performances as operatic. According to Fitts and Posner's theory of motor learning, after extensive practice, a performer will usually reach the autonomous phase, where movements are fluent, accurate and consistent, and movement production is efficient and requires little muscular energy (Fitts and Posner, 1967). At this stage, the skill is performed largely automatically and movement execution demands little to no attention (Fitts and Posner, 1967; Wulf, 2012). Considering the extensive motor learning involved in the years of training required to master the classical singing technique, it is remarkable that classical singers were able to adapt their performances to produce recognizable performances in other singing styles.

Importantly, some singers were more versatile than others when performing in styles outside their classical training, with large differences in the proportion of correct recognition of performances by different singers – ranging from 60 to 91% for lullaby and from 43 to 83% for pop performances (from 50 to 85% for lullaby and from 38 to 87% for pop performances in the control experiment). We investigated the relationship between singers' demographics, musical training and practice and the proportion of correct recognition of singers' performances in different styles. We found no relationship between these variables and singers' versatility when singing in pop and lullaby styles. In other words, the amount of classical training did not seem to enhance singers' versatility in pop and lullaby singing. This finding is in line with the point made by vocal pedagogues concerned with the limitations of the standard classical singing training in face of a highly dynamic, challenging and competitive job market (e.g., LeBorgne and Rosenberg, 2021).

One limitation of our study is that we only analyzed around one third of all recorded singing material. While it is conceivable that results might vary with analysis of the full singing material, we do not anticipate a significant impact – our (admittedly subjective) observation was that most singers were consistent in their productions, that is, that repeated takes within each condition did not vary much. This consistency is not surprising considering that singers were highly trained and performing at a professional level. A different concern relates to the authenticity of the recorded performances. In future investigations, it would be desirable to clarify how well classical singers can produce not only recognizable, but also stylistically authentic performances in different styles. A truly versatile singer should be able to produce performances that surpass mere resemblance to a certain stylistic reference. In other words, versatile singers should manage to produce not only stereotypical, but also genuinely convincing performances with artistic quality. An obvious first step could be to have expert judges evaluate our stimulus set in terms of quality and authenticity. This would involve the further challenges of identifying suitable expert judges and establishing corresponding criteria to evaluate the quality and authenticity of performances in each style. One other point worth exploring would be the role of singers' life experiences in their versatility. All singers in this study declared having experience singing in other styles and were professional singers in Brazil, which requires flexibility (e.g., performing at weddings, teaching both classical and popular singing to attract more interested students). It would be interesting to further explore the role of singers' professional experiences (e.g., teaching children), personal experiences (e.g., motherhood; broad music listening habits), and even personality traits (e.g., Costa and McCrae, 1992) in their versatility. Besides clarifying the benefits and limits of intense training, understanding the role of singers' characteristics and diversity of training would also be important from a pedagogical point of view, in order to help singers who are not (yet) very versatile to improve this ability.

Data availability statement

The original contributions presented in the study are publicly available. This data can be found here: https://osf.io/6eyuc/.

Ethics statement

The experimental procedures of the studies involving humans were ethically approved by the Ethics Council of the Max Planck Society. The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

Author contributions

CB and PL-M conceived the study. CB recorded singers, collected data for the perceptual experiments, carried out the statistical analyses and data visualizations, and wrote the first draft of the manuscript. PL-M supervised all mentioned stages and revised the manuscript. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fpsyg.2023.1215370/full#supplementary-material

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Exploring the dynamics of intentional sensorimotor desynchronization using phasing performance in music

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Humans tend to synchronize spontaneously to rhythmic stimuli or with other humans, but they can also desynchronize intentionally in certain situations. In this study, we investigate the dynamics of intentional sensorimotor desynchronization using phasing performance in music as an experimental paradigm. Phasing is a compositional technique in modern music that requires musicians to desynchronize from each other in a controlled manner. A previous case study found systematic nonlinear trajectories in the phasing performance between two expert musicians, which were explained by coordination dynamics arising from the interaction between the intrinsic tendency of synchronization and the intention of desynchronization. A recent exploratory study further examined the dynamics of phasing performance using a simplified task of phasing against a metronome. Here we present a further analysis and modeling of the data from the exploratory study, focusing on the various types of phasing behavior found in non-expert participants. Participants were instructed to perform one phasing lap, and individual trials were classified as successful (1 lap), unsuccessful (> 1 laps), or incomplete (0 lap) based on the number of laps made. It was found that successful phasing required a gradual increment of relative phase and that different types of failure (unsuccessful vs. incomplete) were prevalent at slow vs. fast metronome tempi. The results are explained from a dynamical systems perspective, and a dynamical model of phasing performance is proposed which captures the interaction of intrinsic dynamics and intentional control in an adaptive-frequency oscillator coupled to a periodic external stimulus. It is shown that the model can replicate the multiple types of phasing behavior as well as the effect of tempo observed in the human experiment. This study provides further evidence that phasing performance is governed by the nonlinear dynamics of rhythmic coordination. It also demonstrates that the musical technique of phasing provides a unique experimental paradigm for investigating human rhythmic behavior.

KEYWORDS

phasing, music performance, rhythmic coordination, coordination dynamics, oscillator model, dynamical systems

1. Introduction

Synchronization is a natural phenomenon found widely in both living and non-living systems (Pikovsky et al., 2001; Strogatz, 2003). Humans synchronize their movement to external rhythms seemingly effortlessly and automatically (Repp, 2005; Repp and Su, 2013), and interpersonal synchronization is fundamental to the coordination and communication in social interaction (Schmidt and Richardson, 2008; Shockley et al., 2009; Keller et al., 2014). Humans can also desynchronize intentionally under certain circumstances such as competitive sports (Yamamoto et al., 2013; McGarry and De Poel, 2016) and argumentative conversations (Paxton and Dale, 2013, 2017). Intentional desynchronization, however, is not a simple switch of behavior but involves complex dynamics because humans, despite the intention, tend to synchronize sometimes unknowingly. For example, a study of music performance in an Afro-Brazilian ritual showed that two independent groups playing different music synchronized unintentionally when they were in close proximity (Lucas et al., 2011). Intentional desynchronzation offers an interesting setup for studying human coordinative behavior, but little work has been done to study it systematically. Here, we aim to study the dynamics of intentional sensorimotor desynchronization in a controlled situation that originates from music performance, called *phasing*.

Phasing is a compositional technique in contemporary art music popularized by the composer Steve Reich. It is a process in which two identical patterns are played in and out of phase, with their relative phase (or phase difference) varying over time (Cohn, 1992; Yust, 2021). In Steve Reich's Drumming (1971/2011), two drummers start a phasing process by repeating the same six-beat pattern *in phase*, that is, with their performance aligned in time (Figure 1A). Then, they gradually desynchronize, with Drummer 2 (the moving part) increasing tempo slightly while Drummer 1 (the steady part) holds the original tempo, so that Drummer 2 is one quarter note ahead of Drummer 1 after about 20 or 30 s (Figure 1C; Reich, 1971/2011). Thus, according to the musical score, the relative phase between the musicians should increase linearly while phasing. Given that typical ensemble performance requires synchronization between musicians, phasing asks for an unusual (and somewhat unnatural and counterintuitive) skill of intentional desynchronization.

In a previous case study, two world-renowned percussionists performed the phasing section from *Drumming* (Hartenberger, 2016; Schutz, 2019). It was found that despite their intention to follow the musical score (i.e., one increases tempo while the other holds a constant tempo), both musicians sped up and slowed down together throughout the phasing process. A further analysis of the performance data revealed systematic nonlinear trajectories in the tempi and the relative phase (Kim, manuscript in preparation).[1] The relative phase, instead of increasing in a steady rate, advanced in a series of plateaus and abrupt transitions. The relative phase plateaued when the combined rhythm formed a simple pattern, such as the interlocking pattern where the note onsets are aligned (Figure 1B) and the interleaved pattern where the onsets form a steady sixteenth-note stream (e.g., halfway between Figures 1A, B). The drummers increased tempo together while they were engaged in one of these stable patterns until their tempi eventually diverged, after which they quickly moved to the next stable pattern.[2]

The nonlinear trajectories found in the expert data suggest that phasing performance is governed by the nonlinear dynamics of rhythmic coordination. Previous research showed that the coordination of rhythmic movements is stable when individual movements are arranged in either in-phase or antiphase relationship (Kelso, 1984, 1995). This means that the coordinated movements, when described as a dynamical system (Strogatz, 1994), have attractors at the in-phase and the antiphase states (Haken et al., 1985; Kelso, 2008). For the phasing performance in *Drumming*, the interlocking patterns (Figures 1A–C) and the interleaved patterns (halfway between the interlocking patterns) serve as attractors because the beats played by two musicians are either aligned (in-phase) or interleaved (antiphase) in these patterns. When one drummer increases tempo while locked in one of these stable patterns, the other drummer is also inclined to increase tempo involuntarily (and unknowingly) due to the stability and attraction of the coordinated pattern. Hence, the nonlinear trajectories found in phasing performance can be interpreted as resulting from the dynamic interaction between the intention of desynchronization (phasing) and the involuntary tendency of synchronization. This dynamical systems interpretation was supported by a model of

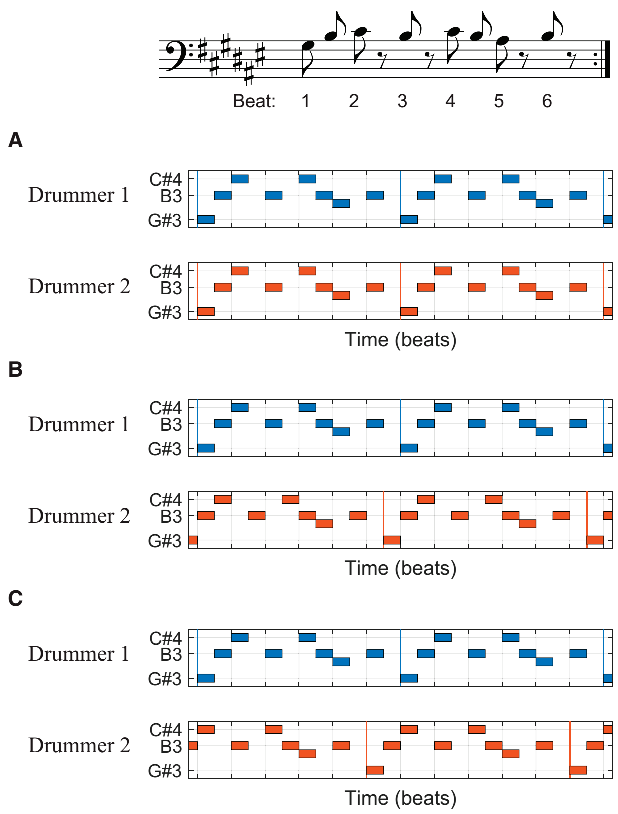

FIGURE 1
A phasing section from Steve Reich's Drumming (1971/2011). The basic six-beat pattern is shown in musical notation **(top)**, and different alignments of two drummers are shown in piano-roll representations **(A–C)**. Vertical colored lines indicate the beginning of each repetition of the pattern. **(A)** Two drummers' beats are aligned at the beginning of the phasing process. Drummer 2 is **(B)** a half beat (an eighth note) ahead of Drummer 1 in the middle and **(C)** one full beat (a quarter note) ahead at the end of phasing.

1 Kim, J. C. (manuscript in preparation). Push and pull: The dynamics of phasing performance in Steve Reich's music.

2 The dynamical systems analysis and modeling of the Drumming data was first reported in Kim (2019).

two mutually coupled oscillators, which showed similar nonlinear trajectories to those found in the expert performance (Kim, in preparation).

The above case study suggests that phasing performance offers a unique window into the dynamics of human rhythmic coordination (see also Van Kerrebroeck et al., 2021, for an interesting study of phasing in virtual reality) and this led us to the idea of using phasing as an experimental paradigm. We conducted an exploratory study with non-expert participants (i.e., no professional musicians) who performed phasing against a metronome by finger tapping (Hall et al., 2023). The goal of the study was to observe a wide range of phasing behaviors beyond what is seen in the highly controlled performance of expert musicians. Since phasing with a human partner is difficult even for trained musicians (see Hartenberger, 2016, for suggestions for practicing phasing) we began the investigation with a simplified task of phasing against a metronome. This simplifies the task in two ways: Phasing is performed (1) with a non-responsive partner who does not react to the participant's tempo change, and (2) using a simple isochronous rhythm rather than a complex rhythmic pattern (such as the one in Figure 1). We reported elsewhere the results of multidimensional recurrence quantification analysis of the relative phase data (Hall et al., 2023). The analysis showed that tapping was more stable when the taps were near in-phase or antiphase relation with the metronome, confirming the existence of in-phase and antiphase attractors in phasing performance.

In the present paper, a further analysis and modeling of the data from the exploratory study (Hall et al., 2023) is reported. Here we examine various types of phasing behavior observed in non-expert participants and analyze the effect of metronome tempo which was the only parameter systematically varied in the study. It will be shown that successful phasing depends on gradual advancement of each tap relative to the metronome. This finding, along with the effect of tempo on phasing performance, is replicated in a dynamical model consisting of an adaptive-frequency oscillator coupled to a periodic stimulus. To help the readers, a brief version of the experimental procedure is given below (see Hall et al., 2023, for the original description).

2. Materials and methods

2.1. Participants and materials

Twenty-five undergraduate students (17 females, 8 males; 18–21 years, M = 18.7 years) at the University of Connecticut were recruited from the Department of Psychological Sciences Experiment Participant Pool and received course credit for participating in the experiment. Nineteen out of 25 participants (12 females, 7 males) reported no experience in playing musical instrument. Six participants (5 females, 1 male) reported 1 to 13 years of experience in playing musical instrument(s), but none of them were music-major students.

Seven audio stimuli were created, each containing a series of identical metronome beats (woodblock sound) at a constant tempo, ranging from 80 BPM (beats per minute) to 140 BPM in 10-BPM increments. Each stimulus was 2 minutes long and contained a bell sound (serving as a cue signal) coinciding with a metronome beat at around 7 s after the first metronome beat.

2.2. Procedure

The participants first filled out a demographic survey including the length of experience in playing musical instruments (in years). Then, the experimenter gave the instructions for performing phasing against a metronome, accompanied by audio and audiovisual demonstrations (audio: metronome and tapping sounds; audiovisual: a video of a person performing phasing in the same experimental setup). The participants were instructed (Figure 2) to (1) start tapping to the metronome using a finger of their choice and maintain in-phase (synchronous) tapping, and (2) upon hearing the cue signal (bell sound), begin phasing in a steady but self-paced manner by placing each tap increasingly ahead of the metronome.[3] (3) Once they completed one phasing lap by coming back to in-phase tapping, they were asked to tap a few more times in phase and stop (the audio stimulus stopped 5 seconds after tapping stopped).

The participants then practiced phasing with an interactive audiovisual display (Practice 1). The visual display included an arrow on a circle (like a clock face) which indicated the relative phase of each tap, with in-phase (relative phase = 0) at 12 o'clock and antiphase ($\pm\pi$ or 180°) at 6 o'clock. Thus, the goal was to make the arrow move clockwise from 12 o'clock and stop when it comes back to 12 o'clock after one lap. The number of phasing laps (i.e., the number of clockwise rounds made by the arrow) was displayed on top of the display. After each practice trial, feedback was given on the screen about the number of phasing laps made in total (the target was one lap) and a score indicating whether the phasing was gradual enough. The score of 100% was given when the participant made at least 16 taps while phasing. This excluded initial and final in-phase taps. This minimum required number of taps was not known to the participants to encourage self-paced tapping. The minimum number of phasing taps was not used in data analysis. In Practice 2, the same feedback was given on the screen after each trial, but no visual aid was provided. In both practice sessions, three metronome tempi (90, 110, and 130 BPM) were used to prepare the participants for the range of tempo used in the main experiment (80–140 BPM).

The main experiment included 21 trials, three trials for each of 7 metronome tempi. Metronome tempo was the only independent variable in this exploratory study. The order of the trials was pseudo-randomized for each participant such that the same tempo was not presented in any two consecutive trials. No feedback was provided during the main experiment. The audio stimuli were played at a comfortable listening level through two loudspeakers

3 The direction of phasing (getting ahead of the metronome, instead of getting behind) follows the original phasing process in Reich's *Drumming* in which Drummer 2 places each note increasingly ahead of Drummer 1 who tries to hold a constant tempo. Phasing in the opposite direction (i.e., by falling behind a metronome) may prove more difficult because it would be harder to break away from in-phase synchronization when the metronome precedes the tap. This would make an interesting follow-up study.

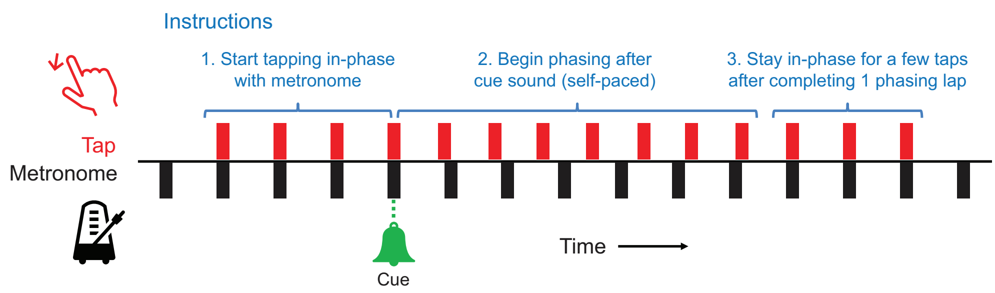

FIGURE 2
The procedure of a phasing trial.

placed in front of the participant. The participants tapped their finger on HandSonic HPD-15 Hand Percussion Pad (Roland Corporation), and the MIDI signal was converted to keystrokes using MIDI Translator Pro (Bome Software GmbH & Co. KG). Hitting on the drum pad created an audible thud, and no additional sound was played in response to tapping. The timestamp of each tap was recorded with custom code written in MATLAB (MathWorks, Inc.) using Psychophysics Toolbox (Psychtoolbox) Version 3.0.15.

2.3. Analysis

The relative phase of the nth tap, ψ_n, was calculated from the timestamp of the tap, t_n, and the timestamp of the closest metronome beat, m_n, by

$$\psi_n = \frac{2\pi(m_n - t_n)}{T}, \tag{1}$$

where T is the period of the metronome. Thus, the relative phase ranged from $-\pi$ to π (before upwrapping, see below), and a positive relative phase resulted when the tap preceded the metronome beat.[4] The time series of relative phases in an individual trial were then unwrapped (using MATLAB's `unwrap` function) so that the relative phase can increase continuously beyond π toward 2π, instead of jumping down to $-\pi$. This allowed counting the number of phasing laps as described below.

From the relative phase data for each trial, we determined (1) the number of phasing laps made (i.e., the number of 2π-rounds made by the relative phase), and (2) the number of taps made during phasing (i.e., taps made between initial and final in-phase tapping). We first determined the range of relative phase during initial in-phase tapping by taking the minimum and the maximum relative phase during the second half of the pre-cue interval (see Figure 3). The initial range was determined for each trial because it is known that the mean asynchrony between taps and metronome beats during in-phase synchronization varies across individuals and also depends on tempo (Aschersleben, 2002; Scheurich et al., 2018). The number of phasing laps was calculated as the number of complete 2π-rounds made between the minimum initial relative phase and the maximum unwrapped relative phase in the trial.[5] The number of taps during phasing was determined by identifying the phasing window, which begins after the last tap inside the initial in-phase range and ends before the first tap inside the final in-phase range (indicated by the pink background in Figure 3).

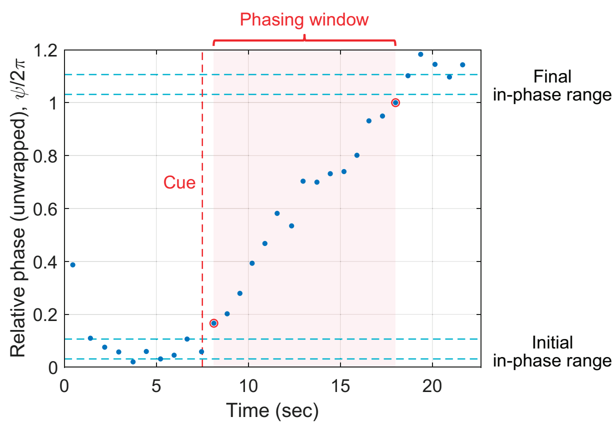

FIGURE 3
Parsing of a phasing trial. The unwrapped relative phase of each tap is plotted vs. its timestamp. The vertical axis displays unwrapped relative phase divided by 2π to show the number of phasing laps clearly. In this particular trial, one phasing lap was made, with 15 taps within the phasing window. See text for details.

4 Note that relative phase defined this way has an opposite sign from asynchrony commonly used in the sensorimotor synchronization literature. Relative phase, favored in dynamical systems research, is based on system states, while asynchrony is based on event times. When the tap is ahead of the metronome, the tapper's relative phase to the metronome is positive because the tapper's state (phase) is more advanced than the metronome's state at a given moment in time. The asynchrony is negative in this situation because the tap time is earlier than the metronome tick time.

5 This was done by subtracting the minimum initial relative phase from the maximum unwrapped relative phase reached in the trial, dividing the result by 2π, and then applying the floor function.

3. Results and discussion

3.1. Successful vs. unsuccessful trials: gradualness of phasing

3.1.1. Classification of phasing outcomes

A phasing trial was counted as "successful" if the participant was able to follow the instructions and perform only one phasing lap (Figure 4A). Only 38% of all trials (200 out of 525 trials) were successful trials, indicating the difficulty of the phasing task. The trials with more than one phasing lap were named "unsuccessful", and they accounted for 41% of all trials (213 trials; Figure 4B). The trials with no complete phasing lap were labeled "incomplete", accounting for 19% of all trials (102 trials, Figure 4C). The trials in which the participant did not maintain in-phase tapping before the cue signal were flagged as "noncompliant" (the remaining 2%, 10 trials) and excluded from subsequent analysis because initial in-phase range could not be determined.[6]

3.1.2. Gradualness of phasing: number of taps per phasing lap

A major difference found between the successful and the unsuccessful trials was the gradualness of phasing, which was quantified by the number of taps per phasing lap (only the taps in phasing window were counted, excluding initial and final in-phase taps). A high number of taps per lap indicates small increments of relative phase by individual taps on average. It was found that significantly fewer taps were made per phasing lap in the unsuccessful trials (M = 8.77, SD = 4.44) than in the successful trials (M = 21.15, SD = 13.16), $t(241.2) = 12.65$, $p < .001$, 95% CI [10.45, 14.31] (Welch's two sample t-test).[7] The box plots in Figure 5A show the distribution of the number of taps per lap in individual trials grouped by the number of phasing laps made. Note that the shaded notch for the successful trials (one phasing lap, green background) does not overlap with the notches for the unsuccessful trials (2 or more laps, red background). This indicates that the median number of taps per lap was greater in the successful trials than in the unsuccessful trials at a 95% confidence level (McGill et al., 1978).

The same relationship was also found at the level of individual participants. The average number of taps per phasing lap for individual participants predicted the percentage of successful trials, $R^2 = 0.275$, $F_{(1,23)} = 8.70$, $p = 0.007$ (Figure 5B). However, the years of playing musical instruments (indicated by different markers in Figure 5B) did not predict the success rate, $R^2 = 0.028$, $F_{(1,23)} = 0.658$, $p = 0.426$.

6 The classification of successful, unsuccessful, and incomplete trials was initially reported in the original paper (Hall et al., 2023). All other results described here are new.

7 The incomplete trials are not included in this analysis because taps per lap could not be computed when no complete lap was made.

3.2. Effect of tempo

3.2.1. Phasing outcome types by tempo

Figure 6A shows that the number of successful trials did not vary significantly with the tempo, $r(5) = -0.11$, $p = 0.807$, but clear and opposite trends were found for the unsuccessful and the incomplete trials. The number of unsuccessful trials decreased as the tempo increased, with a strong negative correlation, $r(5) = -0.94$, $p = 0.002$, whereas the number of incomplete trials was positively correlated with the metronome tempo, $r(5) = 0.95$, $p = 0.001$. This indicates different types of failure were prevalent at slow vs. fast tempi. At slow metronome tempi, the participants often failed to stop at the in-phase target after one phasing lap. At faster tempi, on the other hand, more participants were not able to reach the in-phase target.

3.2.2. Number of taps per lap by tempo

An effect of metronome tempo was also found in the number of taps per phasing lap. For both the successful and the unsuccessful trials, phasing was more gradual (i.e., more taps per lap) at higher tempi (Figure 6B). A multiple linear regression indicated that outcome type (successful = 1, unsuccessful = 2) and metronome tempo explained a significant portion of the variance in the taps/lap data, $R^2 = 0.30$, $F_{(2,410)} = 89.4$, $p < 0.001$. Both outcome type ($B = -12.03$, $t = -12.58$, $p < 0.001$) and metronome tempo ($B = 0.068$, $t = 2.80$, $p = 0.005$) were significant predictors in the model. This finding might be related to the decrease of unsuccessful trials and the increase of incomplete trials with increasing tempo shown above (Figure 6A). Gradual phasing at fast tempi may reduce the chance of overshooting and skipping over the goal, but at the same time, it may make it more difficult to leave the initial in-phase tapping. Although this did not change the success rate across tempi, this might have impacted the composition of failed trials (i.e., unsuccessful vs. incomplete). We discuss this possibility further in Section 4.1.

3.3. Subtypes of incomplete trials

The above finding encouraged closer examination of the incomplete trials as to how phasing failed when no complete phasing lap was made. Multiple subtypes of the incomplete trials were identified (Figure 7A). In the first subtype named "trapped", taps did not leave the initial in-phase range significantly. A trial was determined to be trapped if the relative phases of all taps after the cue signal were inside the initial range plus and minus one width of the range (indicated by the magenta dotted lines). A second subtype is called "return" because taps leave the initial in-phase range but return to it without reaching the goal. In a third subtype, taps leave the initial range but stop before reaching the goal, hence called "halfway". The last subtype is called "backward", in which taps leave the initial range but go in the wrong direction. Figure 7B shows that return trials were the most common subtype of incomplete trials for all tempi. It is noteworthy that all incomplete trials at the lowest tempo (80 BPM) were return trials and that trapped trials were found only at the mid to high tempi.

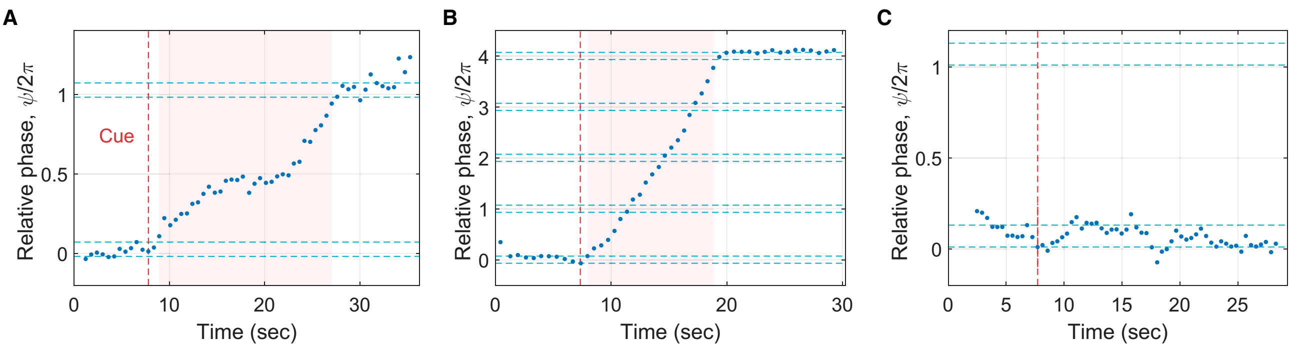

FIGURE 4
Examples of different phasing outcomes. **(A)** A successful trial (one phasing lap made as instructed), **(B)** an unsuccessful trial (more than one phasing lap; 4 laps were made in this particular trial), and **(C)** an incomplete trial (no complete phasing lap made).

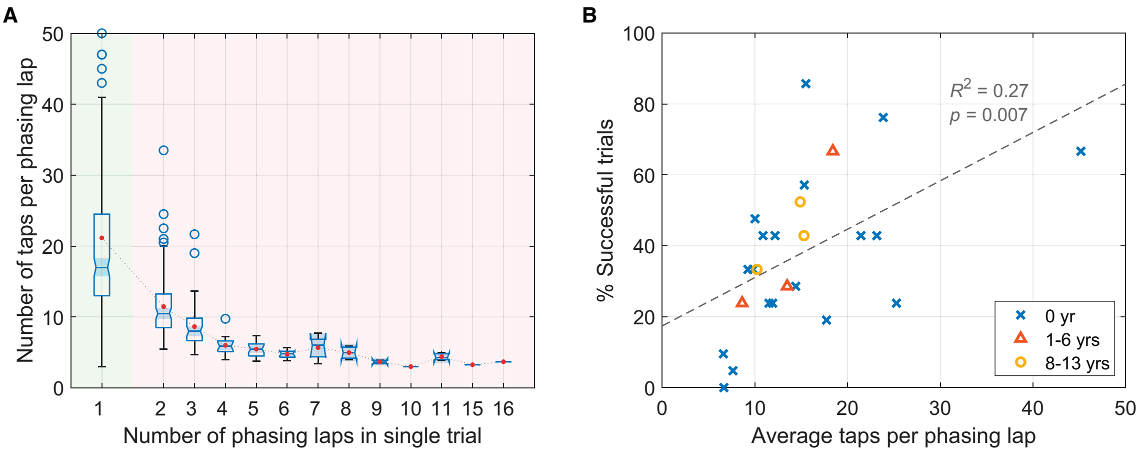

FIGURE 5
(A) Box plots showing the number of taps per phasing lap for trials grouped by the total number of phasing laps (green background: successful trials, red background: unsuccessful trials). The red dots show the mean taps per lap for each group. Nine trials with more than 50 taps/lap (the max at 84 taps, all successful trials) are beyond the plotting range and not shown. **(B)** Success rate (the percentage of successful trials) for individual participants (N = 25) plotted against their average taps per phasing lap (for the successful and the unsuccessful trials combined). Participants with different levels of musical experience (in years of playing musical instruments) are indicated by different markers (see the legend).

4. Dynamical systems modeling

4.1. Dynamical systems account of the experimental results

Unlike the professional percussionists in the expert study (Hartenberger, 2016; Schutz, 2019), the non-expert participants in the exploratory study further analyzed here (Hall et al., 2023) often failed to perform phasing as instructed (in unsuccessful and incomplete trials). By recruiting non-expert participants, we hoped to observe a diverse range of phasing behaviors (especially failures), which can reveal more about the underlying dynamics of phasing performance than the highly controlled performance of expert musicians does. Here we discuss the findings of the exploratory study from a dynamical systems perspective, attempting to characterize the various phasing outcomes observed in the experiment as different possible behaviors of a single dynamical system. The ideas developed here are tested with model simulations below.

Dynamical systems theory describes the behavior of complex dynamical systems with mathematical equations which capture the contribution and interaction of underlying forces and constraints (Strogatz, 1994; Kelso, 1995; Schiavio et al., 2022). As was done for phasing between human partners (see Section 1), the dynamics of phasing against a metronome can be characterized in terms of the interaction between the intrinsic tendency of synchronization and the intention of desynchronization. In-phase coordination is an intrinsically stable mode of rhythmic coordination,[8] so that a coordinated rhythmic movement such as finger tapping to a metronome is attracted to the in-phase state when the current state is near it (Kelso, 1984; Scholz et al., 1987). To perform

8 Intrinsic stability means that a pattern is stable and occurs spontaneously in the absence of specific task requirements (Schöner and Kelso, 1988a). Task-specific intention interacts with the intrinsic dynamics of the system and alters the attractor layout, inducing behavioral change.

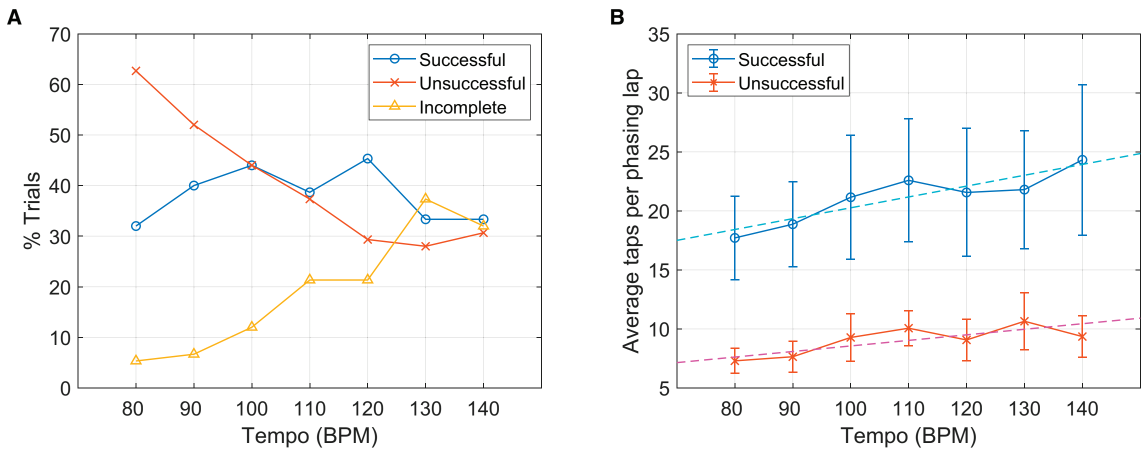

FIGURE 6
Effect of metronome tempo. **(A)** The proportions of three different phasing outcomes for each metronome tempo. **(B)** Average taps per phasing lap in the successful and the unsuccessful trials shown for each tempo. Error bars indicate 95% confidence intervals, and dashed lines show the linear fits for the successful and the unsuccessful trials separately.

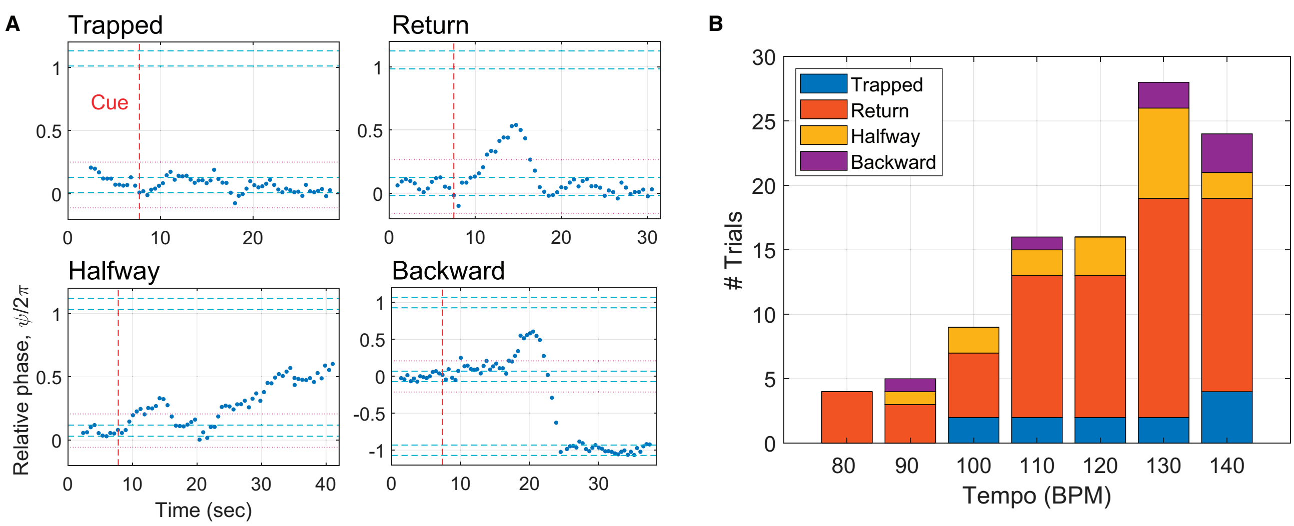

FIGURE 7
(A) Subtypes of incomplete trials: trapped, return, halfway, and backward. The magenta dotted lines indicate the initial in-phase range ± one width of the range, which was used to determine trapped trials. **(B)** The number of the subtypes of incomplete trials shown for each metronome tempo.

phasing, however, the tapper has to overcome the attraction of in-phase coordination by increasing tapping tempo and place each tap increasingly ahead of the metronome. This requires a precise control of tapping tempo because if the tempo increase is not big enough, taps would be pulled back toward the metronome beats and hence unable to escape the in-phase attractor, as found in some of incomplete trials. To use an analogy, this is like a car trapped in a valley and unable to climb up the hill because it cannot overcome the gravity (the car labeled "Incomplete" in Figure 8A).

If the tempo increase is too big, on the other hand, the tapper would be able to escape the initial in-phase attractor but would also be prone to miss the target by overshooting. An unsuccessful trial can be depicted as a system with high kinetic energy enough to escape the origin attractor but is unable to stop at the goal attractor (like the car labeled "Unsuccessful" in Figure 8A). This interpretation agrees with the finding that fewer taps per phasing lap were made in the unsuccessful trials (Figure 5), which indicates that the participants tended to miss the target and kept phasing when they increased tapping tempo too much.

Successful phasing, however, requires more than just the precise amount of tempo increase. The control of tapping tempo has to be context-dependent because the attractor one wants to escape from (i.e., in-phase coordination) is the same attractor one wants to land on (Figure 8B). Hence, tapping has to accelerate to start phasing and decelerate when finishing, just as the "Successful" car in Figure 8A must accelerate uphill and then decelerate downhill to stop at the stop sign.

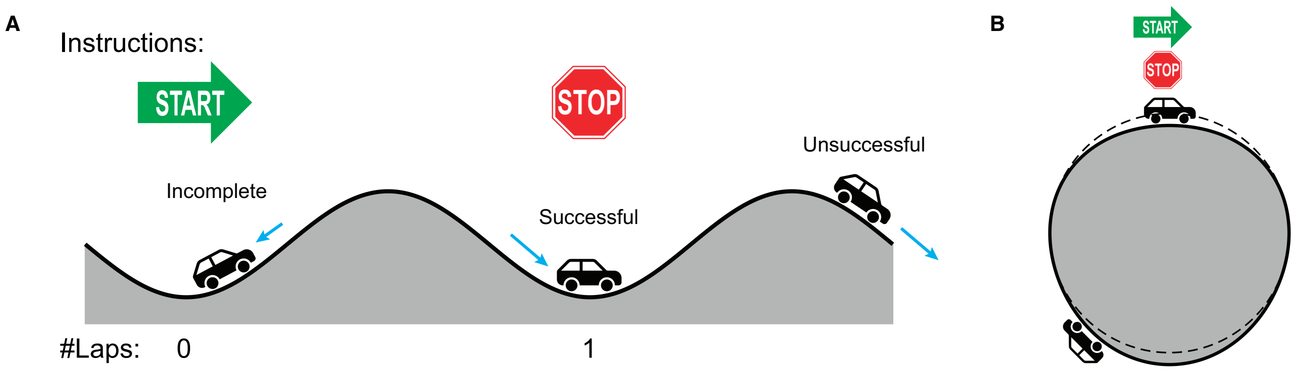

FIGURE 8
A car analogy for the dynamic landscape of phasing performance. **(A)** An unwrapped flat representation. The in-phase attractor is depicted as a valley. **(B)** The true circular landscape where phasing starts and ends at the same point. The dashed line depicts a perfect circle so that it is a valley if the ground is below the dashed line and a hill if above the dashed line.

Another important finding that must be addressed in the dynamical systems account is the effect of metronome tempo. It was found that unsuccessful trials were more common at slow tempi, while incomplete trials were found more often at fast tempi (see Figure 6A). One possible interpretation that follows from the dynamical systems account is that the attraction of in-phase coordination might be stronger at fast tempi. A strong attractor would be harder to escape, resulting in more incomplete trials, whereas a weak attractor would be easy to escape but also easy to overshoot, leading to more unsuccessful trials. This idea seems consistent with the finding that more taps were made per phasing lap at faster tempi (Figure 6B). The same amount of tempo increase would result in a slower advancement of relative phase when attempting to escape a stronger attractor (imagine a rocket launch from a heavy planet).

But why would the in-phase attractor be stronger at fast tempi? A clue can be found in the experiments of sensorimotor synchronization in the presence of distractors (Repp, 2003, 2004). In these experiments, participants were instructed to synchronize finger taps with a target sequence of isochronous tones while ignoring a sequence of distractor tones which were presented at a different pitch. The results showed that the taps were attracted toward the distractor tones when they were close in time. Repp (2004) found that the strength of distractor effect depended on the absolute temporal separation between the target and the distractor (measured in milliseconds, for example) rather than the relative phase between them (e.g., in radian). In dynamical systems language, this means that the temporal basin of attraction for in-phase coordination, where taps are pulled toward metronome beats, may have a fixed width when measured in absolute time regardless of metronome tempo. Then, the basin of in-phase attraction would take up a bigger portion of the metronome period when the tempo is fast (because the period is short), and this could result in stronger in-phase attraction at fast tempi. We test this idea below with a dynamical model of phasing performance.

Our goal is to construct a minimal dynamical model capable of producing various phasing behaviors observed in the human participants and test if the model can replicate the main findings of the experiment. We start with a simple, well-known model of periodically forced oscillation and discuss additional dynamical features necessary to model human phasing behaviors (Section 4.2). We then present a minimal model with such features and test if it can replicate the experimental results (Section 4.3).

4.2. Model with fixed frequency detuning

Systems showing periodic activities, such as flashing fireflies and the human sleep-wake cycle, can be modeled as oscillations (Pikovsky et al., 2001; Winfree, 2001), and human rhythmic movement such as periodic finger tapping has been studied with oscillator models (Haken et al., 1985; Large and Kolen, 1994; Large et al., 2015). Let us consider a phase oscillator coupled to a periodic external stimulus as a model of phasing performance against a metronome,

$$\frac{d\phi}{dt} = \omega + c\sin(\theta - \phi), \tag{2}$$

where ϕ is the oscillator phase,[9] t is time, ω is the oscillator's natural frequency, c is the coupling strength, and $\theta = \omega_0 t$ is the stimulus phase where ω_0 is the stimulus frequency (hence we assume $\theta = 0$ at $t = 0$ without loss of generality). In the absence of external stimulus (i.e., when $c = 0$), ϕ increases at the constant rate of ω. (Hence, the phase ϕ obtained by integrating the differential equation, Equation (2), is an unwrapped phase, which is not confined to a 2π-range.) We assume that the oscillator produces a "tap" whenever the wrapped ϕ crosses zero[10] (or when the unwrapped phase crosses a multiple of 2π), an arbitrary choice that does not alter the overall results. Similarly, the stimulus is

9 "Phase" refers to the angular component of oscillation, not to be confused with "phasing" which refers to the act of varying the phase relation between patterns.

10 The wrapped phase is obtained by mapping the original unwrapped phase onto the range from $-\pi$ to π by adding or subtracting a multiple of 2π.

assumed to produce a "tick" (like a metronome) whenever the wrapped θ crosses zero.

The synchronization and desynchronization of the oscillator with the external stimulus can be described by the relative phase defined as $\psi = \phi - \theta$. Thus, ψ is positive when the oscillator is ahead of the stimulus, as defined for the experimental data (see Equation 1). Since $d\theta/dt = \omega_0$, the relative phase is governed by the differential equation,

$$\frac{d\psi}{dt} = \Delta\omega - c\sin\psi, \tag{3}$$

where $\Delta\omega = \omega - \omega_0$ is *frequency detuning*, the difference between the oscillator's natural frequency and the stimulus frequency. This equation represents a vector field that determines the flow of ψ over time (Figures 9A–C, the direction of flow is indicated by arrows). The points where $d\psi/dt = 0$ are called fixed points because ψ does not change over time at these values (indicated by circles). If the local flow is toward a fixed point, it is called a stable fixed point or an attractor (filled circles). If the flow is away from a fixed point, it is called an unstable fixed point or a repeller (empty circles).

When $\Delta\omega = 0$ (no frequency detuning), there is a stable fixed point at $\psi = 0$ (Figure 9A), which indicates that ψ converges to 0 over time. Thus, the oscillator synchronizes in phase with the stimulus when its natural frequency matches the stimulus frequency. In the presence of frequency detuning, the oscillator may or may not synchronize with the stimulus depending on the size of detuning. When the detuning is small compared to the coupling strength ($|\Delta\omega| < c$, Figure 9B), ψ converges to a nonzero steady-state value, indicating that the oscillator synchronizes (or phase-locks) with the stimulus maintaining a constant nonzero relative phase. When the frequency detuning is larger than the coupling strength ($|\Delta\omega| > c$, Figure 9C), no fixed point exists, and the flow is in one direction which depends on the sign of $\Delta\omega$. This indicates that the oscillator desynchronizes with the stimulus when the detuning is large enough. (See Section 4.5 of Strogatz, 1994, for a more detailed and reader-friendly analysis of the model).

The above analysis suggests that different phasing behaviors may be simulated by manipulating the model parameters $\Delta\omega$ and c. Figure 9D shows two simulations with the different amounts of detuning shown in Panels B and C. To simulate in-phase tapping at the beginning of a phasing trial, the natural frequency was first set identical to the stimulus frequency (i.e., $\Delta\omega = 0$, Panel A). After the cue signal at 5 s, the natural frequency was increased (i.e., detuned) by a fixed amount to simulate the intention of phasing. When the frequency increase was small ($\Delta\omega < c$, the circle markers in Panel D), the oscillator did not perform phasing but remained phase-locked to the stimulus with a positive relative phase. In other words, the oscillator "tapped" ahead of the metronome but could not escape the influence of the in-phase attractor. This behavior corresponds to the incomplete trials found in the human experiment. When the frequency increase was larger than the coupling strength ($\Delta\omega > c$, the + markers), the oscillator desynchronized with the stimulus. However, it did not resynchronize after one phasing lap but continued phasing because the large frequency detuning had eliminated the attractor (Figure 9C). This behavior corresponds to the unsuccessful trials. Thus, the simulations show that the model with a fixed amount of frequency detuning can produce only the incomplete and the unsuccessful types of phasing behavior.[11] The results suggest that a context-dependent control of frequency detuning is required to simulate successful phasing as discussed in the previous section.

4.3. Phasing model with context-dependent frequency dynamics

Based on the above observations, we expanded the simple oscillator model discussed above (Equation 2) with additional features. The resulting model is described by two differential equations,

$$\frac{d\phi}{dt} = \omega + cf(\phi, \theta, \rho), \tag{4}$$

$$\frac{d\omega}{dt} = \gamma f(\phi, \theta, \rho) - \lambda g(\phi, \theta, \rho)(\dot{\psi} - \Delta), \tag{5}$$

which determine the dynamics of the phase (ϕ) and the natural frequency (ω) of the oscillator, respectively. Here we present a synopsis of the model structure first (see Table 1 for a summary) and describe the details of each model component below (Section 4.3.1). (Readers may choose to skip the details and proceed to the replication results.)

The phase equation (Equation 4) includes the natural frequency (ω) and the coupling term (strength c). The pulse-like function f is used as the coupling function (instead of the sine function in Equation 2) so that phase attraction is strong only when the tap and the metronome tick are close in time. We will keep the temporal width of the coupling function constant across different metronome tempi and test if this allows the model to replicate the tempo effect found in the human data as discussed above (Section 4.1).

The frequency equation (Equation 5) includes frequency adaptation (adaptation rate γ) and frequency bias (strength λ), which have opposing effects. The former causes the natural frequency to adapt to the stimulus frequency (promoting synchronization), while the latter causes the natural frequency to deviate (detune) from the stimulus frequency to keep the relative phase increasing at the constant rate of Δ (promoting desynchronization and phasing). The context-dependent gating function g manipulates the balance between the two terms to initiate and end phasing, by starting with strong frequency bias and switching to weaker bias once the system escapes the initial in-phase attractor. We will manipulate Δ (target change rate,

11 When $\Delta\omega = c$, the $d\psi/dt$ curve touches the ψ axis at $\pi/2$ or 90° (imagine a case between Figures 9B, C). In this case, there is a half-stable fixed point at $\psi = \pi/2$: it is stable when approaching from below (lower than $\pi/2$) but unstable from above (higher than $\pi/2$). Thus, when the relative phase is perturbed upward towards π (e.g., by stochastic noise), it would keep increasing until it stops at the half-stable point, completing only one phasing lap. However, phasing in this system ends at $\psi = \pi/2$, not at $\psi = 0$ (in-phase) as required in the experiment. Thus, this system is implausible as a model of phasing performance.

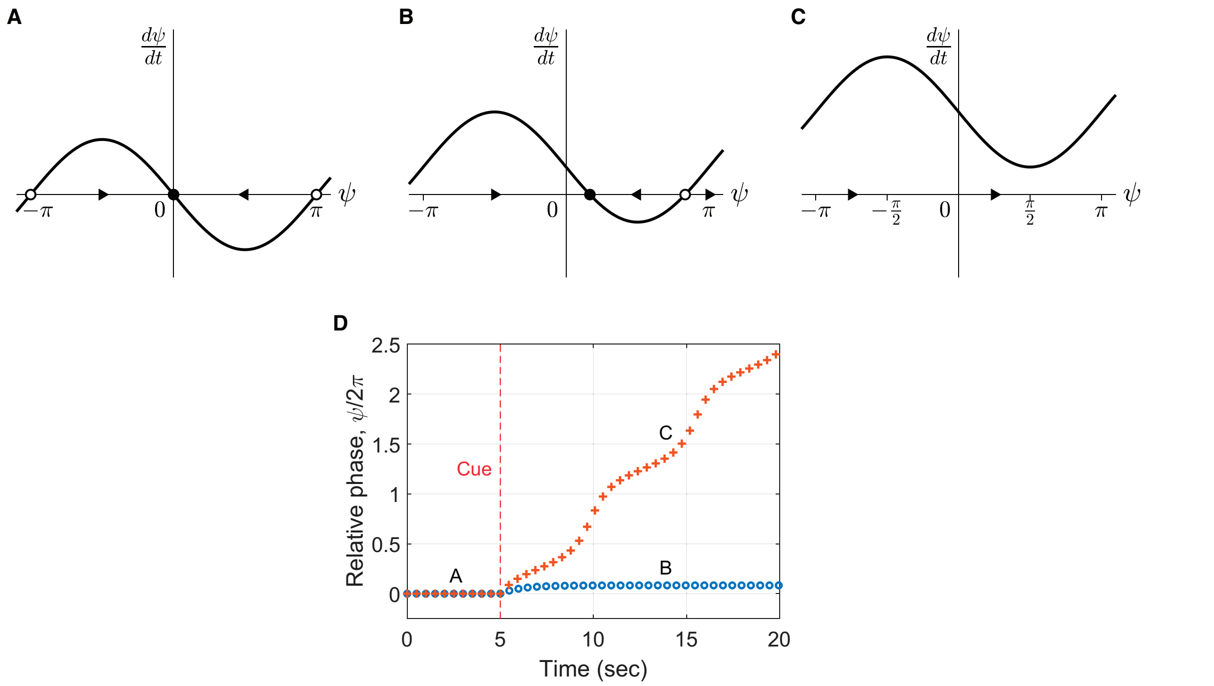

FIGURE 9
Flow in the vector field defined by Equation (3) for **(A)** $\Delta\omega = 0$, **(B)** $\Delta\omega = 0.5$, and **(C)** $\Delta\omega = 1.5$ for $c = 1$. The arrows indicate the direction of flow. The filled and empty circles denote stable and unstable fixed points, respectively. **(D)** Simulations of the model with fixed detuning (Equation 2) with the parameters in **(B, C)**. Frequency detuning is introduced at $t = 5$ sec. The markers indicate the (unwrapped) relative phase of individual "taps" produced by the oscillator (phase zero-crossing). Common parameter: $\omega_0 = 4\pi$ rad/sec (i.e., 2 Hz or 120 BPM).

TABLE 1 **Components of the context-dependent phasing model (Equations 4–5).**

Variables	ϕ	Oscillator phase
	ω	Oscillator natural frequency
	θ	Stimulus phase (external)
Parameters	c	Coupling strength (phase attraction)
	γ	Frequency adaptation rate
	λ	Frequency bias strength
	Δ	Target change rate of relative phase (controls gradualness of phasing)
	ρ	Parameter controlling the width of pulse-like functions
Functions	f	Pulse-like coupling function
	g	Context-dependent gating function (frequency bias weakens once the system escapes the in-phase attractor)

which determines the gradualness of phasing) and γ (frequency adaptation rate) to replicate the multiple phasing outcomes found in the human experiment as well as the effect of metronome tempo on the composition of phasing outcome types.

4.3.1. Detailed model description

The phase equation of the context-dependent model (Equation 4) is identical to the simple model (Equation 2) except the coupling function. f is a pulse-like coupling function defined as

$$f(\phi, \theta, \rho) = \mathrm{Im}\left[h(\theta, \rho) \cdot h(-\phi, \rho)\right], \quad (6)$$

where $\mathrm{Im}[x]$ denotes the imaginary part of x, h is a complex analytic function with a pulse-like shape defined in Appendix, and $\theta = \omega_0 t$ is the stimulus phase. The width of the pulse function $h(x, \rho)$ depends on the parameter ρ, becoming sharper as ρ increases between 0 and 1 (Figure 10A; Appendix for more details). The coupling function f is a product of two pulse-like functions, one generated by the stimulus (θ) and the other by the oscillator (ϕ). This is a more realistic coupling function for modeling tapping to a metronome than $\sin(\theta - \phi)$ in Equation (2), given that the stimulus sound used in the experiment (a woodblock sound) is a discrete event and that taps are attracted toward stimulus tones when they occur in temporal proximity (Repp, 2003, 2004). Figure 10B shows that the coupling interaction is strong when both θ and ϕ are near zero, in other words, when the metronome beats and the taps are close in time.[12] f can be considered a general coupling function that encompasses the sine coupling in Equation (2) because when $\rho = 0$, $f(\phi, \theta, 0) = \sin(\theta - \phi)$, that is, Equation (4) becomes Equation (2) when $\rho = 0$ (see Appendix).

The second differential equation of the model (Equation 5) describes the dynamics of the natural frequency of the oscillator ω, which is now made a variable (it was a parameter in the first model). The dynamics of ω is determined by two factors. The

12 Figure 10B is the two-dimensional vector field for ψ when $\omega = \omega_0$, which can be compared to the one-dimensional vector field in Figure 9A.

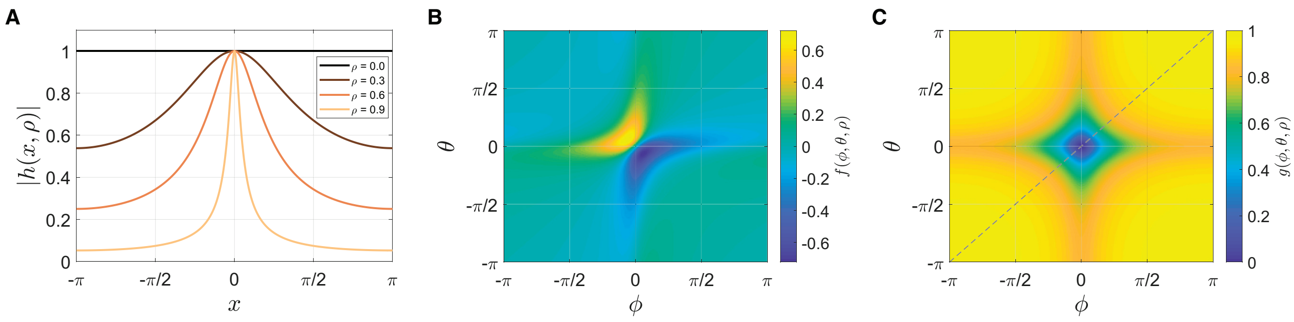

FIGURE 10
(A) The amplitude of pulse-like function $h(x, \rho)$ for $\rho = 0$, 0.3, 0.6, and 0.9 (see Appendix for the equation). **(B)** The coupling function $f(\theta, \phi, \rho)$ for $\rho = 0.7$ (Equation 6). **(C)** The gating function $g(\theta, \phi, \rho)$ when $\psi > \psi_\theta$ for $\rho = 0.7$ (Equation 7). The diagonal indicates where the relative phase is zero ($\psi = \phi - \theta = 0$).

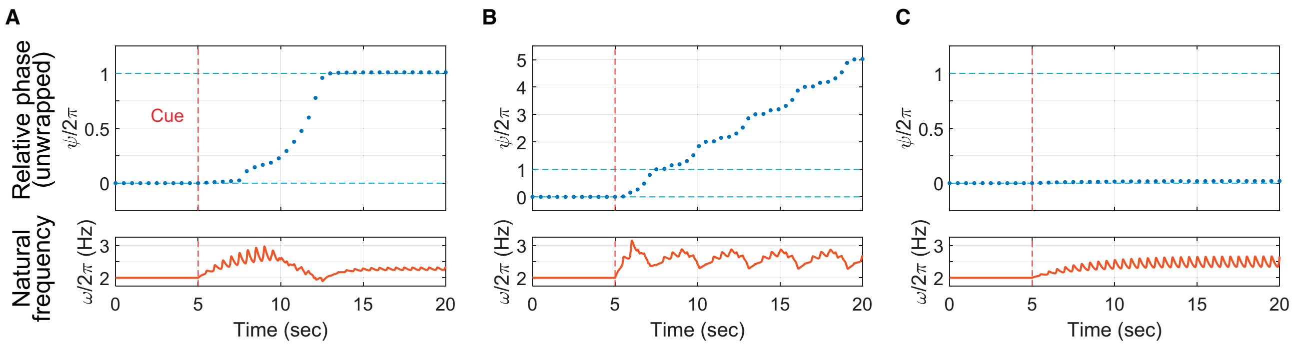

FIGURE 11
Simulations of the context-dependent model (Equations 4–7): **(A)** successful phasing ($\Delta = 1$ rad/sec), **(B)** unsuccessful phasing ($\Delta = 3$ rad/sec), and **(C)** incomplete phasing ($\Delta = 0.5$ rad/sec). The top plots show the unwrapped relative phase at the time of each "tap" (zero crossing of the wrapped oscillator phase). The bottom plots show the continuous time series of the natural frequency ω. Common parameters: $c = 30$, $\gamma = 15$, $\lambda = 0$ ($t < 5$ sec), $\lambda = 3$ ($t \geq 5$ sec), $\psi_\theta = \pi/2$, $\omega_0 = 4\pi$ rad/sec (i.e., 2 Hz or 120 BPM), and $\rho = 0.7012$.

first term on the right-hand side introduces frequency adaptation, similar to the period adaptation (or correction) in previous models (Large and Kolen, 1994; Loehr et al., 2011; Jacoby and Repp, 2012), so that the natural frequency is attracted toward the stimulus frequency. The pulse-like coupling function f is used here too so that frequency adaptation is strong when both θ and ϕ are near zero (Figure 10B).

The second term on the right-hand side of Equation (5) describes a possible mechanism for context-dependent control of tapping frequency during phasing. Here we assume that the tapper tries to maintain a constant rate of relative phase increase, Δ, and also that the tapper can sense the current change rate, $\dot{\psi} = d\psi/dt$. The term applies a positive frequency bias when the current rate is slower than the target rate (i.e., $\dot{\psi} < \Delta$), and the term becomes zero when the current rate matches the target rate. Hence, small Δ would result in gradual phasing with many taps per lap, and large Δ would lead to less gradual phasing with fewer taps per lap. λ is the strength of frequency bias resulting from the intentional control. g is a context-dependent gating function that allows different behaviors when beginning and ending phasing by controlling the strength of frequency bias. It is defined as

$$g(\phi,\theta,\rho) = \begin{cases} 1 & \text{if } \psi \leq \psi_\theta \\ 1 - \left|h(\theta,\rho)\cdot h(-\phi,\rho)\right| & \text{if } \psi > \psi_\theta \end{cases}, \quad (7)$$

where ψ_θ is the threshold ψ for switching behaviors. When phasing begins, the unwrapped relative phase is near zero and smaller than a threshold, say, $\psi_\theta = \pi/2$. In this case, $g = 1$ so that the second term exerts full frequency bias to facilitate escaping the initial in-phase attractor. Once the relative phase escapes the vicinity of zero (satisfying $\psi > \psi_\theta$), g is made dependent on ϕ and θ such that g gets small (i.e., weak frequency bias) when the tap and the metronome beat are close in time again (i.e., when both ϕ and θ are near zero, see Figure 10C).[13] With weak

13 Both the coupling function f and the gating function g are based on the same complex pulse function $h(\theta,\rho)\cdot h(-\phi,\rho)$, but the former uses the imaginary part while the latter uses the absolute value. See Figure A1 in Appendix.

frequency bias, frequency adaptation (the first term in Equation 5) dominates the frequency dynamics, and this allows the oscillator to slow down and end phasing successfully by converging to stable in-phase coordination. Since the gating function is also pulse-like, however, it is possible to overshoot and skip over the in-phase goal if frequency bias is big enough, resulting in unsuccessful phasing.

Note that given the difficulty and self-paced nature of the phasing task, there could be multiple viable strategies for successfully performing phasing. The mechanism of intentional frequency control implemented in Equations (5) and (7) is not proposed as the best or sole mechanism but as one of possible strategies that may be employed by human tappers (see Section 5 General discussion).

4.3.2. Replication of successful, unsuccessful, and incomplete trials

To demonstrate that the context-dependent model can show all three phasing behaviors observed in the human experiment, the model was run for three different values of Δ (the target change rate of relative phase which quantifies the intended gradualness of phasing) while other parameters were fixed. To start each "trial" with in-phase tapping, λ was set to zero for the first 5 s of the simulation and increased to a nonzero constant at $t = 5$ sec ($\lambda = 3$ was used for all three simulations). For the intermediate target rate ($\Delta = 1$ rad/sec), the model performed successful phasing by breaking away from the initial in-phase tapping and advancing the relative phase until it reached the in-phase tapping after one phasing lap (Figure 11A). After the cue at 5 s, the natural frequency (the bottom plot) increased gradually (but in a spiky manner due to the pulse coupling) until the relative phase (the top plot) escaped the in-phase attractor (notice the jump around $t = 8$ sec). After that, the natural frequency gradually decreased down to the stimulus frequency (2 Hz) as the relative phase approached and landed on the goal successfully.[14]

For the large target rate ($\Delta = 3$ rad/sec), the model replicated an unsuccessful trial by continuing phasing without stopping after one lap (Figure 11B). The natural frequency decreased when the oscillator was near in-phase with the stimulus (this is when the unwrapped relative phase ψ was near an integer multiple of 2π), but the frequency bias was still too strong for the frequency adaption to attract the oscillator to in-phase coordination. Finally, with the small target rate ($\Delta = 0.5$ rad/sec), the oscillator failed to escape the attraction of in-phase tapping, replicating an incomplete trial (Figure 11C). The natural frequency increased after phasing started at $t = 5$ sec, but the small Δ did not yield strong frequency bias enough to overcome the frequency adaptation. The simulations show that the strength of frequency bias, controlled by Δ in the model (along with λ), should be just right (not too weak or not too strong) to perform successful phasing. The simulation results for the intermediate and large values of Δ (Figures 11A, B) are consistent with the human experimental finding that phasing was more gradual with more taps per lap in the successful trials than in the unsuccessful trials (Figure 5; see also the next section).

4.3.3. Replication of tempo effect

Next, we tested if the model can replicate the effect of metronome tempo observed in the human experiment. As discussed above (Section 4.1), our hypothesis is that the temporal basin of in-phase attraction (i.e., the temporal range near a metronome beat in which taps are attracted toward the metronome) has a constant width in absolute time regardless of tempo (Repp, 2003, 2004), which results in stronger in-phase attraction at faster tempi. This effect is accounted for in the model by keeping the temporal width of pulse-like function h constant across different tempi. This is done by choosing a different ρ for each tempo so that the full width at half max of $|h|$ is constant in duration across the tempi (the full width of 100 msec was used in the following simulations; see Figure 12D).[15]

For each metronome tempo used in the human experiment, we ran the context-dependent model for a range of combinations of Δ and γ to sample different model behaviors. γ controls the strength of frequency adaptation and, along with Δ, determines the dynamics of the natural frequency (Equation 5). Previous research on sensorimotor synchronization has shown that while phase correction (phase attraction) is a largely automatic and involuntary process, period correction (frequency adaptation) is in part under voluntary control so that it can be suppressed intentionally (Repp, 2001; Repp and Keller, 2004). Here we assume that untrained participants try different "parameters" for frequency dynamics as they explore and tune their phasing skills. Then, the outcomes of phasing trials during this calibration process could be replicated in simulations with different values of Δ and γ. Here we examine a fixed region of the parameter space (Δ, γ) to obtain the distribution of different phasing outcomes and see if this distribution changes with tempo as found in the human experiment. The coupling strength c is fixed in the simulations, assuming phase attraction is not under voluntary control.

Figures 12A–C show the simulation results for the slowest (80 BPM), the middle (110 BPM), and the fastest tempi (140 BPM). For all seven tempi including the three shown in the figure, incomplete phasing was found in the upper left region of the (Δ, γ) space where frequency bias is weak, and frequency adaptation is strong. Unsuccessful phasing was found in the lower

14 Notice that after the model ended phasing successfully at around $t = 13$ sec, the natural frequency increased back by a small amount (Figure 11A). This is because the pulse-like gating function g does not suppress frequency bias completely even when the oscillator is stably entrained in phase with the stimulus: g is zero only at the time of taps (phase zero-crossing) and nonzero at other times (see Figure 10C, along the diagonal). In this simulation, frequency bias is suppressed enough so that frequency adaptation can keep the oscillator in phase with the stimulus. To model the switch of intention after reaching the goal, we could introduce another mechanism that, for example, eliminates frequency bias after the relative phase stops advancing at the intended goal. To keep the model minimal, however, we did not explore such additional features here.

15 For a fixed ρ, the temporal width of h is proportional to the metronome period (i.e., it is wider at slow tempi) because h is a function of phase, not of time (see Appendix). When the pulse width is fixed in measures of *time*, it is wider at faster tempi in measures of *phase*.

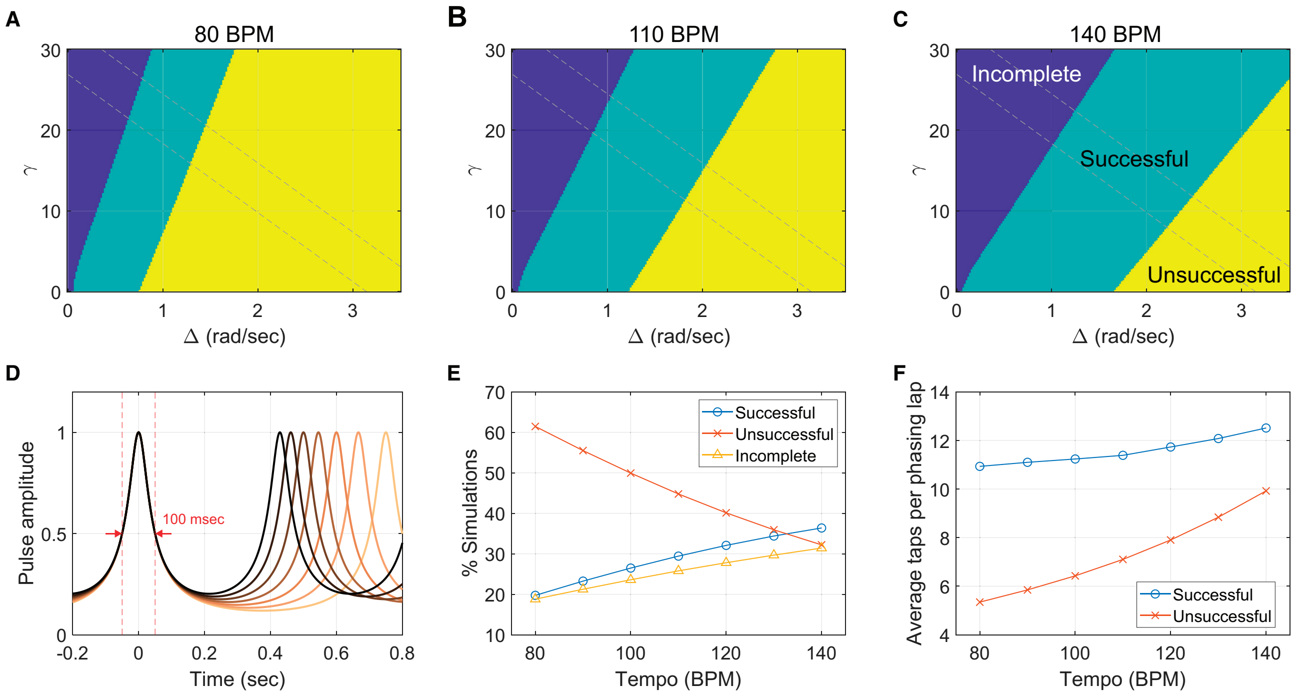

FIGURE 12
Tempo effect in the context-dependent model. **(A–C)** The classification of model simulations as successful (one phasing lap), unsuccessful (more than one lap), and incomplete (0 lap). For each of seven tempi, 40,401 simulations were run for different combinations of γ and Δ ($201 \times 201 = 40401$). Only the results for the lowest, the middle, and the highest tempi (80, 110, and 140 BPM) are shown. Dashed lines demarcate the anti-diagonal region used for Panels E and F. Parameters: $c = 30$, $\lambda = 0$ (before cue), $\lambda = 3$ (after cue), $\psi_\theta = \pi/2$, and $\rho = 0.7870$ (80 BPM), 0.7643 (90 BPM), 0.7425 (100 BPM), 0.7214 (110 BPM), 0.7012 (120 BPM), 0.6817 (130 BPM), and 0.6630 (140 BPM). **(D)** The amplitude of the pulse-like function, $|h(\theta, \rho)|$, plotted as function of time for different metronome tempi from 80 BPM (the lightest color) to 140 BPM (black). A different ρ was chosen for each tempo (listed above) so that the full width at half max is constant at 100 msec. **(E)** Simulated trial outcomes per metronome condition (only the anti-diagonal area between the dashed lines was counted). **(F)** Average taps per phasing lap in the "successful" and the "unsuccessful" simulations for each tempo.

right region, with strong frequency bias and weak frequency adaptation. Successful phasing resulted in the region between the incomplete and the unsuccessful regions where frequency bias and frequency adaptation are balanced (see Figure 11 for examples of individual simulations).

An effect of tempo was found in the proportion of different phasing results, which was measured by the sizes of the successful, unsuccessful, and incomplete regions in the (Δ, γ) parameter space (Figures 12A–C). The number of incomplete simulations increased as the tempo increased whereas the number of unsuccessful simulations decreased, both of which correspond to the trends found in the human experiment (Figure 6A). A difference from the human results was also found in that the proportion of successful simulations increased significantly with tempo and occupied more than half of the space at 140 BPM (Figures 12A, C), whereas the human data did not show any clear trend for the successful trials (Figure 6A). The discrepancy may be explained in part by the rectangular region of the (Δ, γ) space chosen for the analysis. Some parts of the region may have not been explored much by the human participants (e.g., where both Δ and γ are very small or very large). A better match with the human data was obtained when only the anti-diagonal region of the parameter space was included in the analysis (demarcated by the dashed lines in Figures 12A–C), which appears to be a more reasonable choice because here the balance between Δ and γ is varied while their sum is maintained comparable. The proportion of successful simulations still increases with tempo (Figure 12E), but all three types have comparable proportions at the fastest tempo as in the human results (compare with Figure 6A). Also, the number of taps per phasing lap in simulations matched the trends in the human data. More taps were made per phasing lap in the successful simulations than in the unsuccessful simulations, and both the numbers increased with tempo (Figure 12F, compare with Figure 6B).

5. General discussion

The present study investigated the dynamics of intentional sensorimotor desychronization by analyzing and modeling the experimental data obtained with a novel task of phasing against a metronome. First, the data from an exploratory study (first reported in Hall et al., 2023) were analyzed further to identify the various types of phasing behavior observed in participants who were unfamiliar with the task. Individual trials were categorized as successful, unsuccessful, or incomplete based on the number of phasing laps made in the trial, and the incomplete trials were further categorized into four subtypes. It was found that the number of taps per phasing lap was significantly greater in the successful trials as well as in the participants with higher success rates, suggesting that the gradual increment of relative phase was a key to successful phasing. A strong effect of metronome tempo was found in the proportion of outcome types, with the number of incomplete trials increasing with the increase of tempo while the number of unsuccessful trials decreased with tempo increase. It was also found that phasing was more gradual at fast tempi, with more taps per phasing lap. A dynamical systems interpretation of the results was given, which characterizes phasing performance as an intentional goal-directed action under the constraints of intrinsic attractor dynamics (i.e., the presence of in-phase attractor). Based on this view, a minimal dynamical model was presented which captures the interaction of intrinsic constraints and intentional control in a periodically forced oscillator with context-dependent frequency dynamics. It was shown that the single model can produce all three types of phasing behavior as well as replicate the tempo effect observed in the human experiment, supporting the dynamical systems explanation of phasing performance.

The present study demonstrated that the musical technique of phasing offers a unique setup for investigating human rhythmic behavior. Phasing involves desynchronization from a sensory stimulus. Thus, the processes underlying phasing performance cannot be described as error correction, the mechanism commonly attributed to sensorimotor synchronization (Mates, 1994; Jacoby and Repp, 2012). Also, intentional desynchronization in phasing is different from the experimental tasks that require participants to intentionally ignore distractor tones (Repp, 2003, 2004) or to suppress period correction after a tempo change (Repp and Keller, 2004). Phasing requires a controlled manipulation of the relative phase between the motor output (taps) and the sensory stimulus (metronome beats). Therefore, participants cannot perform successful phasing if they intend to ignore or suppress the stimulus entirely. Gradual desynchronization during phasing is also distinct from the intentional switching of coordination modes studied in the coordination dynamics literature which requires an instant change of behavioral patterns (Scholz and Kelso, 1990; Serrien and Swinnen, 1999).

The present study showed that it is plausible to describe the dynamics of phasing performance in terms of the interaction between the intrinsic stability of in-phase synchronization and the task-specific intention of desynchronization. Dynamical systems theory provides the right language to describe such cooperation and competition among multiple underlying constraints as well as the pattern of behaviors emerging lawfully from such interactions (Beek et al., 2000; Temprado and Salesse, 2004). In the proposed model of phasing performance (Equations 4–5), the intrinsic dynamics (the stability of in-phase coordination) and the intentional control (context-dependent frequency bias) are expressed as distinct terms in the differential equations, and their collective dynamics determine the behavior of the model. The dynamical systems approach presented in this study is not limited to music performance but could be applied to intentional desynchronization in other areas of human coordination such as sports, conversation, and crowd behavior (Passos et al., 2016; Paxton and Dale, 2017; Warren et al., 2023).

The context-dependent phasing model presented here is a continuous-time model described by two differential equations (Equations 4–5). The present continuous-time model can be compared to previous discrete-time models of rhythmic entrainment described by the difference equations for phase attraction and period adaptation (Large and Kolen, 1994; Large and Jones, 1999). More recently, the frequency adaptation in continuous-time oscillators was analyzed (Righetti et al., 2006) and studied as a model of the perception of musical rhythms (Lambert et al., 2016). The present model can be considered equivalent to these models (in qualitative dynamics) if the frequency equation included only the frequency adaptation term. Thus, the construction of the present model can be understood as a new term for intentional frequency control added to the general intrinsic dynamics underlying the synchronization and frequency adaptation to an external rhythm. Such synergistic combination of intrinsic and task-specific dynamics is also found in other models of rhythmic coordination. For example, the process of learning a new specified phase of bimanual coordination (other than in-phase and antiphase, e.g., 90°) can be modeled by introducing additional terms that stabilize the new phase to a model describing the intrinsic dynamics of bimanual coordination, such as the Haken–Kelso–Bunz model (Haken et al., 1985) for which in-phase and antiphase modes are stable (Schöner and Kelso, 1988b; Schöner et al., 1992).

In this paper, a continuous-time model was used to describe the dynamics of phasing performance, but the same qualitative dynamics should be achievable with a discrete-time model because most interactions in the model (e.g., coupling and frequency adaptation) are temporally confined. To capture the discrete nature of the stimulus (metronome beats) and the motor output (taps), a new analytic pulse-like function h was introduced which varies the width with the parameter ρ (see Appendix). This allowed replicating the tempo effect by keeping the pulse width constant in absolute time. It was also shown that the coupling function f, which is a product of two h functions (Equation 6), can vary the form continuously between the sine coupling (used in standard continuous-time phase models) and the impulse coupling (equivalent to the coupling in discrete-time models). Hence, the analytic form of the present model can be used to understand the relation and transition between continuous-time and discrete-time models, which is left for future studies.

The context-dependent frequency control in the present model is a simple mechanism that is in no sense intended as the best or only strategy for phasing performance. It was assumed that the current change rate of relative phase is available to the tapper and that the tapper tries to maintain a constant rate of change. With this mechanism, the model can produce all three main types of phasing behavior, but not all subtypes of the incomplete phasing. The present model cannot produce the halfway subtype because it does not have an attractor at the antiphase relation ($\psi = \pm\pi$). As in the Haken–Kelso–Bunz model (Haken et al., 1985), the antiphase attractor can be introduced by adding higher-order coupling terms to the model. With the antiphase attractor, the model would also show the slowdown of phasing near the antiphase relation which was observed in some trials in the human experiment (see the plateau of relative phase near $\psi/(2\pi) = 0.5$ in Figure 4A). These modeling possibilities, however, are beyond the scope of the present paper and will be studied elsewhere. The backward subtype of incomplete trials, in which the relative phase decreased over time, suggests that the participants were sometimes confused about the direction of phasing. This behavior is not possible in the present model because it assumes that the tapper knows the current change rate of relative phase. To replicate the backward behavior, this assumption must be relaxed by making the information available on the current state less accurate or partial (e.g., with stochastic noise). Such possibilities could be explored in future research to study the initial stages of learning phasing performance as a new skill.

Here we focused our discussion on in-phase and antiphase coordination, but it is known that humans can produce rhythms at other phases as well. Both musicians and nonmusicians were shown to be capable of producing rhythms made of two unequal intervals, with produced rhythms attracted to a ratio near 1:2 or 120° phase (Repp et al., 2011, 2012). Also, it was shown that bimanual coordination in 90° can be learned by training with pacing signals (Zanone and Kelso, 1992). These coordination phases may be related to different ratios of multifrequency coordination, for example, 120° coordination related to 1:3 frequency ratio (triple subdivision), and 90° coordination to 1:4 frequency ratio (quadruple subdivision; Dotov and Trainor, 2021). As dynamical systems analysis indicates (deGuzman and Kelso, 1991; Haken et al., 1996; Kim and Large, 2019), and both perception and production studies showed (Razdan and Patel, 2016; Mathias et al., 2020), these coordination phases are less stable than in-phase and antiphase relations, which may be related to the simple frequency ratios of 1:1 and 1:2 respectively. Due to low dynamic stability (especially in the presence of noise inherent to motor movements), the attraction toward phases other than in-phase and antiphase may not be clearly observed during phasing performance, where intentional control competes with stronger attractors. One way to study the attraction at other phases is to measure the stability of sensorimotor coordination at a set of fixed phases in separate trials (Yamanishi et al., 1980; Tuller and Kelso, 1989; Dotov and Trainor, 2021). Our ongoing study involving finger tapping to a metronome at a specified phase suggested the presence of weaker attractors near ±120° as well as stronger attractors at in-phase (0°) and antiphase (180°) relations.

The present study adds to the growing body of research that employs dynamical systems theory to study music performance (Demos et al., 2014; Schiavio et al., 2022; Tichko et al., 2022). Early oscillator models focused on the perception and production of musical rhythms in individuals (Large and Kolen, 1994; Large and Palmer, 2002; Loehr et al., 2011). More recently, dynamical systems analysis and modeling has extended to the interpersonal coordination in musical dyads and ensembles (Demos et al., 2019; Heggli et al., 2019; Roman et al., 2019; Bégel et al., 2022; Dotov et al., 2022). The present study, motivated by a case study of phasing between two expert musicians (Hartenberger, 2016; Schutz, 2019), aimed to uncover the underlying dynamics of phasing performance by studying non-expert participants with a simpler task of phasing against a metronome. Both successful and failed attempts at controlled phasing informed the identification of underlying dynamics and the construction of a minimal dynamical model. In contrast, the first model developed for the expert phasing data was not able to miss the target (see text footnote 2), although this can also happen to professional musicians (Hartenberger, 2016). A next step in this research would be to study interpersonal phasing systematically in controlled experiments, with both expert musicians and non-experts. Future studies could explore the manipulation of sensory feedback and informational coupling (Rosso et al., 2021, 2022) and the use of a virtual agent (governed by a dynamical system) as a more controlled phasing partner (Kelso et al., 2009; Van Kerrebroeck et al., 2021). The findings of the present study will guide the design and analysis of future experiments and modeling works.

The dynamical systems account presented in this paper provides an intuitive explanation of what happens in phasing performance. We described the dynamics of phasing performance in terms of the cooperative and competitive interactions of different underlying forces (intrinsic dynamics and intentional control). Musicians and music scholars have long described the experience of music listening and performance in terms of dynamic qualities and forces (Zuckerkandl, 1956; Larson, 2012). For example, when we listen to a tonal melody, we feel the attraction of the leading tone toward the tonic (Lerdahl, 1996). Russell Hartenberger, one of the expert percussionists in the case study, described in detail the forces of attraction and resistance he experienced in phasing performance (Hartenberger, 2016). The dynamical systems account suggests that these subjective and bodily experiences are not merely metaphors but actual forces involved in music making which can be quantitatively measured and mathematically formalized. At the same time, dynamical systems theory provides conceptual tools that can help musicians to understand and describe their subjective experience (Schiavio et al., 2022). An intuitive understanding of performance dynamics may provide musicians with new insights that can enrich their musical experience and help with performance and practice strategies.

Data availability statement

Publicly available datasets were analyzed in this study. This data can be found here: https://osf.io/4uhtb/.

Ethics statement

The studies involving humans were approved by the UConn-Storrs Institutional Review Board (IRB). The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

Author contributions

JK conceived and designed the study, analyzed the data, created the models, and wrote the manuscript.

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Conflict of interest

The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Appendix

The pulse-like function h is a 2π-periodic complex analytic function of phase x defined as

$$h(x,\rho) = \frac{(1-\rho)e^{ix}}{1-\rho e^{ix}} \\ = (1-\rho)\left(e^{ix} + \rho e^{2ix} + \rho^2 e^{3ix} + \cdots\right), \tag{8}$$

where $0 \le \rho < 1$ is a parameter controlling the width of the pulse (Figure A1), and i is the imaginary unit. It is an infinite series containing a complex sinusoid e^{ix} and its harmonics. The normalization factor $(1-\rho)$ is multiplied so that the maximum amplitude $|h(0,\rho)|$ is constant regardless of ρ. The n-th harmonic has a coefficient proportional to ρ^{n-1}, so the strength of high-order harmonics depends on ρ. On one extreme, h becomes a sinusoid when $\rho = 0$ (only the fundamental survives). On the other end, h approaches the Kronecker delta function (an impulse function) when ρ approaches 1. Between the two extremes, the shape of h changes continuously between a perfect sinusoid and a discrete impulse, depending on ρ (Figure A1).

As mentioned in Section 4.3, the pulse coupling f in Equation (4) is a general coupling function that includes the sine coupling in Equation (2) as a special case. Since $h(x,0) = e^{ix}$,

$$f(\phi,\theta,0) = \mathrm{Im}\left[h(\theta,0)\cdot h(-\phi,0)\right] \\ = \mathrm{Im}\left[e^{i(\theta-\phi)}\right] \\ = \sin(\theta-\phi). \tag{9}$$

This shows that Equation (4) becomes Equation (2) when $\rho = 0$.

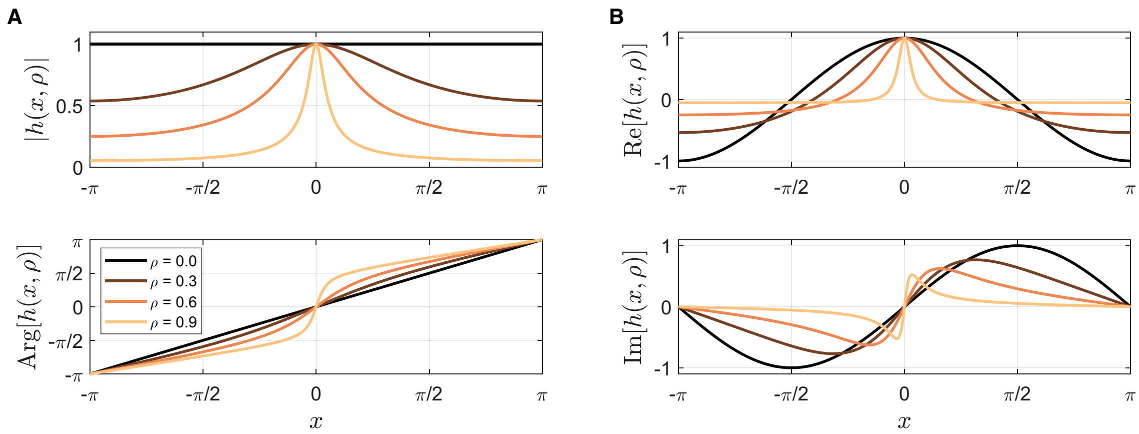

FIGURE A1
(A) The amplitude and phase, and **(B)** the real and imaginary parts of the pulse function $h(x,\rho)$ for $\rho = 0$, 0.3, 0.6, and 0.9.

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Body motion of choral singers

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Recent investigations on music performances have shown the relevance of singers' body motion for pedagogical as well as performance purposes. However, little is known about how the perception of voice-matching or task complexity affects choristers' body motion during ensemble singing. This study focussed on the body motion of choral singers who perform in duo along with a pre-recorded tune presented over a loudspeaker. Specifically, we examined the effects of the perception of voice-matching, operationalized in terms of sound spectral envelope, and task complexity on choristers' body motion. Fifteen singers with advanced choral experience first manipulated the spectral components of a pre-recorded short tune composed for the study, by choosing the settings they felt most and least together with. Then, they performed the tune in unison (i.e., singing the same melody simultaneously) and in canon (i.e., singing the same melody but at a temporal delay) with the chosen filter settings. Motion data of the choristers' upper body and audio of the repeated performances were collected and analyzed. Results show that the settings perceived as least together relate to extreme differences between the spectral components of the sound. The singers' wrists and torso motion was more periodic, their upper body posture was more open, and their bodies were more distant from the music stand when singing in unison than in canon. These findings suggest that unison singing promotes an expressive-periodic motion of the upper body.

KEYWORDS

togetherness, ensemble singing, motion capture, joint-actions, music perception, flow, voice matching

1 Introduction

Choir singing is a popular recreational activity, with proven benefits for choristers' social and mental wellbeing performing in face-to-face (Clift et al., 2010; Livesey and Camic, 2012; Judd and Pooley, 2014) and virtual (Daffern et al., 2021) choirs. Nevertheless, it requires blending several expressive parameters (such as intonation, timbre, timing and dynamics), and coordination of body movements, regardless of the level of expertise of the singers (Himberg and Thompson, 2009).

It is well-established that musicians' body motion is a core element of music performance. Research, primarily based on instrumental performances, has shown that musicians' body motion supports sound production and facilitates communication of expressive intentions and interactions with the co-performer(s) and the audience (Davidson, 2001; Jensenius et al., 2010). Certain body motions can also be unintentionally mimicked: emotional facial expressions whilst singing can lead viewers to produce subtle facial movements mimicking those of the musician (Livingstone et al., 2009).

In the context of singing, body movements of singers and conductors are fundamental aspects of choral music education and classical singing lessons. These movements represent powerful physical metaphors that can broaden singers' learning of musical ideas and enhance the singing experience during singing rehearsals (Apfelstadt, 1985; Peterson, 2000; Nafisi, 2013). A set of creative movements can be used in choir rehearsal to efficiently elicit certain musical concepts that might be less effectively communicated if taught only verbally. Hand gestures demonstrating phrase structure or dynamics can help perform the musical phrase and the dynamics contrast; changes from sitting to standing can facilitate the choir's perception and performance of diverse dynamics; walking, clapping or tapping the rhythm can support rhythm understanding (Peterson, 2000).

However, the literature regarding choristers' body motion is still in its infancy. Previous studies on small ensembles suggest that musicians' body motion can reflect the extent to which musicians are together (D'Amario et al., 2022) and features of the musical score (Palmer et al., 2019; D'Amario et al., 2023). This study focuses on ensemble singing and investigates if and how singers' body motion reflects the sensation of voice-matching with a co-performer and the complexity of the performance task, such as singing in unison (i.e., singing the same melody simultaneously) and canon (i.e., singing the same melody at a temporal delay related to a co-performer). In the next section, we reflected on (i) the choral sound factors that can affect singing preferences and how body motion can relate to (ii) the musicians' sensation of voice-matching, (iii) the complexity of the singing task, and (iv) certain sound parameters. We conclude by posing some hypotheses and drawing some predictions for this study.

1.1 Singers' preferences of choral sound factors

Singers agree, to some extent, on their preferences for several sound factors, which can be objectively measured. Choir singers and listeners prefer intentional intra-section singer configurations (in which choristers stand next to each other based on their timbral and acoustic compatibility) to random configurations, because of higher blend and tone quality and better ability to hear self and others in the intentional configurations (Gilliam, 2020). Soprano, alto, tenor, and bass (SATB) choristers prefer spread configurations between singers to close configurations, as spread spacing was found to increase hearing of the self and the ensemble and also contribute to a better choral sound compared to close configurations (Daugherty et al., 2012, 2019). The preferences of experienced singers for pitch scatter in unison choir sound were also explored. Results show that most listeners prefer a 0 level of pitch dispersion (i.e., same mean fundamental frequency between voices), and they would tolerate a 14 cents standard deviation in fundamental frequency (Ternström, 1993).

Singers might also have preferences for how their sound spectral components match those of the co-performer. Evidence from barbershop quartet performances demonstrates that singers spread their formant frequencies rather than align them (Kalin, 2005). This suggests that singers probably control their voice spectrum to blend their voices with the ensemble (Kalin, 2005). Preferences for voice-matching might reflect musicians' experiences of togetherness, i.e., feelings of being and acting together during joint music performance (Hart et al., 2014; Noy et al., 2015; D'Amario et al., 2022). These togetherness feelings are particularly relevant to choirs, in which choristers are required to blend their pitch, intensity, vibrato, timbre and timing with those of the co-performers. However, singers' preferences for voice-matching and their perception of togetherness in choirs lack a thorough investigation. The present study investigates whether singers' sensation of voice-matching with a co-performer depends on the spectral envelope of the sound. In order to control and manipulate the spectral components of the co-performer, we used a singer-loudspeaker paradigm in which choristers performed along to a pre-recorded tune presented via a loudspeaker.

1.2 Body motion and interpersonal interactions

Research on interpersonal interactions during joint action activities, such as dancing and ensemble playing, has investigated the relationship between body movements' synchrony and judgments of togetherness, pro-sociality and aesthetic experiences of the performing arts. The perceived and performed synchrony of a group of dancers can positively correlate with an audience's perceived enjoyment (an index of their aesthetic appreciation), depending on the dances performed (Vicary et al., 2017). This suggests that judgements and performance of movement synchrony can relate to the aesthetic experience of the performance. Similarity in body movements in collective dance improvisations can correlate with dancers' enjoyment (Himberg et al., 2018). Manipulated interpersonal movement synchrony also correlates with pro-sociality. It has been found that patterns of distributed coordination emerging in large group dancing movements predict pro-social effects and group bonding (von Zimmermann et al., 2018). Overall, dancing studies show that moving together with others can bring aesthetic pleasure to the participants and audience members, and increase a sense of group affiliation.

In the context of music ensemble performances, body motion can also contribute to the perception of interpersonal interactions. Similarity in body movements coordination in non-pulsed duo improvisations can relate to judgments of interactions bouts (Eerola et al., 2018). The strength of synchronicity in common periodic movements of co-performers can positively relate to ratings of perceived synchrony (Jakubowski et al., 2020). In small ensembles, certain measurable patterns of body motion, such as similarity in arm and chest motion, can contribute to the judgments of togetherness, i.e., the extent to which musicians were together as judged by audience members (D'Amario et al., 2022). Body motion might also reflect togetherness sensation that musicians feel with a co-performer during ensemble playing, as they can be more open to communication. Behavioral studies suggest that posture openness can relates to communication intentions (McGinley et al., 1975; Grachten et al., 2010). It was found that singers' body was more open when performing in the presence rather than the absence of an audience (Grachten et al., 2010); and, that an open body posture can facilitate the communicator's intention to change opinion in others (McGinley et al., 1975). It is still unclear whether choristers' body posture reflects the sensation of voice-matching perceived in singing ensembles. Furthermore, the extent to which musicians experience togetherness could affect their peripersonal space, i.e., the region of space immediately surrounding our body. A recent study on jazz duo performances suggests that music performances might affect the perception of the space between performers by prompting them to withdraw from their partner under uncooperative conditions (Dell'Anna et al., 2020). However, the relationship between body position and voice-matching has not been investigated yet. The current study investigates if and how the sensation of voice-matching, which can be seen as an aspect of musical togetherness, affects musicians' body openness and peripersonal space.

Furthermore, social interactions in ensembles are multimodal processes involving different sensory modalities (Keller and Appel, 2010), featuring continuous adaptations with the co-performers (Timmers et al., 2014), and skilful body co-regulations (Leman, 2007) within and between performers. Recent attempts to investigate social interactions in virtual reality suggest that real-time interactions between performers in small ensembles, which are mediated by embodied avatars, might induce strong feelings of social presence; however, the interactions between a real musician and a computer-controlled agent, highly affecting co-performer responsiveness, might negatively impact the quality of the subjective experience (Van Kerrebroeck et al., 2021). In the current study, we implemented a singing-loudspeaker paradigm to investigate if and how voice-matching preferences impact body motion. This paradigm allowed the participants to manipulate the co-singer voice and identify the spectrum envelope they felt most and least together with at the expense of the co-performers' real presence and the associated continuous response. Although this paradigm does not allow the thorough study of social presence and togetherness feelings, this set-up enables the study of how a specific aspect of musical togetherness (i.e., voice-matching) contributes to choristers' body motion.

1.3 The effects of task complexity on musicians' body motion

Differences in the auditory feedback from the self or the co-performer can influence the accuracy of the music performance. Pfordresher (2005) and Pfordresher and Palmer (2006) found that mismatches between the production of pitch events and the corresponding auditory feedback disrupted the accuracy of the performance, measured in terms of pitch errors. The relationship between the auditory feedback produced by two performers affects the temporal coordination of duo performances. Zamm et al. (2015) found that onset synchronization was tighter, mutual adaption higher and tempi faster when piano duos performed the same melody in unison than in canon, suggesting that unison playing was easier. These findings were also somewhat corroborated by a later study, investigating acoustics and head coordination in singing duo performances, and observing slower tempi (but no differences in overall asynchrony) when singing with an offset than in unison (Palmer et al., 2019). Interestingly, the authors also found that these different singing productions affected head movements in the Follower (i.e., co-performer entering at a temporal delay): the Follower exhibited higher variability of head movements, changed head orientation more away from the co-performer and bobbed the head more when singing the same melody at a temporal offset than in unison. Overall, these results suggest that task complexity can affect performance accuracy and musicians' head movements. When a music stand is available, musicians might also stand closer to the music stand to improve sight-reading with increased task complexity. This study analyses changes in singers' head motion and distance from their music stand, during unison and canon singing.

Furthermore, task demands might also impact singers' hand motion, often free from external constraints such as holding an instrument or a music score. Similarly to the above findings analyzing head motion during canon and unison performances (Palmer et al., 2019), the disruption of a singer's own auditory feedback that occurs during canon singing might induce a disruption in the hand motion as well. The periodicity of hand motion during ensemble singing could reflect the ease of unison singing compared with the increased complexity of a canon performance. We tested the hypothesis that unison performances feature higher hand motion periodicity than canon singing by analyzing hand motion while a singer performed the same tune in unison and in canon.

1.4 Sound parameters

A line of research investigated the relationship between sound and motion. Eitan and Granot (2006) observed how changes in musical parameters related to images of motion; listeners in the study were asked to associate melodic stimuli with imagined motions of a human character and then describe the type, direction, pace-change and forces of these motions. The authors found that listeners map musical parameters to kinetic features: decreases in one parameter (e.g., pitch descents, ritardandi, and diminuendi) were associated with spatial descents, whilst intensifications of musical features (e.g., pitch rising, accelerandi, and crescendi) were paired with increases in speed rather than the ascent. Importantly, they revealed this relationship's complex and multifaceted nature: musical parameters were simultaneously associated with multiple motion parameters. Motion can also be correlated with the musical structures of the piece, for example in line with the *ritardandi* (Repp, 1992). So-called sound-tracing experiments, focused on the listeners' spontaneous gestural renderings of sound, have further analyzed listeners' immediate association between music and motion (Godøy et al., 2006; Nymoen et al., 2010, 2011, 2013). Interestingly, a strong positive correlation was found between vertical hand position and pitch, in listeners instructed to move their hands in the air as if they were creating the sound themselves whilst listening to a set of short sounds, with manipulated pitch, timbral and dynamic contours (Nymoen et al., 2011, 2013). These results are in line with findings based on mental imagery (Eitan and Granot, 2006). This association could be understood through learned metaphors: the pitch is explained as a vertical dimension in line with the order of the notes in a musical staff (Nymoen et al., 2013).

Among music performers, the analysis of spontaneous gestural responses to music in singers whilst performing is particularly valuable, since singers' hand motion is not constrained by a musical instrument. Certain singers' arm gestures have been found to be related to specific acoustical measures of singing, such as intonation and timbre. A low, circular hand gesture, as well as an arched hand gesture, were found to be related to singing timbre, as formant frequencies were lower when singers performed with gestures than without (Brunkan, 2015). A low, circular arm gesture can also impact tuning, depending on the piece being performed and the vowels analyzed. Intonation of the /u/ vowel of the word "you", analyzed in 49 singers performing the final phrase of "Happy birthday to you", was found to be closer to the target pitch when singing was paired with a low circular arm gesture than without (Brunkan, 2016). However, a low, circular gesture did not impact intonation when performing "Over the rainbow" (Brunkan, 2015; Brunkan and Bowers, 2021). In addition to the circular arm gesture, a pointing arm gesture can also affect intonation. Brunkan (2015) and Brunkan and Bowers (2021) found that singers performing "Singin' in the rain" were more in tune when singing with a pointing gesture than with no arm movements. A coupling between gesture and tuning was also found in Karnatak music performances, i.e., a south Indian music performance featuring multimodal expression (Pearson and Pouw, 2022). The authors also found that the coupling between wrist gestures and tuning was stronger than between gestures and voice amplitude envelope.

Overall, these studies suggest that certain arm gestures can affect intonation of certain sustained vowels; however, the specific direction of this gesture during entire music performances remains unclear. We further investigated these aspects, by testing the hypothesis that the continuous vertical motion of the right and left hands during singing performances are positively related to intonation tracking.

1.5 The current study

The current study investigates the effects of the perception of voice-matching and the complexity of the task on choristers' body motion whilst performing along with a pre-recorded tune presented over a loudspeaker. Voice-matching is conceptualized as a musical parameter contributing to togetherness feelings, i.e., feelings of being and acting together with a co-performer when performing in singing ensembles. The pre-recorded tune was chosen to replace a live singer's performance and allow manipulation of the tune they were listening to and singing along to.

We were first interested in analyzing the sensation of voice-matching with a co-performer in relation to the spectral envelope of the co-performer, which we addressed by asking singers to manipulate the filter settings. Based on barbershop quartet performances (Kalin, 2005), we hypothesized (hypothesis, H hereafter) that the long-term specrum envelope of the stimulus sound, as assessed over an entire song, has an effect on the sensation of voice match with a co-performer (H1). We then tested the hypothesis that singing along to recordings they felt most or not together with impacts body motion (H2). Based on recent investigations on togetherness judgment in small ensembles (D'Amario et al., 2022), we hypothesized that singers, whose body is not constrained by holding a musical instrument, stay further apart from the loudspeaker (representing a co-performer) when singing along to recordings featuring the least together setting rather than recordings they felt most together with (H2.1). Moving away from the least together setting could also be considered an avoidance behavior. Based on behavioral studies (McGinley et al., 1975; Grachten et al., 2010), we also conjectured that singers' upper body posture is more open (i.e., with head, shoulders and elbow more distant from the chest when singing along with the most than the least together setting), as they might be more open to communicating and interacting with the co-performer when singing with the most together setting (H2.2).

Furthermore, we hypothesized that task demands (i.e., singing the same tune in unison or canon) affect body motion (H3), based on studies suggesting the effects of task demands on interpersonal synchronization and body motion during ensemble performances (Zamm et al., 2015; Palmer et al., 2019). Specifically, we hypothesized that, when singing in canon, singers display higher quantity of body motion (in line with an overall increase of energy in the performance, H3.1), stand closer to the music stand (to follow better the score during the most challenging task, H3.2) and exhibit lower periodicity in wrist movements [based on disruptive aspects of the auditory feedback (Pfordresher and Palmer, 2006), H3.3]. In addition, we were also interested in analyzing the relationship between tuning and singers' wrist motion. In line with previous studies on singers' hand gestures (Brunkan, 2015; Brunkan and Bowers, 2021), we hypothesized that the vertical displacement of the wrists is positively correlated with intonation (H4), as singers would use the wrists' vertical motion to support tuning of higher notes, which is anecdotally reported as being more difficult than for the lower notes.

2 Methods

2.1 Design

The research study comprised a 2 (task mode: perception and production) × 2 (task complexity: unison and canon) × 2 (voice-matching: most and not at all together) × 2 (takes: take 1 and take 2; i.e., repetitions of the same task complexity / voice-matching condition) × 2 (blocks: block 1 and block 2; i.e., repetitions of both take 1 and take 2) design. The perception task focused on singers' voice-matching perception; the production task centered on singers' performance based on the voice-matching preferences collected during the perception task. Overall, this design provided a total of 16 perception trials per participant for the perception task, and 16 production trials per participant for the production task.

The order of task mode (i.e., perception and production) and block (i.e., block 1 and block 2) was fixed. The order of conditions in the perception task was fixed within block as follows: (i) first, two consecutive repetitions in unison then in canon of the least together setting; second, (ii) two consecutive repetitions in unison then canon of the most together setting. Within each

TABLE 1 Design of the perceptual task, showing block, take and trial number as well as the voice matching and task complexity levels.

Block	Take	Voice-matching	Task complexity	Trial
1				
	1	Least together	Unison	1
	2	Least together	Unison	2
	1	Least together	Canon	3
	2	Least together	Canon	4
	1	Most together	Unison	5
	2	Most together	Unison	6
	1	Most together	Canon	7
	2	Most together	Canon	8
2				
	1	Least together	Unison	9
	2	Least together	Unison	10
	1	Least together	Canon	11
	2	Least together	Canon	12
	1	Most together	Unison	13
	2	Most together	Unison	14
	1	Most together	Canon	15
	2	Most together	Canon	16

block of the perception task, the least together setting was presented before the most together setting as the former can be seen as a practice condition to honing the participant's listening. Table 1 shows the design of the perception task. The order of conditions in the production task was randomized within part. Twenty-five production trials (of the 240 collected during the perception task) were excluded from the analysis because singers did not perform the piece according to the researchers' requirements (i.e., singing in canon or unison) or temporarily stopped singing. The corresponding perceptual trials were also excluded from the analysis.

2.2 Experimental set-up and apparatus

The experiment was conducted in a large multipurpose seminar room at the Department of Music Acoustics of mdw – University of Music and Performing Arts Vienna, equipped with a motion capture system suspended from the ceiling. The participant stood near the center of the motion capture rig, whilst two researchers sat at their desks behind the participant, to record audio and motion capture data. A small high-quality active studio loudspeaker was stand-mounted 0.7 m to the singer's right (Genelec model 8020C, www.genelec.com, with its built-in tone controls set to flat). The sounds of the pre-recorded performances were played at a sound level calibrated such that the loudspeaker radiated the same acoustic power as had the singer who pre-recorded the stimulus sound. The participant and the loudspeaker faced a wall with acoustical drapes at 2.7 m distance, facing away from the researchers' desks. A music stand holding the score was placed in front of the singer, angled so as to avoid acoustic reflection back to the singer. A computer screen 2 m in front of the singer, also angled away, displayed visual prompts and instructions from the computer to the participant. Figure 1 shows an example of the experimental setup. For the perception task a small MIDI controller device (Native Instruments, model 4CONTROL) was placed in front of the participant; on this device, two (out of four) endless, unmarked rotary knobs were used by the participant to control the gains (±15 dB) of two parametric filters centered on 2.7 and 6.2 kHz. The 2.7 kHz frequency band corresponds to the "singer's formant (cluster)". When the level in this band is very high, the voice timbre is perceived as "piercing" or "projecting" or even "harsh". The 6.2 kHz frequency band corresponds to a region in which a moderately raised level gives an impression of "clarity", "proximity", or "airiness". When the level in this band is lowered, the voice sounds occluded, as if facing away. An on-screen yellow indicator would light up if a participant repeatedly tried to change the gain in either band beyond ±15 dB, to indicate that further change in that direction would be futile. Also, one push button (out of two) on the controller was used to signal "Next". All movable flat surfaces (screens, music stand, display) were angled so as to avoid direct reflection paths from the singer's mouth to the microphones. As a pandemic precaution, plexiglass screens separated the experimenter tables from the participant.

A 12-camera (Prime 13) OptiTrack motion capture system was used to record the participants' body motion at a sampling rate of 240 Hz. Singers' body motion data consisted of trajectories from 12 reflective markers placed on the head and upper body: three markers on the head, two on the back, one per shoulder, arm, and wrist, and one on the chest. Three additional markers were placed on the loudspeaker (one on top and two on the side near the loudspeaker) and five more on the music stand (one in each corner and one on the top of the stand). These additional markers were used to investigate the position of the singers with respect to the loudspeaker and the music stand.

Participants also wore electroglottography (EGG) electrodes (Glottal Enterprises model EG2-PCX—using the analog output) placed on the neck, either side of the thyroid cartilage. EGG is widely used to analyse the singing voice (D'Amario and Daffern, 2017; Herbst, 2020) and allows individual fundamental frequency analysis for each singer based on vocal fold activity rather than microphone recordings. Therefore, it was used in this study for tuning analysis without cross-talk. In addition, a 'backstage' microphone (Neumann KM A P48) was placed near the experimenters' desk recording motion data, to synchronize motion and audio recordings. Audio recordings were synchronized with OptiTrack recordings using an audiovisual signal produced by a film clapboard, marked with reflective markers. The clapper was placed in view of the motion capture cameras and close to the "backstage" microphone. The clapboard was struck at beginning of each part, and all recordings were synchronized retrospectively to this point. At the start of each trial, the control program also issued a sequence of N clicks on the same channel, to facilitate the localization of trial N on the motion capture recordings.

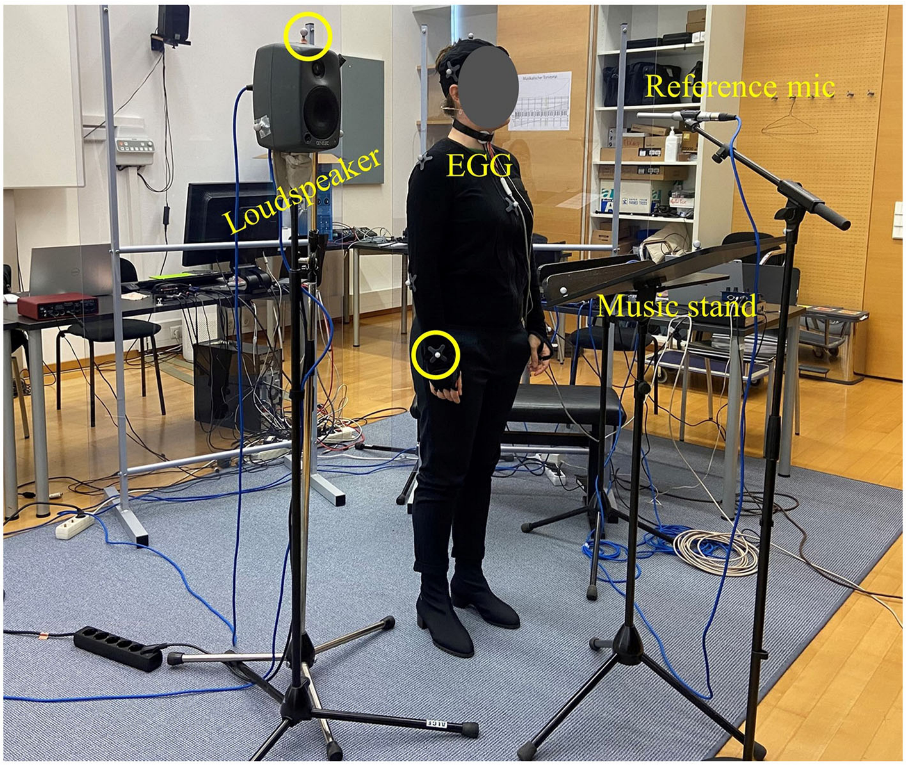

FIGURE 1
Example of the experimental set-up, showing some of the motion capture markers placed on the singer's right wrist and the loudspeaker (circled). The figure also displays the electroglottography (EGG) electrodes on the singer's neck as well as the reference microphone and the music stand placed in front of the singer.

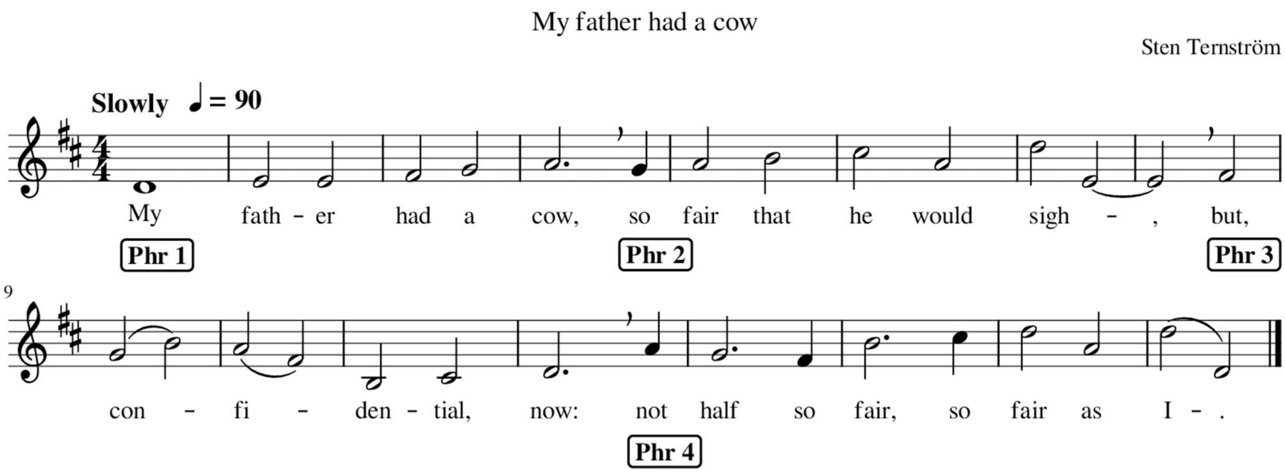

FIGURE 2
Tune composed for the current investigation, displaying the beginning of its four musical phrases, as marked in the score.

Furthermore, four additional microphones were used, including a reference microphone in front of the singer, a headset microphone near the singer's mouth, and two binaural microphones just in front of either ear. These microphones acquired signals for an acoustic corollary study that is out of scope here; it will be reported elsewhere.

MIDI and audio input and output data (excluding that of the backstage microphone) were routed through a multichannel, multipurpose digital audio interface (RME model UFX II) to the computer (Microsoft model Surface Book 2, Windows 10 Enterprise). Audio from the backstage microphone fed into a multi-channel audio interface (Focusrite Scarlett 18i8), recorded using a digital audio workstation (Ableton Live) at a sampling

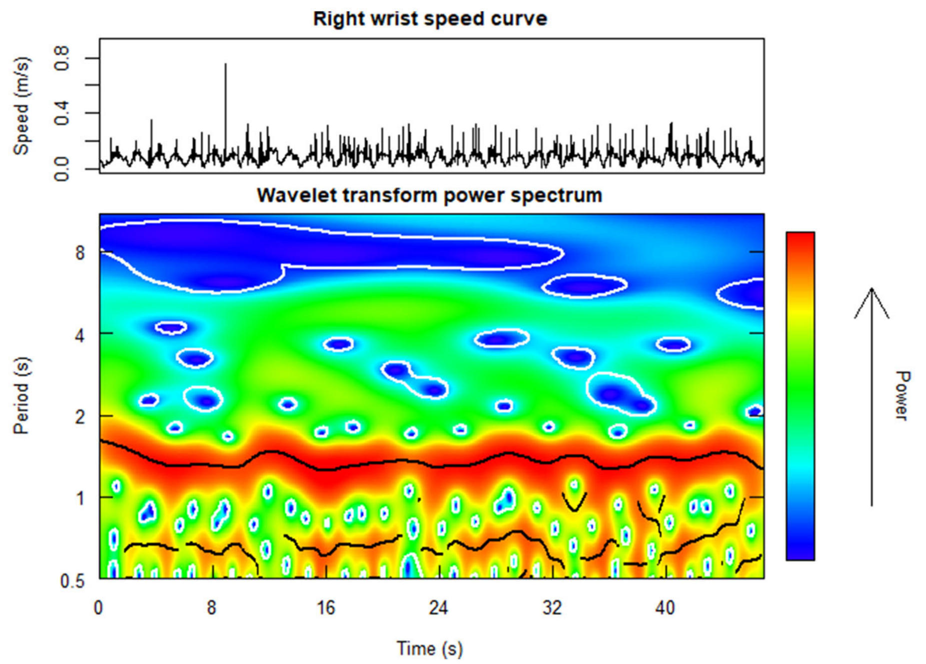

FIGURE 3
Example heat plot of the wavelet transform (WT) power spectrum (at the **bottom**) as computed from the right wrist speed curve (at the **top**) for a chorister performing the short tune in unison along with a pre-recorded performance of the same piece. The warmer the map, the more periodic the signal is.

frequency of 44.1 kHz and 32-bit depth, using a second PC. Experimental instructions to participants, stimulus presentations and audio recordings were run automatically by custom programs written in SuperCollider (v 3.12.1, http://supercollider.github.io).

2.3 Participants

Seventeen participants (age $M = 31.2$ years old, $SD = 11.2$ years; 6 women, 11 men) took part in the study. Fifteen of them took part in the perception and production tasks of the experiment; these were semi-professional singers, singing students at mdw – University of Music and Performing Arts Vienna and/or choral singers of local choirs at the time of the experiment. They reported having on average 9.5 years of formal training ($SD = 4.3$ years) and practicing on average 1.5 h per day ($SD = 0.7$ h). All participants self-reported normal hearing, and three self-reported perfect pitch. They received a token compensation of 30 Euros. The Ethics Committee at mdw – University of Music and Performing Arts Vienna approved the procedures of this study (reference EK Nr: 05/2020).

In addition to the above 15 participants completing the perception and production tasks, two participants took part in the study as pre-recorded co-performers and their singing recording were presented through a loudspeaker. These were professional singers, with advanced choral experience. They had on average 7.5 years of formal singing training.

The sample size was set in line with the relevant literature (Livingstone and Palmer, 2016). Participants were recruited on a voluntary basis through advertisements on mdw social media and semi-professional choirs.

2.4 Stimulus

2.4.1 Music score

A short 16-bar piece (as shown in Figure 2) was composed for the study by the second author (ST), such that the piece was simple enough to be learned quickly and could function as a two-part canon at two bars offset. Many long sustained notes were employed in the piece, to facilitate intonation stability throughout. The lyrics, in English, were written to contain many open vowels and few sequences of multiple consonants. None of the participants had any difficulties with pronunciation.

2.4.2 Co-performer stimulus pre-recording

In order to create the stimulus recordings to be presented to the participants completing the perception and productions tasks, two professional musicians came to our multi-purpose seminar room before beginning the experiment and practiced the tune for about 15 min, then performed the piece until they reached satisfaction. Singers were instructed to perform as they would normally do in the choir, with a strict tempo and a limited vibrato. During the practice trials, four metronome beats at 90 beats per minute cued the tempo; after that, the metronome was turned off. Audio recordings of repeated performances were collected. The recording considered the best choral performance was chosen as the pre-recorded stimulus for the current study, so the participants could sing in duo along with it. The singers judged and chose their best performance.

2.5 Procedure

Participants were invited to take part in a single session. First, participants received spoken and written explanations of the research project and the tasks, then they gave written consent to participate in the study and filled in a background questionnaire regarding their music experience. They were also asked whether they had ever experienced optimal voice matching when singing with a singer in a choir or small ensemble; if yes, they were invited to describe their feelings at that moment.

Having practiced the score in the laboratory, participants first made a baseline recording without a co-performer stimulus. This was recorded using a reference microphone at 0.3 m in front of the participant, in addition to the headset and binaural microphones, in order to determine the relative frequency responses of the latter. This aspect will be reported in a companion study, as the acoustics analysis is out of the scope of the current study.

Then, the perception task was presented. Singers listened to and sang the song together with a set of recordings, in each trial modifying the stimulus sound using the two rotary knobs until they heard the sound they felt "most" or "not at all" together with, according to text prompts provided on a screen. The participants were not told what the knobs did; they had to hear it for themselves. Participants were free to move "as they might do in a choir". Headset and binaural microphones were fixed to the singer, so recording quality was not affected if they drifted away from the starting point. The initial filter gain settings were invisibly randomized at the start of each trial. The stimulus song was looped continuously until the participant pressed "Next". The filter settings ultimately chosen by the participant for each trial were saved.

Ultimately, the performance task was presented, and participants sang the piece, performing in duo with the pre-recorded performance processed using the filter settings they had chosen in the perception task. Participants were asked to perform along to loudspeaker pretending to be on stage and performing with a choral singer. Participants were left free to sing by memory or look at the score (placed on the music stand in front of them) as best for them. Therefore, no particular instructions regarding looking at the music score were given. Pre-recorded stimuli were gender-matched with the participants, since we needed to control the spectral differences between stimulus and performer as closely as possible. The stimulus song was played only once per trial, without looping. Singers took a 5-min rest between the two tasks and also between the two blocks during the performance task.

2.6 Analysis

To investigate singers' body motion in relation to voice-matching perception and task complexity, the following metrics were computed:

- Magnitude of the gains of mid and high-band
- Quantity of motion (*QoM*) measuring the overall energy of the performance
- Singer's upper body posture
- Singer's distance from the loudspeaker and the music stand
- Periodicity of the singer's head and wrist motion
- Wrist's vertical motion

To assess whether preferences for spectral components of the sound change based on the perception of voice match, we computed the magnitude of the settings of the mid and high-band filters that singers chose during the perception task. Magnitude was operationalized by taking the square root of the sum of the squares of the chosen filter gains in dB. This magnitude is the length of a vector and represents the distance from the origin (0,0) dB to the endpoint of the vector.

To compute the metrics related to singers' movements, motion capture data were first subject to pre-processing: data of all markers were smoothed and velocity derived using a Savitzky-Golay filter (polynomial order 3, window size 25), through the "prospectr" package (Stevens and Ramirez-Lopez, 2021) in R (R Core Team, 2013). The speed was then calculated as the Euclidean norm of the three-dimensional (3D) velocity data.

Then, the total quantity of motion (*QoM*) was calculated as the sum per second of the Euclidean norm of 3D velocity values across all markers for each singer and repeated performance. Then, the *QoM* was averaged across time stamps within phrases. This step produced four *QoM* values (one per phrase) for each singer and repeated performance. Because *QoM* data were not normally distributed, they were log-transformed before the analysis.

Regarding the singers' upper body posture, this was operationalized as the summing of the 3D distance between the chest and the front head, and between the chest and all the peripheral joints under investigation (i.e., left and right shoulder and elbow). In other words, large distances between body parts would suggest a more open body posture, while small distances would suggest a more contracted posture. The distance between the singer and the loudspeaker was computed as the 3D distance between the front head marker and the marker placed on the loudspeaker near the singer. Similarly, the distance between the singer and the music stand was computed as the 3D distance between the front head marker and the marker placed at the bottom left corner of the music stand. The vertical motion of the wrists was computed based on the Y-axis position data, perpendicular to the ground plane. These metrics were averaged within phrases.

The periodicity in the singers' front head and wrist motion was computed by extracting the power of the wavelet transforms (*WT*) of the speed curves of chosen markers (i.e., front head, left and right wrist), for each repeated performance and singer, as shown in Figure 3. *WT* were extracted using the R package "WaveletComp" (Roesch and Schmidbauer, 2018) with the complex-valued Morlet wavelet as mother wavelet. The range of periods to be considered was set in line with the phrase structure and the tempo of the piece, and ranged from about 1 beat (mean duration = 0.667 s) to 4 bars (mean duration = 10.36 s). Thus, the range of the *WT* extraction was from 0.5 s to 11 s. Within this broadband, the average *WT* power was computed within a narrow band centered around the maximum power spectrum with a width of ± 1 beat. Ultimately,

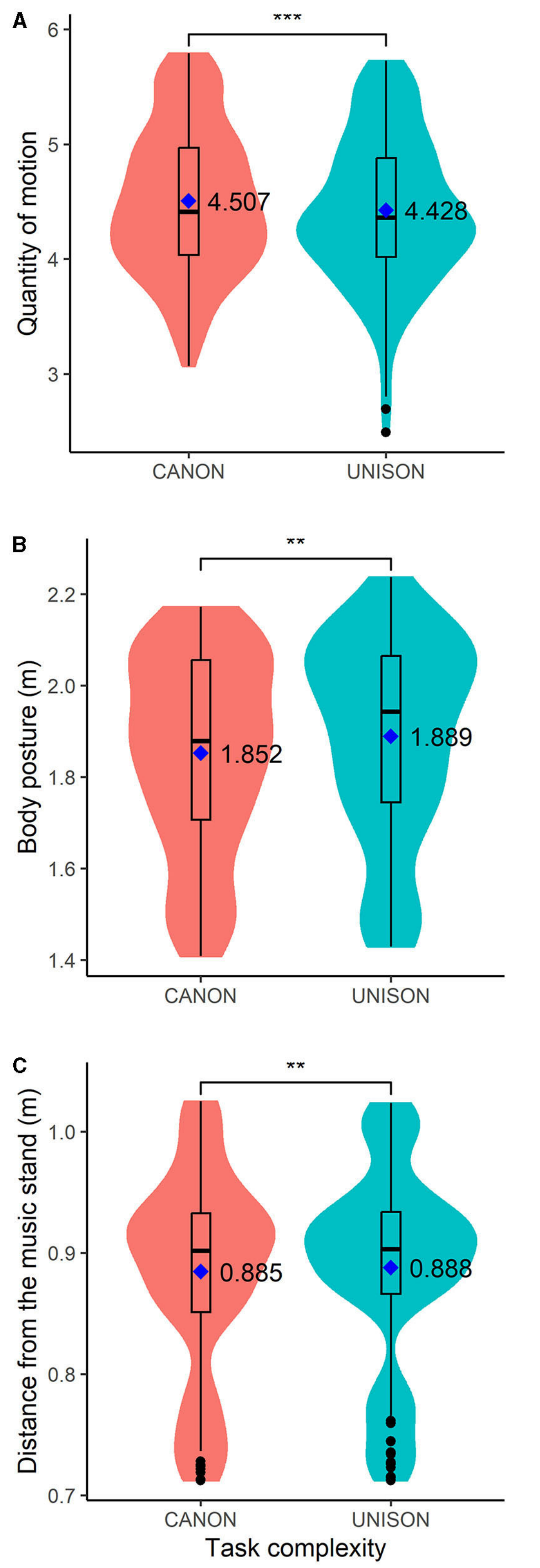

FIGURE 4
Box plots of motion data related to the quantity of motion **(A)**, body posture **(B)**, and the distance from the head to the music stand **(C)** when singing in canon and in unison. The figure also displays the mean values for each singing condition. $^{**}p < 0.01$; $^{***}p < 0.001$.

TABLE 2 **Raw responses (corrected for spelling mistakes) to the question regarding previous experiences of optimal voice matching.**

Have you experienced optimal voice matching?	If yes, could you please describe that moment?
yes	n.a.
yes	When I got the feeling, everything flowed, and we got one.
yes	n.a.
no	n.a.
yes	All locked in! Sound amazing!
n.a.	n.a.
yes	Feeling as if we are one.
yes	It was a surprise, "a miracle".
yes	Matching vibrato
yes	n.a.
yes	Matching in terms of voice color
n.a.	n.a.
yes	It makes me feel more confident, and I appreciate better the beauty of the sound.
yes	It felt effortless and easy.
yes	n.a.

WT data were averaged across timestamps within phrases; this produced a list of four *WT* values (one per phrase) for each performance and singer.

A linear mixed model was implemented to analyse the effects of voice match and task complexity (fixed effects) on the magnitude of the spectral components (response variable). Block, take, and trial were entered in the model as fully crossed random effects. In addition, two sets of linear mixed models were then implemented to investigate whether the above body motion metrics were predicted by the following explanatory variables:

- Block, take, trial, and phrase, and
- Voice match (i.e., most and not at all together) and task complexity (i.e., singing in unison vs. canon).

For each body metric, two models were run. The first model included block, take, trial, and phrase as fixed effects. Only significant effects were retained for the second model, which additionally tested the effects of voice match and task complexity. For example, for *QoM*, the first model showed significant effects of take, trial, and phrase, but no significant effect of block. *QoM* was therefore averaged across blocks, and the second model tested the effects of voice match, task complexity, take, trial, and phrase. These models were implemented via the residual maximum likelihood (REML) in R using the lme4 package version 1.1-27.1 (Bates et al., 2015); *p*-values for fixed effects were calculated using Satterthwaite approximation through the lmerTest package version 3.1-3 (Kuznetsova et al., 2017).

TABLE 3 Results of the linear mixed models measuring the relationship between block, take, phrase (phr), voice-matching and task complexity (i.e., the predictors) with the total quantity of motion and the posture (i.e., the response variables).

Response variable	Model *n*	Predictors	Estimate	SE	*t*-value	Random effects
Quantity of motion						
	1					Participant, trial
		block	0.03	0.03	0.29	
		take	0.07*	0.02	2.7	
		phr 2 vs. phr 1	0.26***	0.03	9	
		phr 3 vs. phr 1	0.26***	0.03	9	
		phr 4 vs. phr 1	0.34***	0.03	11.7	
	2					Participant, take, phrase
		voice-matching	0.03	0.02	1.43	
		task complexity	−0.09***	0.02	−4.13	
Posture						
	3					Participant, trial
		block	−0.02	0.01	−1.4	
		take	−0.007	0.01	−0.06	
		phr 2 vs. phr 1	−0.05**	0.01	−3.33	
		phr 3 vs. phr 1	−0.065***	0.01	−4.72	
		phr 4 vs. phr 1	−0.072***	0.01	−5.24	
	4					Participant, phrase
		voice-matching	−0.01	0.01	−1.07	
		task complexity	0.04*	0.01	0.004	

The table also displays the model number (n) and random effects variables (i.e., participant, take, phrase and trial, depending on the model) used in the analysis. The FDR method has been used for adjusted p-values. $^{*}p < 0.05$; $^{**}p < 0.01$; $^{***}p < 0.001$.

In addition, to investigate whether the wrists' motion was affected by tuning, the fundamental frequency (f_0) estimates were extracted from the electroglottography (EGG) recordings using the "PraatR" package in R (Albin, 2014). The tuning analysis relied on the EGG recordings collected during the experiment, as EGG allows estimating the individual contribution of the singer without cross-talk from the co-performer (i.e., loudspeaker). The f_0 trackings were extracted in 10 ms time steps in the frequency band from 70 to 660 Hz. This frequency band was chosen to cover the male and female expected voice range profile featuring this piece. Tuning data were then standardized (i.e., scaled and centered) based on singers' gender to account for differences in voice range between males and females. The time-series f_0 estimates of each performance and singer were then averaged per decisecond; similarly, wrists' vertical position data presented above were also averaged per decisecond in order to have the two data set sampled at the same frequency (i.e., 10 Hz).

Eventually, to investigate the effects of tuning on the wrist's vertical displacement, four linear mixed models (i.e., one for each combination of block [block 1 and block 2] and task complexity [unison and canon]) per wrist were implemented using the glmmTMB package (Brooks et al., 2017) in R. In each model, times were entered within stimuli with the Ornstein–Uhlenbeck covariance structure, which can handle unevenly spaced temporal autocorrelation. Tuning data included short pauses due to the singers breathing for tone production or in line with the score requirements (e.g., see Figure 2 bar n. 4) or due to own errors (i.e., singers occasionally skipping a note). In each model, tuning data was entered as the response variable and the wrist's vertical position data as the independent variable; participant and trial number were entered as random effects.

Benjamini and Hochberg (1995)'s false discovery rate (FDR) correction was applied for multiple linear mixed models. The correction was based on a total of 81 p-values (i.e., 70 related to the 20 body motion models, 8 related to the 8 tuning models, and 3 related to the model testing singers' preferences of optimal matching) resulting from the analysis of the fixed effects, i.e., voice matching, task complexity, tuning, block, part, phrase number.

3 Results

3.1 Singers' preferences of optimal matching

The magnitude of the absolute gains in dB of the mid and high-band filters was predicted by voice match ($\beta = 5.2$, $SE = 0.9$; $t = 5.7$, $p < 0.001$), and the mean magnitude was significantly greater for the least together settings ($M = 17.4$, $SD = 4.32$) than for the settings chosen as all together ($M = 12.9$, $SD = 5.42$). The main effect of task complexity and the interaction effect between voice match and task complexity were non-significant.

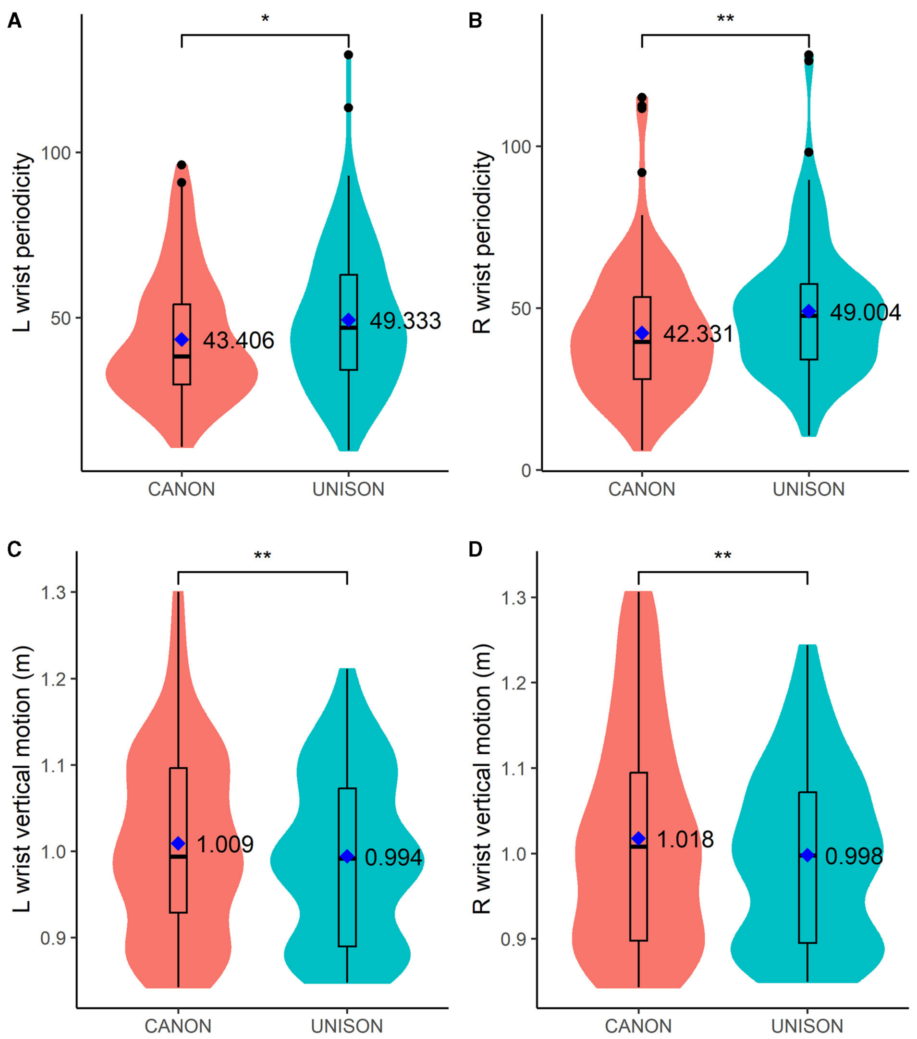

FIGURE 5
Box plots of motion data related to the left (L) and right (R) wrist periodicity (**A, B**, respectively) and vertical motion (**C, D**, respectively). The figure also displays the mean values for each singing condition and motion parameter. $^{*}p < 0.05$; $^{**}p < 0.01$.

Table 2 presents the raw responses to the questions: "Have you experienced optimal voice matching when singing with a singer in a choir or small ensemble? If yes, could you please describe that moment?". Most of the participants (12 out 15) reported they experienced optimal matching in the past. During those recalled times, three of them felt as if everything flowed and was locked in so as to become one entity. Three of them focused on the positive emotions perceived, as they felt the moment was effortless, magical and rewarding.

3.2 Quantity of motion

Table 3—models 1 and 2 exhibit the results of the analysis of the quantity of motion (*QoM*). *QoM* increased in take 2 compared to take 1, and also in phrases 2, 3, and 4 compared to phrase 1. There were no significant differences in *QoM* between block 1 and block 2. *QoM*, averaged across blocks, was not predicted by voice match but by task complexity: *QoM* was lower when singing in unison than canon (as shown in Figure 4A).

3.3 Posture

Table 3—models 3 and 4 provide the results of the analysis of the posture data. Block and take number did not predict body posture, but the upper body posture was less open in phrases 2, 3, and 4 compared with phrase 1. Body posture, averaged across blocks and takes, was not predicted by voice match, but by task complexity: body posture was more open when singing in unison than in canon (as shown in Figure 4B).

3.4 Distance from stand and loudspeaker

Table 4—models 5 and 6 present the results of the analysis of the distance between the singer's head and the music stand. Block

TABLE 4 Results of the linear mixed models measuring the relationship between block, take, phrase (phr), voice-matching and task complexity (i.e., the predictors) with the 3D distance from the head and to the music stand, and from the head to the loudspeaker (i.e., the response variables).

Response variable	Model *n*	Predictors	Estimate	SE	*t*-value	Random effects
Distance from stand						
	5					Participant, trial
		block	−0.001	0.002	−0.4	
		take	0.001	0.002	0.7	
		phr 2 vs. phr 1	−0.006*	0.002	−2.85	
		phr 3 vs. phr 1	−0.008**	0.002	−3.63	
		phr 4 vs. phr 1	−0.005	0.002	−2.13	
	6					Participant, phrase
		voice-matching	−0.0003	0.001	−0.2	
		task complexity	0.003*	0.001	2.6	
Distance from speaker						
	7					Participant, trial
		block	−0.004	0.004	−1.34	
		take	0.003	0.003	1.38	
		phr 2 vs. phr 1	−0.001	0.002	−0.56	
		phr 3 vs. phr 1	−0.0002	0.002	−0.11	
		phr 4 vs. phr 1	0.0007	0.002	0.32	
	8					Participant
		voice-matching	0.003	0.002	1.42	
		task complexity	0.0002	0.002	0.083	

The table also displays the model number (*n*) and random effects variables (i.e., participant and trial, depending on the model) used in the analysis. The FDR method has been used for adjusted *p*-values. $^*p < 0.05$; $^{**}p < 0.01$.

and take were not significant predictors of the distance from the head to the stand, but singers were closer to the stand in phrases 2 and 3 than in phrase 1. Voice match did not predict the distance from the stand, but singers were more distant from the stand when singing in unison than in canon (as shown in Figure 4C).

Table 4—models 7 and 8 present the results of the analysis of the distance between the singer's head and the loudspeaker. Block, take and phrase numbers were not significant predictors of the distance from the loudspeaker. The latter, averaged across blocks, take and phrase numbers, was not predicted by voice match or task complexity.

3.5 Periodicity of wrist and head motion

Tables 5, 6—models 9 to 14 present the results of the analysis of the periodicity of left and right wrist and head motion. Block and take did not predict the periodicity of the right and left wrist and head (see models 9, 11, and 13). The wrists were more periodic in phrases 2 and 4 than in phrase 1; the head was more periodic in phrase 2 than in phrase 1 (see models 9, 11, and 13).

Voice match did not predict the periodicity of the wrist or the head, averaged across blocks and takes (see models 10, 12, and 14). The right and left wrists were more periodic when singing in unison than in canon (see Table 5 models 10 and 12 and Figures 5A, B), but task complexity did not predict the periodicity of the head motion, averaged across blocks and takes (see Table 6 model 14).

Having found that task complexity predicted the periodicity of the wrists but not the head motion, it was of interest to investigate whether the wrist motion was related to body sway or not. To test this, we measured the *WT* power of the marker placed on the back top of the singer, similarly to the *WT* power of the head and wrist. We then implemented two linear mixed models (see Table 6 models 15 and 16), based on the same structure of the head and wrist periodicity computation. We found the torso was more periodic when singing in unison than in canon (see Table 6 model 16), in line with the wrists' motion. These results suggest that task complexity predicted singers' body sway.

3.6 Wrist vertical motion

Table 7—models 17 to 20 present the results of the analysis of the vertical motion of the right and left wrist, related to the effects of block, take, phrase, voice match and task complexity. Block and take number did not predict the vertical motion of the right and left wrist, but phrase number did: left and right wrists were higher in phrases 2, 3, and 4 compared with phrase 1 (see Table 7

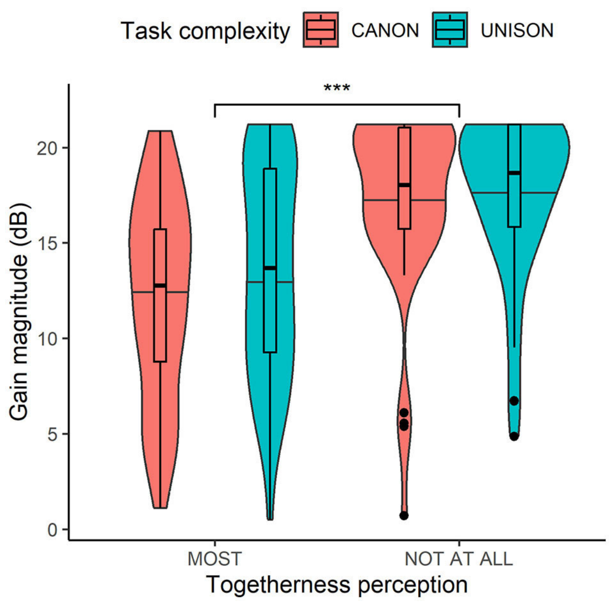

FIGURE 6
Box plots of the magnitude in dB of the chosen filter settings related to the togetherness perception (i.e., most and not at all together) and task complexity (i.e., singing in unison and in canon). ***$p < 0.001$.

models 17 and 19 and Figures 5C, D). The vertical position of both wrists, aggregated across blocks and takes, was lower when singing in unison than in canon (see models 18 and 20). The position of the right wrist was also higher when singing along with the least together setting than with the most together setting; but, voice match did not predict the vertical position of the left wrist (see models 18 and 20).

Interestingly, tuning estimates predicted the wrists' vertical position, depending on block and task complexity. When singing in unison, the higher the pitch, the higher the right wrist in block 1 was ($\beta = 0.004$, $p < 0.005$). When singing in canon, the higher the pitch, the higher the left wrist was in block 1 and block 2 (for block 1: ($\beta = 0.002$, $p < 0.001$; for block 2:($\beta = 0.002$, $p < 0.01$). We found no evidence of an effect of tuning on the right wrist when singing in unison in block 2 or canon. We also found no evidence of an effect of tuning on the left wrist when singing in unison.

4 Discussion

This study focused on choral singers and investigated how body motion is affected by the perceived voice match with a co-performer (as measured based on the sound spectral envelope) and by the complexity of the singing task (such as singing in unison or canon). We were also interested in whether the tuning tracking of the piece performed predicted the continuous vertical displacement of the choristers' wrists. We used a singer-loudspeaker paradigm where choristers performed along to a pre-recorded tune presented over the loudspeaker; this allowed the chorister to manipulate the spectral envelope of the co-performer and identify the settings that they felt most together with and least together with.

Our results revealed that choristers' perceived voice match with the pre-recorded tune was related to the long-term spectrum envelope (hypothesis, H1). The mean magnitude of the high and mid-band filter settings was 13 dB for the recordings judged most together and 17 dB for those identified as least together. This suggests that singers' ratings for the least together performance relate to extreme differences between the spectral components. As shown in Figure 6, some participants appeared to develop a strategy of exploiting the min/max gain color signal in order to find the extreme settings rapidly; and, those settings would often but not always be chosen as "not at all together". However, given that the spectral manipulations offered were rather subtle and unfamiliar, we found it was helpful to be able to exaggerate the spectral changes, such that it would become obvious which aspect of the sound one was controlling. Furthermore, the extent to which the spectral components are blended might also be related to the choristers' roles and intentions. It has been found that boys with the deepest voices (the basses) boosted the energy of a high-frequency band (2.500–3.500 Hz) of the vocal spectrum when performing in the presence of female listeners, which might be an indication of competitive mechanisms between males (Keller et al., 2017). Future investigations might also investigate the notion of togetherness in relation to the spectral components and the choristers' roles and intentions within the choir.

Contrary to our expectations (H2), we did not find evidence of a significant impact of the chosen voice-matching settings on singers' body motion. The chosen settings did not predict singers' body posture, quantity of motion and head and wrist periodicity, or distance from the speaker. This suggests that voice-matching perception, quantified in terms of spectral components, might be irrelevant to body motion. However, it might be that these models lacked the necessary power to find the effect. Future investigations with a larger sample size and power tests might provide comprehensive results on the null effects of voice matching on body motion that we observed in this study. It might also be that the singer-loudspeaker paradigm we implemented in this study did not capture the interpersonal dynamics of a singing duo. A recent case study analyzing music interactions in virtual reality reported that performing in a piano duo with a computer-controlled agent can be inadequate for the musicians' subjective experience (Van Kerrebroeck et al., 2021). Authors found that a professional pianist reported lower scores on enjoyment, closeness, and naturalness when performing with a controlled agent (i.e., in which an algorithm aligned the audio-visual information of an avatar to the real-time performance of the pianist) than in duo with a virtual avatar (i.e., a pianist visually perceiving the co-performer as a human-embodied virtual avatar). Future empirical investigations with a larger sample size are needed to analyse the impact of non-human entities on musicians' immersion in ensemble performances. The absence of an audience might also have underestimated the effects of the sensation of togetherness on body motion. The increased level of immersion of a real public performance might emphasize the impact of togetherness on musicians' body motion.

In line with our expectations, we found that singing the same tune in unison or canon (i.e., with a temporal delay) affected body motion in several ways (H3). First, the quantity of motion was

TABLE 5 Results of the linear mixed models measuring the relationship between block, take, phrase (phr), voice-matching and task complexity (i.e., the predictors) with the periodicity of the left (L) and right (R) wrist motion (i.e., the response variables).

Response variable	Model *n*	Predictors	Estimate	SE	*t*-value	Random effects
L wrist periodicity						
	9					Participant, trial
		block	−0.1	2.13	−0.05	
		take	1.22	2.15	0.57	
		phr 2 vs. phr 1	7.48*	3	2.49	
		phr 3 vs. phr 1	5.03	3	1.68	
		phr 4 vs. phr 1	9.48**	3	3.16	
	10					Participant, phrase
		voice-matching	−3.3	2.42	−1.36	
		task complexity	5.93*	2.42	2.45	
R wrist periodicity						
	11					Participant, trial
		block	0.89	1.97	0.45	
		take	0.91	2	0.46	
		phr 2 vs. phr 1	8.35**	2.78	3.01	
		phr 3 vs. phr 1	5.6	2.78	2.02	
		phr 4 vs. phr 1	10.7***	2.78	3.86	
	12					Participant, phrase
		voice-matching	−2.67	2.3	−1.16	
		task complexity	6.67*	2.3	2.9	

The table also displays the model number (*n*) and random effects variables (i.e., participant, trial and phrase, depending on the model) used in the analysis. The FDR method has been used for adjusted *p*-values. $^{*}p < 0.05$; $^{**}p < 0.01$; $^{***}p < 0.001$.

higher when singing in canon, in line with the overall increased energy of the performance (H3.1). Then, choristers were closer to the music stand when singing in canon (H3.2): this suggests the increased complexity of the canon task and might reflect the need to be closer to the music to see more clearly and cut out distractions by reducing the visual field. However, standing closer to the music stand does not necessarily indicate that the singers were looking at the score. Future analysis investigating eye-gaze might shed more light in this respect. Furthermore, the motion of both wrists were more periodic when singing in unison than canon (H3.3). These results can be interpreted as a disruptive mechanism in the auditory feedback affecting hand motion: during canon singing, hearing the pre-recorded tune as auditory feedback—serially shifted relative to their own tones—might have disrupted the periodicity of the hand motion. This hypothesis is in line with research suggesting that music performance is disrupted, i.e., increased errors of sequencing and timing, when the auditory feedback of actions is disrupted (Pfordresher and Palmer, 2006; Palmer et al., 2019). It is also interesting to notice that the higher periodicity of the wrists was paired with that of the torso, suggesting that the unison singing promotes upper body swaying. This might be due to the ease of the task complexity and/or to the fact the singers might feel more integrated when singing in unison. Their body posture was more open when singing in unison than canon: singers might have felt more open to communication whilst performing the easier task, which might have manifested in a more open body posture in the unison than canon task.

Interestingly, we did not find an effect of voice-matching perception or task complexity on singers' head motion. The latter is often associated with visual expressivity (Glowinski et al., 2013; Bishop et al., 2019) and was found to be more variable when singing in canon than unison (Palmer et al., 2019). More recently, it has been found that the similarity in common periodic oscillations of musicians' head motions was related to the musicians' empathic profile and the phrase structure of the piece (D'Amario et al., 2023). It has also been found that musicians' head motion in ensembles can change under conditions that require more self-regulation, suggesting that head motion, in addition to communicative functions, can support regulation of the own performance (Laroche et al., 2022). In the current study, the lack of a real co-performer and an audience might have underestimated its role. Future ecologically valid investigations involving real singing ensembles might test whether musicians' perception of voice matching with a co-performer and the singing task impact their head motion.

We found that the vertical position of the wrists was positively related to the performed pitch (H4). These results corroborate the literature revealing a coupling between singers' arm gestures and intonation (Brunkan, 2015; Brunkan and Bowers, 2021; Pearson and Pouw, 2022). Our findings are in line with the sound-tracing experiments suggesting that hand motion is a spatial

TABLE 6 Results of the linear mixed models measuring the relationship between block, take, phrase (phr), voice-matching and task complexity (i.e., the predictors) with the periodicity of the head and chest motion (i.e., the response variables).

Response variable	Model *n*	Predictors	Estimate	SE	*t*- value	Random effects
Head periodicity						
	13					Participant, trial
		block	−1.6	1.79	−0.89	
		take	1.43	1.82	0.78	
		phr 2 vs. phr 1	9.03**	2.53	3.57	
		phr 3 vs. phr 1	4.46	2.53	1.77	
		phr 4 vs. phr 1	5.68	2.53	2.25	
	14					Participant, take, phrase
		voice-matching	−2.27	2.33	−0.98	
		task complexity	3.32	2.33	1.43	
Torso periodicity						
	15					Participant, trial
		block	2.5	2.5	1	
		take	1.2	2.3	0.5	
		phr 2 vs. phr 1	10.8**	3	3.6	
		phr 3 vs. phr 1	9.7**	3	3.2	
		phr 4 vs. phr 1	10.6**	3	3.6	
	16					Participant, phrase
		voice-matching				
		task complexity	6.6*	2.4	2.7	

The table also displays the model number (*n*) and random effects variables (i.e., participant, trial and phrase, depending on the model) used in the analysis. The FDR method has been used for adjusted *p*-values. $^{*}p < 0.05$; $^{**}p < 0.01$.

representation of space or the pitch order (Godøy et al., 2006; Nymoen et al., 2010, 2011, 2013). This positive correlation could also be understood in light of the increased difficulty in tuning higher notes, which singers anecdotally report. The fact that we found evidence of this correlation mostly in the most difficult performance contexts, i.e., when singing in canon and when singing in unison for the first times, suggests that singers' hand motion, although not strictly linked to the sound producing, might fulfill musical purposes, by coming into play to facilitate the performance context. These findings also expand the literature analyzing hand motion of instrumental musicians, which suggests that certain hand and finger movements, such as increased movement amplitude, facilitate faster tempi in piano performance (Palmer and Dalla Bella, 2004).

We also found that the right wrist position was associated with tuning in the unison performance, whilst the left wrist was related to tuning in the canon performance. This might indicate that the left hand supports the most difficult context performance; however, this might also depend on the singer being left- or right-handed, an aspect not assessed in this study. Future investigations might shed more light in this respect to evaluate whether the left hand plays a technical supporting role stronger than the right hand. We also found that when singing along with the least-together performance, the right wrist position was higher than that singers had when singing with the most-together setting. This result can be understood in light of the previous results regarding task complexity and tuning: the wrist's vertical position seems to play a fundamental role in singing by supporting tuning of higher pitch (anecdotally considered more difficult than the lower ones) and performance in the most difficult context, such as singing in canon vs. unison and along the least than most together setting.

5 Limitations

At the beginning of the experiment, most of the participants self-reported past experiences of high levels of togetherness feelings with a co-performer. During moments of optimal matching experienced in the past, they felt as if their voices became *one* and everything was *locked in* and *flow*, as shown in Table 2. These experiences are in line with many dimensions of individual and group flow (Csikszentmihalyi, 1996). Importantly, these self-reported experiences demonstrate that our participants were familiar with the concepts of togetherness feelings and optimal matching. Nevertheless, it remains unknown whether our participants experienced feelings of togetherness *during* our production task. Future follow-up investigations could investigate continuous ratings of togetherness feelings in singing performances, resulting from the manipulation of the sound spectral envelope, to investigate the relationship between sound

TABLE 7 The table also displays the model number (*n*) and random effects variables (i.e., participant and trial, depending on the model) used in the analysis. The FDR method has been used for adjusted *p*-values. *$p < 0.05$; **$p < 0.01$; ***$p < 0.001$.

Response variable	Model *n*	Predictors	Estimate	SE	*t*-value	Random effects
L wrist position						Participant, trial
	17					
		block	0.01	0.01	1.88	
		take	−0.01	0.01	−1.38	
		phr 2 vs. phr 1	0.02*	0.01	2.6	
		phr 3 vs. phr 1	0.02*	0.01	2.55	
		phr 4 vs. phr 1	0.02**	0.01	3.22	
	18					Participant
		voice-matching	0.01	0.01	0.12	
		task complexity	−0.01*	0.01	−2.84	
R wrist position						
	19					Participant, trial
		block	−0.01	0.01	−0.61	
		take	0.01	0.01	1.6	
		phr 2 vs. phr 1	0.02**	0.01	3.2	
		phr 3 vs. phr 1	0.03**	0.01	3.67	
		phr 4 vs. phr 1	0.03***	0.01	4.87	
	20					Participant
		voice-matching	0.02*	0.01	2.6	
		task complexity	−0.02**	0.01	−3.02	

Results of the linear mixed models measuring the relationship between block, take, phrase (phr), voice-matching and task complexity (i.e., the predictors) with the vertical position of the right (R) and left (L) wrist (i.e., the response variables).

envelope and togetherness. It also remains unknown how their perceived optimal match (conceptualized in terms of spectral components) relates to the broad range of togetherness feelings (resulting from the social and cognitive alignment with the co-performer that varies as the music unfolds (Bishop, 2023; D'Amario et al., 2023). Future studies based on self-reported experiences might shed more light in this respect by investigating how musicians conceptualize togetherness feelings and voice match sensation.

6 Conclusion

By adopting a singer-loudspeaker paradigm, this study showed that the sound spectral envelope affects the sensation of being together with a pre-recorded voice. However, the present results suggest that voice-matching preferences do not make a major impact on choristers' body motion. The study also revealed that many aspects of the choristers' body motions relate to the complexity of the singing task (i.e., singing in unison or canon). Interestingly, wrist motion responded to togetherness perception, task complexity and tuning, revealing its importance in singing. These results can be of interest to choir and solo singing pedagogy aiming at identifying strategies for performance excellence.

Data availability statement

The datasets presented in this study can be found at https://doi.org/10.5281/zenodo.8380830.

Ethics statement

The studies involving humans were approved by Ethics Committee at mdw - University of Music and Performing Arts Vienna. The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study. Written informed consent was obtained from the individual(s) for the publication of any potentially identifiable images or data included in this article.

Author contributions

SD and ST equally contributed to the conception and design of the study. SD was the main contributor to motion data acquisition, analysis and interpretation and drafted the article. ST made a substantial contribution to audio data acquisition. ST, LB, and WG contributed to analyzing and interpreting the data collected. All authors critically revised the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Audience reconstructed: social media interaction by BTS fans during live stream concerts

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COVID-19-motivated social distancing made online concerts common practice in 2020 and 2021, with millions logging into streaming sites to see their favorite artists perform in realtime. For some fans, watching alone at home may have been enough, but concert-concurrent surges of social media activity suggest many virtual performance attendees are doing more. To understand why fans would turn their attention from these precious performance streams to social media, we explored Twitter engagement during four live streamed concerts performed by the Kpop group BTS in 2021. In public Tweets sampled by either concert hashtag or a predefined stream of users and keywords, we evaluated patterns in posting rates in relation to concert program events and investigated the content patterns in 1,200 Tweets sampled from four ranges of popularity (number of Retweets during the concert). Across concerts, short "Shout" Tweets surged at the start of songs, while the rate of retweets often fell during musical performances and shot up when BTS was off stage. Content analysis on the subsample found the materials most widely shared were informational or featured concert visuals, mimicking how fans use their phones at in-person concerts. Most original posts received few Retweets and were more personal and expressive of admiration for the performers. Comparison between the samples (concert hashtag vs. stream) also suggests users were strategic in using or omitting official concert hashtags with the strongest differences in the most widely disseminated content. Postings on Twitter during these performances seemed principally directed to fellow fans and audience members, by individuals choosing to share their own excitement and check in with others. By leveraging their existing social media networks, these concert attendees constructed a collective and interactive concert space, connecting with friends and strangers in the crowd and helping each other capture a richer experience than any broadcasting platform currently supports.

KEYWORDS

audience interaction, Twitter, social media, BTS, Kpop, live stream concerts

1 Introduction

The COVID-19 pandemic produced a period in which online broadcasts were the only option for most fans and musicians to meet in concert. In this time, the Kpop phenomenon BTS performed several live streamed shows with hundreds of thousands of simultaneous paying viewers tuning in from their homes around the world (Kiswe, 2021). While fans were excited to see these realtime performances, their attention was not solely focused on the broadcast stream: concurrent activity on social media suggests that many switched between watching the performance and engaging with other fans on alternative platforms. We use

Twitter data recorded during four concerts to look at when and how fans used this platform during the broadcast shows and what kind of materials they were sharing. The patterns suggest fans use social networks to recreate many of the activities they would perform as audience members in a live concert, from cheering loudly for favorite songs, to capturing clips for future memories, to basking in the emotional journey together.

2 Background

Music concerts are social events, gathering people to watch a performance and share a special experience. The presence of like-minded people adds to the attractiveness of live concerts (Brown and Knox, 2017), bringing a "sense of unity" or *ittaikan* with other audience members as well as between the audience and performer (Tarumi et al., 2017). This social component of concert experiences is often part of people's favorite musical experiences, when they feel connected to friends and strangers (Krause et al., 2020).

How audience members' experiences are shared depends on what the music and venue allow, from occasional rounds of polite applause to continuous writhing and screaming in the mosh pit. These norms of audience behavior during performances still allow individual attendees to be more or less active, according to their own priorities and position in a performance space (Fonarow, 1996; Benzecry and Collins, 2014). This behavior can include conversation at the interval or in the back of the bar, coordinated swaying at the edge of the stage, or enraptured fans watching in determined stillness. An active audience can also be perceived as detrimental to a concertgoer's experience because they can distract from the staged performance (Pitts, 2014; Mulder and Hitters, 2023). Some of the risks of going to live performances come from other attendees and their choices to participate, whether too much or too little. A common point of contention is how audience members use mobile phones at in-person shows. Even audience members who use their mobiles to capture special moments express ambivalence, concerned about how it may impact others in the audience as well as their own engagement in the show (Kjus and Danielsen, 2014).

When music performances are broadcast, audience members' opportunities to see and be seen, hear and be heard, are drastically changed (Charron, 2017). Their contributions to performances depend on what the available technologies allow, from the vague allusions on TV broadcasts like "the nation is watching" (Holt, 2010), to digital avatars jumping around the virtual performance space (Onderdijk et al., 2023). How effectively these mediations allow audience members to feel socially connected is an ongoing topic of research.

2.1 Live stream concerts and livechat

Live stream concerts became more common with the social distancing restrictions imposed to control the spread of COVID-19. Lockdown drove musicians and audiences to find new ways of connecting without risking public health (Hansen et al., 2021). Already a common practice for some portions of the internet, these technologies suddenly became relevant to a larger population, including new genres of concertgoers (Rendell, 2021). Most of these streams include an optional text chat function: besides showing the video feed of the performance, a text chat window is available to attendees to share comments in realtime with everyone watching. How such chat functions are used depends on the genre of stream, distribution platform (and what functions it supports, such as reaction emoji and @ing users), the number of people watching the stream, and of course, individuals' inclination to attend to and use these mechanisms of participation.

In a survey of live streamed concert experiences in the first months of the pandemic restrictions, Swarbrick et al. (2019) explored the experience of remote-concert attendees, including impressions of connectedness and social presence with performers and with the audience. Uses of interaction features like making comments in the livefeed chat correlated with greater *kama muta* and social connectedness. From a secondary analysis on the published survey data (Swarbrick, 2021), it seems survey participants varied in their use these features, with only 1 in 5 reporting sharing multiple or detailed comments on their experience for other audience members to see. Still, these few chatters also reported feeling greater connection and shared feeling with the audience, that others were aware of their presence, and that the streaming audience members were active and engaged (see Supplementary material).

An experimental attempt at investigating social connection through this medium assigned participants to attend concerts in a live streamed music festival in the summer of 2020 (Onderdijk et al., 2021). The condition that allowed audience participants to see each other (Zoom room with participants' cameras on) encouraged the impression of social presence; however, participation in the textchat function was too sparse to consider statistically as a mechanism for social connection.

Comparing behavior in FacebookLive chats for classical music and the Dutch popular music genre *levenslied*, both fairly new to live streaming in the early pandemic period (20 March until 17 April 2020), Vandenberg and Berghman (2023) investigated comments on performances that accrued dozens to hundreds per show. These commonly referred to face-to-face interaction practices (flowers, clapping, other audience actions typical during these shows) with few instances of explicit pairwise interaction between participants.

One likely reason for the limited concentration of audience action and interaction observed in these pandemic-oriented studies is technological unfamiliarity. Watching live streamed classical music concerts was a novelty before the COVID-19 lockdown, requiring extraordinary campaigns to engage audience members in a relatively convenient and low-cost activity (Nguyen, 2018). However, there are other communities with established cultures of interaction between performers and viewers over live stream. Twitch.TV is a massively successful streaming platform that has grown many distinct common practices of interaction through the limited medium of textchat (Jodén and Strandell, 2022). When thousands of users are posting to the same live chat, the flood of text messages becomes unintelligible. This cacophony can be reigned in with some coordination strategies, such as *crowdspeak* where viewers opt to share a common short message, making a cascade of posts that make the content visible to viewers and streamer alike (Ford et al., 2017). These messages can be inside jokes, important questions, or descriptors of more typical audience actions, but crowdspeak depends on viewers catching the impulse to emphasize a message in chat and many more seeing this opportunity and joining in. This culture of chat strategies grew in the context of immediate interaction between viewers and the streamer during live videogame playing. Music concerts rarely allow for this kind of continuous interaction, restricting the performers' responses to between pieces or sets, or in many cases, completely ignoring the chat altogether (Rendell, 2021).

From a series of interviews of individual users' experiences of music concert live streams on Twitch.TV, Vandenberg (2022) found many to follow these performances with less attention than face-to-face performances. According to observed behavior and self-report, the participants' interactions with other online users over chat were less intense or affecting than engagement with people in their preexisting social sphere. While the rare direct interaction between viewers seemed to be strongly felt, the medium of live chat made such exchanges slow and awkward and limited to more generic topics than might be discussed between established friends.

The effectiveness of livechats on concert live streams to satisfy audience members' desire to participate and connect seems highly variable. The experience offered by a small audience without a practice of commenting may allow the few active users to feel seen, while the waves of crowdspeak give users a chance to act together. Both extremes are complicated by the fact that messages posted are broadcast to all virtual strangers in the virtual room, including the performers, if they choose to look.

2.2 Twitter

Before being renamed to *X* in 2023, Twitter was a free social media platform that allowed registered users to post short (≤280 characters) status updates (*Tweets*) that could also include still images (up to four), gifs, or short video clips. Users also followed other accounts, reading these users' Tweets on their Timeline, and had multiple options for interacting with these posts: by favoriting (*Liking*) Tweets to show approval, sharing an existing Tweet on their own profile and the Timelines of their followers (Retweeting), initiating a dialogue by responding to a Tweet with one of their own (replying), or sharing a Tweet with additional media and commentary (*Quote Tweeting*). Replies and Quote Tweets differed primarily in their visibility on other users' timelines. Replies were not directly shared with the replier's followers unless they also followed the account being replied to, however they allowed for conversation chains to be constructed easily in certain interface views. In contrast, Quote Tweets were immediately visible to all of the quoter's followers and were more awkward for extended exchanges. Twitter's web browser and mobile app interfaces also allowed searches of the Tweet database by text, which encouraged the use of hashtags: distinct short connected text strings starting with a hash symbol (#) that people could add to Tweets about a specific event, topic, or theme. Hashtags allowed non-followers to easily find posts of interest and engage with them on (or off) the platform.

Through the 2010s, *live tweeting* became a popular means of documenting and publicizing political and cultural events (Kjeldsen, 2016). One or several Twitter users would post descriptions or commentary of an ongoing event in realtime, often with an identifiable hashtag to facilitate retrieval by strangers. This microblogging practice has been popular amongst academics, journalists, cultural critics, and activists, making inaccessible events visible to a wider public and sharing information with their particular point of view (Pemmaraju et al., 2017; Reyes-Menendez et al., 2018). Live tweeting to broadcast events also allowed everyday spectators to share their take (Hawthorne et al., 2013; Ji and Raney, 2015), and a study of sports spectators reported their enjoyment of both mediated (live broadcast) and in-person games to increasing with the intensity of engagement on the platform, namely by posting Original Tweets or a combination of Original Tweets and Retweets (Smith et al., 2019).

The observation of live tweeted events on Twitter is more difficult to describe. At the time of data collection for this study (2021), the Twitter platform defaulted to filling users' timelines with mostly chronologically-ordered content from the accounts they followed with some algorithmic alterations (Newton, 2016). Besides adding posts by advertisers, Tweet order could be shifted to prioritize recently popular content within their network of followers, and additional out-of-network popular Tweets may have been offered according to user behavior (Johnson, 2021). Many of these adjustments to chronological presentations of Tweets seem geared toward making interesting current events more visible to users, likely facilitating the propagation of live-tweeting activity. Outside of their Timeline and brute searches on the platform, Twitter also presented users with *Trends* in their noted areas of interests: curated lists of currently hot topics, keywords, and hashtags assessed globally, regionally, and by themes like music or sports.

Twitter began allowing researchers to explore the public Tweet database in 2006 through a licensed API access (Tornes, 2021). Besides research into the network properties of topics (Himelboim et al., 2017) and communities using dedicated hashtags (Chandra et al., 2021), the expression of activity on the platform by remote spectators has been of some interest (Highfield et al., 2013), especially for sports (Hsieh et al., 2012; Lanagan and Smeaton, 2021). Twitter analysis might not have been the fastest way to hear about who scored what goal, however evidence of such dramatic moments in matches suggests that this platform has been used by fans to share their elation in parallel to offline shouts and cheers.

2.3 Phones and social media at concerts

Whether the audience is attending concerts face-to-face, over live stream, or through a virtual environment, attendees also have the option to capture and share their experiences outside of these environments. Preparatory, concurrent, and post-concert activity on social media platforms have made these common secondary spaces for concertgoers to extend the event. Pictures and videos of shows are routinely shared in online space, privately and publicly, and in the many shades between.

Tweeting from live concerts has at times been quite controversial. Classical concert spaces have been particularly resistant, and mobile phones and their cameras are still forbidden in some venues (Glitsos, 2018). Tweet Seat concerts, operatic or symphonic performances where a few select audience members were invited to live tweet along, were a seen as daring form of outreach in 2016 (Nguyen, 2018).

Live tweeting and mobile phone recording became common at popular music performances much earlier, bringing events in the concert hall to a large audience through commentary, photos, and video clips. By 2014, audience members had strong opinions about how these technologies changed their experiences both in and out of the venue. Bennett's (2014) interviews of Tori Amos fans found mixed experiences. In addition to the benefits of sharing information with people who could not be there, which strengthens an interested online community, the people sharing also reported some interference with their own engagement with the show. As one participant said: "I definitely don't feel as connected to the moment when I'm texting/tweeting. I try to pause and take in the music and the performance before sending an update." Using these technologies to communicate with fans outside of the concert space has costs.

More commonly, audience members are taking video and photos for their own private enjoyment as evidence of "being there" and to capture "novel performance moments," whether or not they are shown to others (Kjus and Danielsen, 2014; Kim and Kwon, 2019). Holding up a phone and pressing a button is less cognitively demanding than formulating and typing up messages to post, and it still captures precious material. The consequence of glowing screens across an audience has been lamented by many (Glitsos, 2018). Still, for some venues, shows, and particularly for shorter audience members, the phone raised high allows for a better view of the action than they could get from standing (personal experience). Whether or not users are recording or reporting on social media, the mobile phone screen is a ubiquitous component of live face-to-face music shows wherever they are allowed.

2.4 The active Kpop audience

In the Kpop culture, fans are used to being active audience members. Fans normally shout and sing along, follow bits of choreography, and perform the relevant *fanchant* for many, if not most, songs performed. A fanchant is "a chant that fans recite in unison during the artists' performances consisting of parts of the lyrics, names of the group/members, or other words" (Bhattacharya et al., 2023), and this concert practice requires that fans obtain the official fanchant instructions for the expected set list of the show and practice their part before attending the performance. Derived from the Korean folk music tradition of *Chuimsae* (Takayanagi, 2021), fanchants are an example of the degree of preparation and participation Kpop culture expects of the audience.

Around face-to-face concert events is also a culture of community forming between attendees. Hours-long lines for entering stadium venues and accessing merchandize give these fans time to chat and bond with like-minded people while performing effortful devotion (Benzecry and Collins, 2014). It is also common practice for fans to bring materials like photo cards and trinkets to share with the people they meet at the venue (Guillen, 2022). And like other pop genres, it is normal to watch in-person shows with phones up (when allowed in the venue), capturing photos and videos so that these precious moments can be replayed for personal enjoyment and shared with others (Kjus and Danielsen, 2014; Kim and Kwon, 2019).

The participatory nature of Kpop fandom is also very prominent outside of the concert context. In the fan community for the group BTS, officially called *ARMY*, there are different subgroups or types of fans who dedicate their time to engage with BTS-related content through various activities. These subgroups include "Theory ARMYs" who enthusiastically collect, analyze, and interpret the hidden meanings or symbolism based on BTS' song lyrics, music videos, and other content; "ARTMYs" who express their love of BTS through their artistic creations such as drawing, knitting, crafting, etc.; ARMYs who do dance covers of the BTS songs; and so on (Lee, 2019). These activities are often tied to performed music (Lee, 2018) where fans share what they think of as the meaning of the video content shown during the concert, drawing different scenes from the concert, or creating memes with the different screenshots of the concert footage. This kind of content is actively shared on social media, and some of the accounts gain a substantial following as other fans enjoy and appreciate their content. Through these participatory activities and sharing practices, fans connect with each other and build a sense of community.

BTS's ARMY is an audience used to being recognized and acknowledged by performers during the show. Besides addressing fans directly during performances, Kpop group members talk extensively about their personal investment and affection for fans in non-concert live streams and behind-the-scenes footage. Chat messages from fans during these live streams can turn into an inside joke between the artist and the fans (Ringland et al., 2022). For example, once BTS members pointed out the many live stream chat comments saying "Yoongi Marry Me," this phrase turned into a meme, and fans began to bring signs with the same message to face-to-face concerts as a playful joke. Kpop groups also create "fan songs" about their fans and the fan-artist relationship with lyrics containing messages directly for their fans. For instance, BTS created the song "2! 3!" as a way to comfort fans during the hardships they were experiencing due to false accusations and attacks from other fan communities at that time. Each year since their debut (excluding their current break), BTS has celebrated the formation of ARMY with *Festa*, a two-week interval of special promotional activities culminating in a distinctly fan-oriented concert (the *Muster*).

From specific concert activities, established social practices, and explicit acknowledgment from their shared focus, ARMY is a music fan community that is very interested in each others' experiences and empowered to work for their collective benefit both in-person and online.

2.5 COVID compromises for Kpop shows

When the COVID-19 pandemic put a stop to face-to-face performances, Kpop was more prepared to compensate than most sectors of the global music industry. The leading companies had previously been exploring different ways to use augmented reality

(AR), virtual reality (VR), and other technologies to provide high quality "on-tact" (online-contact) events (Kim, 2021). Kpop audiences also had years of experience engaging with live streamed content from these performers on platforms like V Live (Kim et al., 2021). Thus, BTS was able to host online concert events quite successfully in 2020 and 2021.

Several strategies were employed to bring aspects of an audience to the performers for these concerts. In sets built to the scale of stadium stages, sections of the performance spaces were decorated with hundreds of *ARMY bombs*, the light sticks that fans bring to concerts to be part of the Bluetooth-coordinated light show, supposedly representing the absent audience and recreating the typical atmosphere of the concert. Imitations of the sonic presence of an audience were also added through synthesized cheering, and even mixes of fans-submit fanchant recordings were added to the backing tracks for BTS's singing and dancing. At the BTS Map of the Soul ON:E and Sowoozoo muster performances, a prepared group of fans were set up to stream from home into the performance spaces, making a wall or field of faces visibly cheering in near realtime for the group's performances (Lee and Kao, 2023). During these concerts, BTS members mentioned the challenges of performing without a live audience and discussed how the sight of streamed-in ARMYs cheering with their homemade signs made them feel more connected and helped them to stay positive in these difficult conditions.

VenewLive, the ticketed online broadcasting platform supporting these BTS concerts (Kiswe, 2021), offered a built-in live chat function allowing audience members to message everyone following the stream. This chat was open by default but could be hidden with a toggle. As has been observed on Twitch.TV, livechats on streams with massive audiences ($\geq$10,000) quickly become a torrent of messages that cannot support normal chat interactions (Ford et al., 2017). Anecdotal accounts from fans suggested many instead used social media and private communication channels to connect with others watching in realtime. Discord, Zoom, and DM (direct message) groups on many platforms allow for more personally pertinent and manageable sharing of the concert experience while places like Twitter and Tumblr fell in between. These sharing-oriented social media platforms gave fans access to the experiences of known network friends and strangers through reblogging or Retweeting mechanisms and hashtag or topic feeds.

Our choice of looking at online concert activity on Twitter was opportune. This was a platform with highly concentrated online engagement by the followers of BTS (ARMY), and a social media space with a working API which allowed licensed researchers to study online activity. The resultant data is a rare side view into a massive paying remote audience's realtime interactions during a stadium-tour quality concert production.

3 Materials and methods: Tweet timing

Twitter activity during four live streamed BTS concerts was collected in realtime to compare with the broadcast concert timelines. Analysis was performed on the timing of Tweets and their content using automated feature description and manual coding of subsamples.

3.1 Concerts and concert events

Twitter activity was tracked around four concerts in 2021. The first two concerts were BTS's 2021 Muster, named Sowoozoo, which took place on June 13 and 14. Musters are special celebratory performances with a particular focus on their fan community. The program often features more casual conversations between band members and special productions for songs that would not be taken on tour. The last two concerts were online broadcasts of BTS's Permission to Dance (PTD) Tour: PTD on Stage, performed for broadcast in Seoul on October 24, and PTD in Los Angeles on December 3, performed both for broadcast and to a face-to-face audience, as was newly permitted in the United States with changes to COVID-19 pandemic lockdown restrictions. The concert pairs showed mostly the same program, and presumably attendance to the first broadcast of each was higher than the second.

These concert streams combine different types of content that we collapsed into four categories: Live music, Live talking, Video clips, and Off stage. Besides the sets of songs performed live (Live music), there were intervals of live talking as band members addressed the audience and chatted amongst themselves (Live talking). Some of these intervals of talking were quite long, with performers' comments to the audience before the last set of the songs sometimes running up to 20 min. In these talking intervals, members spoke mostly or entirely in Korean, and these broadcasts offered realtime translations in a few common languages. There were also prepared video sequences dispersed throughout the concert consisting of short clips that allowed for costume and set changes (Video clips). These videos, referred to as "VCRs" in Kpop, often follow the band members through a wordless fantastical narrative. Lastly, there was always a cheering section toward the end of the show when the performers were offstage, and the broadcast feed showed live, recorded, or streamed-in fans while they cheered before the closing set (Off stage).

In addition to the intervals defined from the concert live stream program, 5 min intervals before and after the stream were added to the Off stage category. Live music intervals were marked from the start of each song performance, Live talking from when members began talking after a set of songs ended or with a new programmed conversation activity, Video clips and Off stage sections from the change in broadcast feed. Each show lasted between 2 and 3 h, with 25–37 program events, and 19–23 transitions between these categories of stream content. The relative timing of these events was marked manually from the original concert broadcasts and rebroadcasts.

Online broadcasts always have some delay from the stage side, and viewers receive the broadcast with variable additional delays dependent on their geographical location, internet connecting stability, and the broadcasting platform's resources. It is not possible to align the timing of these program intervals perfectly to the times they were seen by all online viewers. Instead, the concert program timelines were brought into approximate alignment by scanning for mentions of performed music tracks. The event onsets were shifted en mass so that the music intervals started within a few seconds of the first cluster of posts about a song. As such, the alignment of concert intervals with the Tweets compensates for both some portion of viewing time offsets and a representative reaction-to-expression delay on this platform.

3.2 Twitter samples

Tweets posted during four live streamed concerts were captured using the Twitter Streaming API, then collected. They were collected and stored by the Center for an Informed Public at the University of Washington. The Streaming API allowed for Tweets to be collected according to predefined monitoring criteria made up of user IDs, keywords, and hashtags (Twitter Developer Platform, 2021). For each Tweet captured, the API logged the text of the post, when it was posted, along with information on Tweets related by Retweet, Quote Tweet, and Reply, and public User Account details for the posting user and users of related Tweets such as their user id, number of followers, and account language. All public Tweets meeting the pre-defined criteria were captured except in cases where rate exceeded limits. Tweets by private accounts and actions like direct messages are not available through the API, nor are actions such as Liking Tweets or views. Additionally, public accounts that explicitly requested exclusion from data collection through common statements in their user descriptions were filtered out prior to analysis (See Supplementary material for details).

For the two Sowoozoo performances, concert Tweets were collected in realtime using exclusively the concert hashtag. After capturing all public Tweets that included the hashtag #SOWOOZOO (ignoring case) in the days around the 2021 Muster, this collection was cut down to an interval of 3.5 h around each concert, 225,934 and 114,724 status updates, respectively. While not all concert-related Tweets used this concert hashtag, this method of sampling captures nearly complete Retweet trajectories for content intentionally associated with the performances, giving a detailed view of network activity within an interested segment of Twitter users.

For the Permission to Dance concerts, the concert hashtags were not used to a comparable degree. The most popular hashtag for the first PTD concert, #PTD_ON_STAGE, occurred 46,321 times, less than half as many as the second Sowoozoo show. During the LA performance, #PTD_ON_STAGE_LA was found in only 7,917 Tweets during the recording interval. This was perhaps due to rumors circulating online about accounts getting suspended for sharing concert feed footage, making attendees shy to tag their content on Twitter. Instead of collecting Tweets with only the concert hashtag, we sampled Twitter activity from a previously-established stream. In 2020, a project at the Center for an Informed Public had defined a select population of BTS-oriented Twitter users ($\leq$5,000) to monitor continuously for activity within this region of Twitter. This population was constructed from a partially random selection of users who followed a few key accounts within the ARMY network, had posting histories focused on Kpop, and matched a minimum rate of posting activity. This group of accounts formed the core of the Stream samples, along with the inconsistently applied concert hashtags and some keywords from other projects. Despite the particular structure of this stream, this cross-section of Twitter still showed a substantial jump in activity during the broadcasts. There were 277,794 and 143,772 status updates collected via the stream through the four-hour intervals covering each PTD broadcast concert, many times the amount captured with the same criteria a week prior (see Supplementary material for more on the off-concert Stream samples). Inspection of subsamples from the concert intervals also found the vast majority to be related to the performances, sufficiently concentrated for quantitative and qualitative analysis. Still, it should be noted that the Stream samples are structured very differently from the Hashtag samples, both by including content that is not posted with an official hashtag, i.e., not intended for a global or commercial audience, and by mostly capturing instances of Tweets passing through a monitored population of longtime Twitter users.

Our interest was primarily in audience actions and interactions in a social network with very high centrality around official accounts. Fan-to-fan engagements can be completely overshadowed by the scale of concurrent responses to accounts with millions of notified followers. To attenuate this type of noise, the samples were filtered for Replies and Retweets of some official accounts, specifically: "@BTS_twt," "@bts_bighit," "@BIGHIT_MUSIC," "@weverseofficial," "@weverseshop," "@HYBE_MERCH," and "@BT21_." These filtering criteria have differing impacts on the samplings: <4% of posts and unique users were cut from the Hashtag samples, while 15–17% of Tweets and 22–25% of users were removed from the Stream samples. Table 1 reports the final number of Tweets studied per concert, including by type.

There are four types of status updates captured in these datasets: Original Tweets, Retweets, Quote Tweets, and Replies. Retweets are by far the most common form of posting activity for these samples. Besides scrolling past or just Liking a Tweet, Retweeting is the least effortful interaction a user can make with content they see on their timeline. The action of Retweeting both propagates the Original Post to followers and preserves the material in the user's own posting history. Quote Tweets and Replies are also interactions that can make posts retrievable; however, they are much more complicated to document. Their prominence in the Stream sampled data is concentrated around interactions prompted by large fan accounts in ways that are ambiguous in their relationship to concert content, while the same pattern of platform activity was negligible in the Hashtag sampled datasets.

TABLE 1 Statistics of the four concert Tweet samples.

Concert (sample source)	Filtered	Originals	QT&Replies	Retweets	RTed	Users
SWZ day 1 (Hashtag)	224,733	26,939	8,459	190,998	6,006	111,147
SWZ day 2 (Hashtag)	111,185	18,816	4,093	89,151	5,451	54,457
PTD on stage (Stream)	228,793	5,548	10,555	214,426	9,323	85,374
PTD in LA 4 (Stream)	116,342	4,013	9,636	107,671	8 548	44,130

Posts counted after filtering, number of posts by type, number of unique posts being retweeted (RTed), and total number of unique user accounts (posting and retweeted).

Table 1 collapses these types together, and they are not included in the analysis to follow.

3.3 Tweets over time

Analysis of the timing of Tweets by type and association was conducted in Python using common libraries and specialized scripts (https://github.com/finn42/Concert_Twt_Open/; https://zenodo.org/doi/10.5281/zenodo.10159761). As described in Section 3.1, the concert program timing was aligned to notable markers in the Tweet dataset, namely the onset of specific tracks. Tweet rates were initially counted in 15 s intervals for dense samples and 60 s intervals for smaller sets such as Retweets of a single post. The smoothed rates per minute seen in Figure 1 are the result of a centered four-point rolling sum, retaining the 15 s hopsize.

The rate of Likes during the first Sowoozoo concert was estimated from the accumulation of Likes on the 1,000 most retweeted Tweets. Total Likes on these posts were counted cumulatively with each recorded Retweet, differenced on the 15 s sample intervals and smoothed like the posting rates. These values are not a complete picture of the Liking actions performed by concert attendees on Twitter during this interval. They are entirely missing Likes on Tweets with the hashtag that were not subsequently publically retweeted within the sampling interval as well as Likes on Tweets that were retweeted <14 times. However, the series' proportions to the other rates reflects the changing number of users attending to their Twitter timelines during the show.

Absolute rates of Tweets cannot be fully modeled from the information available. To consider the impact of concert content on Twitter activity, we instead focus on local shifts in rates between successive segments of the concert program. We defined the *Rate Shift* as the ratio of the average posts per minute through one segment of the concert program, say a set of songs, relative to the average posts per minute through the previous segment. The *Cusp Shift* ratio is a similar comparison made between just the 60 s before and after the onset of a concert event, i.e., the posting rate at the start (cusp) of a song, relative to whatever was happening just before.

4 Results: Tweet timing

The following section graphically depicts rates over time from the first Sowoozoo concert while reporting statistical assessments calculated across all four concerts at once.

Figure 1 shows the smoothed measures of Twitter activity through the Hashtag sample for the first Muster concert. Before the show, there was an average of 200–500 original and Retweet Tweets per minutes using the hashtag #Sowoozoo with Retweets picking up after the first live music set and cresting several times over the course of the show. Through observation, we find that Retweets drop or plateau through the Live music segments (starred purple) and rise during most instances of talking, video clips, and when BTS was off stage. The estimated Likes rate varies from 1 to 3 times the Retweet rate, with proportions becoming more steep during the non-musical segments as well.

Popular Tweets strongly influence the shape of Hashtag sampled datasets with peaks in Retweets over time usually driven by individual hypervisible posts. To check the impact of popular Tweets during these concerts, Figure 2 shows the number of Retweets per minute attributable to each of the top seven Tweets in this data set. Retweets of these posts constitute 28% of all hashtagged Retweets during the displayed measurement interval.

The typical shape for a Retweet over time is a sharp spike on posting or Retweeting by a large account and then a gradual

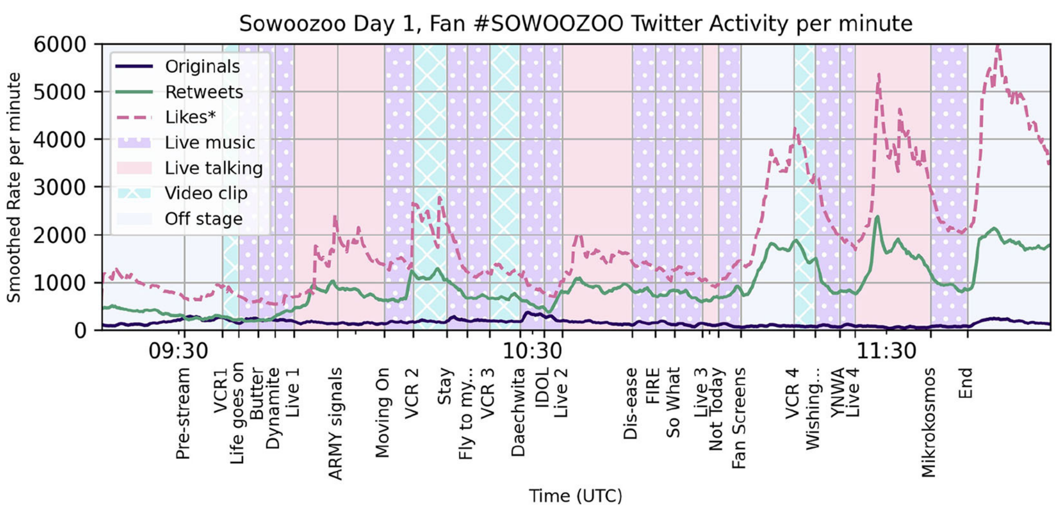


FIGURE 1
Smoothed minute rate for fan Twitter interactions with #Sowoozoo over the course of the Sowoozoo concert live stream on June 13th, 2021. Retweets and Original Tweet rates counted directly from Hashtag sample Tweets excluding official accounts. Likes rate is estimated from the accumulation on the 1,000 most retweeted Tweets. Concert stream content categories color-coded in background with events labeled at onset on the x-axis, including song titles.

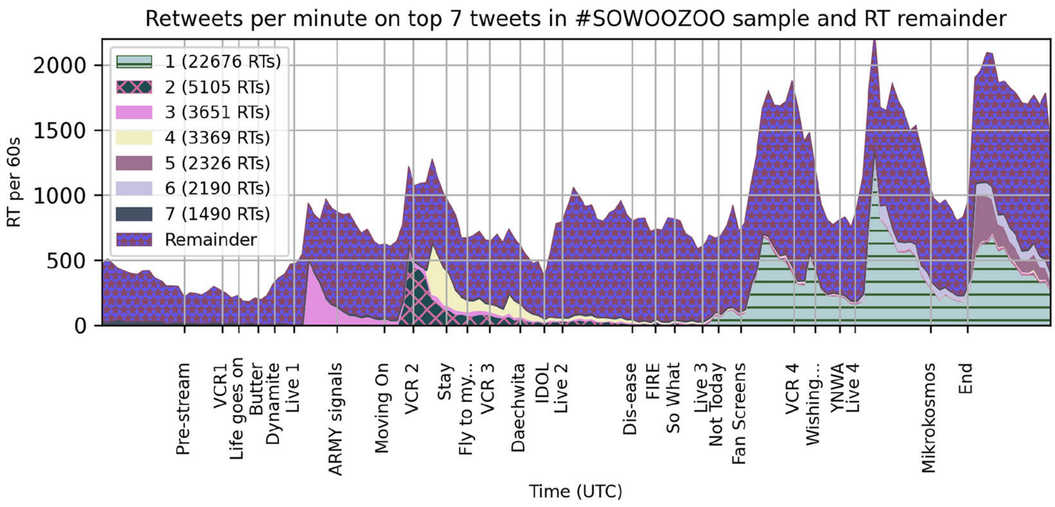


FIGURE 2
Stacked Retweets rates of the seven most retweeted Tweets in #Sowoozoo during the Day 1 concert under the remainder of Retweets, counted in retweet posts per minute. X-axis corresponds to timeline in Figure 1.

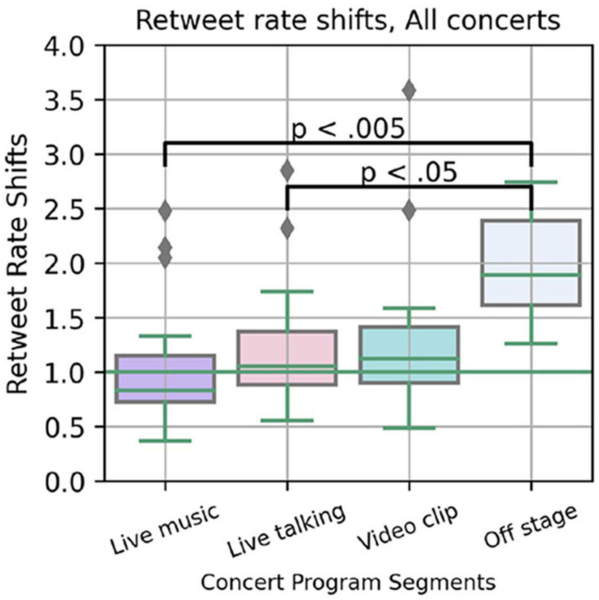


FIGURE 3
Relative Retweet posting Rate Shift per concert program segment (set of songs, talking interval, etc.), aggregated across four concerts.

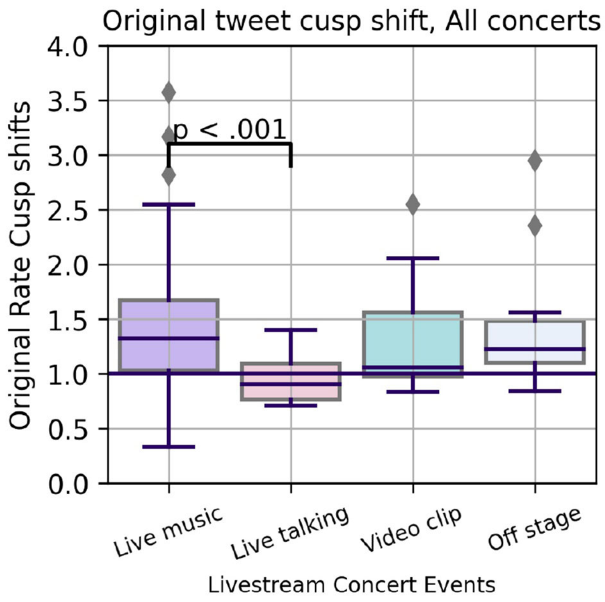
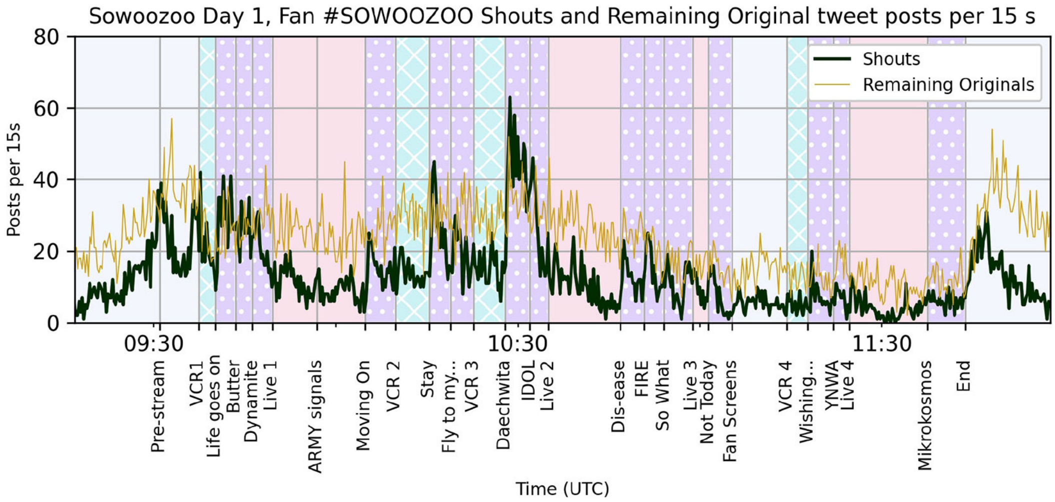


FIGURE 4
Change in relative posting rate of Original Tweets at the Cusp of program events (individual songs, videos, etc.).

tapering off. Some of these top Tweets, say 2 and 3 in Figure 2, follow that structure with a small spike also visible in the total Retweet rate. However, the most popular Tweet in the set, shown in horizontally stripped mint green, goes up and down with the concert program events, suggesting that contour of Retweets is varying more with attention to the time line than to just the presence of retweetable content. These valuable Tweets are in users' timelines, but at some moments in the show, fewer users are looking.

By the Likes and Retweet rates, it seems concert content had a strong impact on users engagement on this platform with the online audience focusing more on the broadcast while music was being performed. To test this pattern across concerts, we calculate the Rate Shift ratio for each contiguous program segment and tested the factor of concert event type on the rate of Retweets per minute with a Welch ANOVA across all four concerts. This test of means is more reliable for samples of unequal variance and number (Liu,

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2021-06-13 10:28:41+00:00: YESSSSSS DAECHWITA LET'S GET IIIIIT @BTS_twt #SOWOOZOO
2021-06-13 10:28:41+00:00: キター(((o( ﾟ💥▽💥ﾟ)o)))  大吹打!!  #SOWOOZOO
2021-06-13 10:28:42+00:00: でじったあ #SOWOOZOO
2021-06-13 10:28:42+00:00: きたきたきたきた！ 大吹打！！！！！！ #SOWOOZOO
2021-06-13 10:28:42+00:00: I AM LITERALLY SCREAMING! #DAECHWITA #SUGA #SOWOOZOO
2021-06-13 10:28:42+00:00: OHHHAA DAECHWİTAAA  #BTS #SOWOOZOO #BTSMusterSoWooZoo
2021-06-13 10:28:43+00:00: DAECHWITA!!!! #SOWOOZOO
2021-06-13 10:28:43+00:00: ДЭЧИТА БЛЯЯЯЯЯТЬ #8YearsToInfinityWithBTS #SOWOOZOO
2021-06-13 10:28:43+00:00: #SOWOOZOO OMGG DAEWHCITE ISHD. WOF AHHAHAHAHA
2021-06-13 10:28:43+00:00: NOOO WAYYY YOONGI  #SOWOOZOO #BTS
2021-06-13 10:28:43+00:00: IM SCREAMING #SOWOOZOO
2021-06-13 10:28:43+00:00: DAECHWITA!🥺😍👀 #BTS #SOWOOZOO
2021-06-13 10:28:44+00:00: NOOOOOO YA ME MORI #DAECHWITA #BTSARMY #SOWOOZOO
2021-06-13 10:28:44+00:00: Morriiiii #SOWOOZOO #MUSTERSOWOOZOO
2021-06-13 10:28:44+00:00: でちた！！！！ #SOWOOZOO
2021-06-13 10:28:44+00:00: SUGA！！！！！！😭💜 #SOWOOZOO
2021-06-13 10:28:45+00:00: ｵｷﾞｬｰｰｰｰｰｰｰ!!!!!!  #SOWOOZOO
2021-06-13 10:28:45+00:00: AJSHDJSJAKDJD #SOWOOZOO AGUST D !!!
2021-06-13 10:28:45+00:00: WEEEEEEY  #SOWOOZOO
2021-06-13 10:28:45+00:00: 아아아아아악 대취타아~~~ #SOWOOZOO
2021-06-13 10:28:45+00:00: HOLYSHITTTTT BRUHHH DAECHWITA #SOWOOZOO
2021-06-13 10:28:45+00:00: Daechwitaaaasrfgyjhgfko #bts #MUSTERSOWOOZOO #SOWOOZOO
2021-06-13 10:28:45+00:00: きたきた #SOWOOZOO
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FIGURE 5
(Top) Number of Shout Tweets (Shouts) and the remainder of Original Tweets with the #Sowoozoo hashtag per 15 s interval over the course of the Sowoozoo concert live stream on June 13th, 2021. Background colors mark concert stream content categories as in Figure 1. **(Bottom)** Example of Shout Tweet content, consecutive run excerpt at the start of Daechwita feat. BTS, by Agust D (Suga).

2015), and finds a significant effect of concert event type, $F_{(3,27.96)} = 5.69, p < 0.005$.

Figure 3 plots the distributions of relative Retweet rate per concert event with significant outcomes of the *post-hoc* pairwise comparisons (Games-Howell, again to allow for unequal sample sizes). While there were some exceptions across these four performances, evidence of attention to Twitter decreased when BTS was singing and dancing (median below the green 1.0 threshold), and it increased most dramatically when they were fully off stage or not on the stream.

4.1 Original Tweet rates

The pattern of Retweet rates fits with the expected narrative of fans' priorities during a concert performance, however one type of Twitter activity did not follow the same trajectory. In Figure 1, the dark line tracing the Original Tweet rate (Originals) shows that while this activity is much rarer than Retweets, the time series often increases in moments when the other rates drop. Retweet and Original rate time series are mildly negatively correlated in this first concert ($r = -0.36$). Why would Original Tweets increase at those moments when attention to the timeline seems to go down?

Closer inspection of this pattern suggested short-lived peaks in posting rates at the onset of songs. To check if this pattern was common across concerts, we defined the Cusp Shift ratio, checking for changes in the rate of Original Tweets posted in the minute before and after the start of individual concert program events. A Welch one factor ANOVA finds a significant effect of concert event type on the Cusp Shift, $F_{(3,35.21)} = 10.04, p < 0.0001$, with a *post-hoc* test identifying the contrast between the start of Live Music segments (individual songs) vs. intervals of Live Talking. Across these performances and sampling methods, there is a measurable tendency for fans to be suddenly posting more (median of 1.3 or 30% more) at the start of songs while the Original Tweet rate tends to slow at the start of an interval of talking (median $<$ 1.0, below the purple 1.0 threshold in Figure 4).

Checking a few instances of these song-triggered spurts of Original Tweets showed a great concentration of short Tweets stating the titles of songs with little more than a hashtag and some intensifying cues, see examples in Figure 5. Short Tweets in this style can be posted without much effort or even a glance at what else might be happening on Twitter. To test if this kind of post was a common, we defined a subcategory of Original Tweet, called *Shout Tweets*, that are original status updates without embedded media and under 60 characters. While many are even shorter, the threshold of 60 characters was chosen to be inclusive across writing systems and allow for concert hashtags. Figure 5 shows the rate of these Shout Tweets counted on 15 s intervals with the remaining Original Tweets (longer and/or with images or videos embedded). At this resolution, the shouting is even more dramatically aligned to the onset of songs, and captures fans' excitement for the special all-member BTS performance of Agust D's Daechwita as they continued this "shouting" for the full duration of the piece.

The variation in Shout Tweet rate with concert program events is extremely strong but over much smaller numbers than the previous posting rates, and here we should acknowledge the limits of Hashtag sampling. It is reasonable to expect that only a small portion of concert attendees were determined to type in the concert hashtags with their shouts of excitement. Comparison of content between the two sampling methods, Hashtag and Stream, exposes more clearly what fans were really posting during these broadcasts.

5 Materials and methods: Tweet content analysis

To get a picture of what fans were expressing (Original Tweets) and sharing (Retweets) during these live concert streams, we wanted to look more closely what was being posted. However, these sets of Tweets per concert are much too large to explore in depth. We chose instead to extract subsamples of Tweets from the first Sowoozoo performance, the first set collected by Hashtag, and from the first Permission to Dance performance, collected from the previously-defined Stream.

5.1 Subsampling concert datasets

A completely random subsample on the full concert datasets would be quite repetitive, as the most commonly retweeted content dominates these samples. Figure 2 demonstrates the concentration of Retweets in the Hashtag sampled datasets, and the ratios of Original Tweets to Retweets are even more extreme in the Stream samples (see Table 1). Individual users experiences of Twitter through their timelines was also more variable than these samplings suggest. While the most popular posts would pop up multiple times in their personal view of platform activity, users often ended up glossing over these repeats (sometimes with the help of algorithmic influences) and paying more attention to Original Posts by their *Mutuals* (people they follow who also follow them). As the majority of Original Posts get zero Retweets, a naive random subsample would miss out on these direct expressions by individual fans.

In order to explore content patterns across this great range of visibility, we used the total number of Retweets recorded during the concert intervals to stratify the unique posts in each sample and picked a few tiers of popularity to draw from. We defined four ranges of Tweets in the first Sowoozoo and first Permission to Dance concerts: the top most retweeted in the dataset (Top RT), Tweets with 6–32 RT (Mid RT), Tweets with 1–3 Retweets (Low RT), and Tweets with no Retweets at the time of sampling (No RT). These strata were then subsampled, randomly for all but the most retweeted, taking 200 from the Sowoozoo sets, and 100 from the PTD on Stage concert sets (with replacement for unrelated or lost content). This stratification also helped compensate for the practical consequences of the two concert sampling methods. Table 2 reports some statistics on these eight subsamples. Descriptors of the subsamples include the size of each strata within each dataset and a rough estimate this strata's visibility based on the follower numbers of the users sharing them. The median statistics point out substantial differences between these datasets with the top Retweets contrasting by an order of magnitude. The differences in median follower counts also suggests that hashtag use increased the visibility of concert-related Tweets beyond many of these users' immediate network.

TABLE 2 Description of database stratification and subsampling used for content analysis with median Tweet statistics and total strata visibility within each sample and across Twitter users' timeline.

Subsets		Visibility		Median Tweet statistics			
Source	Range (selection)	Sample	Timeline*	RT	Likes	Length	Followers
Hashtag	Top RT (Top 200)	138,607	153,482	718	1,306	172	5,433
Hashtag	Mid RT (Rdm 200)	7,378	44,752	13	38	134	1,199
Hashtag	Low RT (Rdm 200)	3,814	18,988	1	2	127	322
Hashtag	No RT (Rdm 200)	25,230	31,336	0	N/A	71	185
Stream	Top RT (Top 100)	66,848	124,968	7,127	18,050	63	214,783
Stream	Mid RT (Rdm 100)	4,429	24,990	17	37	81	16,531
Stream	Low RT (Rdm 100)	1,410	1,926	1	3	73	3,557
Stream	No RT (Rdm 100)	12,665	12,665	0	N/A	38	498

*Indicates estimate from maximum RT counts recorded.
N/A, not available.

5.2 Tweet content coding

To develop criteria for content coding, the Top RT and No RT subsamples from the first Sowoozoo concert were iteratively explored for themes that were usefully descriptive and reliably identifiable.

After a first pass to pick out recurring topics, modes of expression, and media use, the emergent codes were reviewed for reliability. Tweets are small dense expressions that depend on a shared cultural context for accurate interpretation, using memes as a shorthand that are easily misinterpreted without specific knowledge. Additionally, these Tweets included text in many languages. The ratio of English was higher in the Stream sample (75%) than the Hashtag sample (44%), but over 30 languages were represented more than 20 times in each concert dataset. Korean, Thai, Japanese, Indonesian, and Spanish commonly occurred in the subsamples pulled for content analysis. Consultation with multiple machine translations and context clues from user profiles and connected Tweets (Replies) were used to interpret individual Tweets across language barriers and unfamiliar references. However, it was still necessary to restrict the codes of this analysis to qualities that could be discerned by the coder around the unresolved ambiguities. An initial set of 35 codes were collapsed to 16 on reviewing the Sowoozoo the Top RT and No RT subsamples. These 16 codes were assessed on the remaining subsamples Tweets. Of these, 12 codes varied substantially in frequency across the subsamples and are reported on below.

More traditional strategies for large text datasets such as affect analysis were not used because of the limits of translation and the medium-typical use of negative language to express positive or ambiguous reactions. The coding process found almost no Tweets that were commenting critically on the concerts beyond the occasional complaint about stream video quality. While shades of admiration would be interesting to classify more finely along the lines of familiar affection, thirst (lust), respect and the like, these Tweets did not always include enough context to reliably distinguish between these modes of appreciation.

The thematic content codes fell into two categories: *topics* as the discernible subject of the post and *tone* pertaining to how these topics were addressed. The thematic content codes were defined as follows:

- **Affection** (tone): Tweets that expressed admiration, gratitude, appreciation, and love in text or with related emoji such as 🥰, 💜, 🥺 in appropriate contexts.
- **Intensity** (tone): Tweets that used cues typical for these social media spaces to demonstrate intense feelings such as ALLCAPS, repeated characters (with suitable associations), negative emojis (e.g., 😭 😳 💀), swearing, dramatic punctuation, and accusatory or admonishing language like "HOW DARE" to express a positive sentiment such as admiration or enjoyment.
- **Music** (topic): Tweets that made explicit reference to a piece of music performed during the concert or related to an aspect of musical performance in the show such as dance choreography, voice quality, or rap delivery.
- **Show** (topic): Tweets that addressed the staging, costuming, programming, and more technical aspects of the concert production, including the prerecorded VCRs.
- **Info** (topic): Tweets that relayed specific information about the concert such as the set list, access options to live streams, and translations of band members' speeches.
- **Members** (topic): Tweets about the members of BTS, identified individually or as a group, either by explicit mention or through excerpts of the concert such as edited stills, gifs, and videos with a discernible focus.
- **ARMY** (topic): Tweets that included references to the broader BTS fandom, either through direct mention of ARMY or by speaking in the collective voice such as "We were well fed today."
- **Self** (topic): Tweets that referred directly to the person posting through first person pronouns and/or verbal descriptions of their experience and reactions to what they were watching.

A few Tweet features were evaluated more systematically: the inclusion of **Media** as identified by hyperlinks, use of the most prominent concert **Hashtag**, mention of the performers' twitter account (**@BTS**), and Tweet length. The additional tone category of Shout Tweet (**Shouts**) was constructed by Tweet length and absence of media, as a test of the pattern found in the posting rate analysis. Media embeddings were additionally assess for whether they featured material from the performance, **Concert Video** and **Concert Stills**, when this could be verified.

A last note on coding challenges: as some of this analysis was performed many months after the performances, it was not possible the verify the content or even the type of media embedded in some of the sampled Tweets. The distribution of copyrighted materials often lead to Tweets and accounts getting suspended, resulting in entire Tweets disappearing or becoming partially obscured when quoted Tweets were deleted. If the subject of the absent media could not be inferred from context, the Tweet was dropped from the subsample and replaced.

Given the many constraints and complications in how the codes were developed and applied, the analysis that follows is principally descriptive with a focus on large scale trends.

6 Results: Tweet content analysis

The following section discusses patterns in the content identified in subsamples of Tweets taken from the Hashtag sampled Sowoozoo Day 1 concert Tweet dataset and the Kpop Stream sampled Permission to Dance on Stage Tweet dataset. With samplings stratified by Tweet popularity (Number of Retweets), some trends are similar between the two concert sets and others are noticeably different.

The bar graphs in Figures 6, 7 report the frequency of Tweet content categories and tones across the subsamples. Tweets from the first concert dataset evidently all included the concert hashtag, while the use of #PTD_ON_STAGE hashtag was rare in the Stream sampled subset, at most 20% in each range of popularity. Another

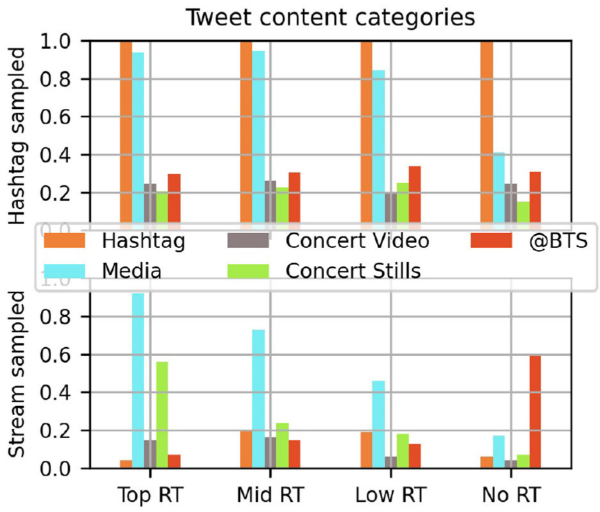

FIGURE 6
Frequencies of Tweet content categories in subsamples by popularity based on Retweets (RT) and sample source.

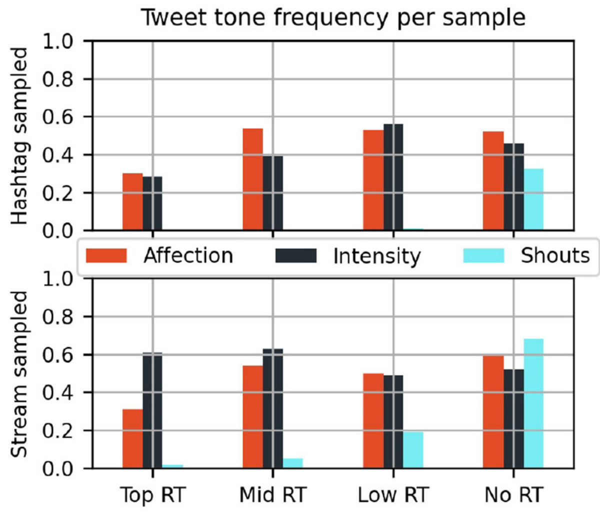

FIGURE 7
Frequency of Tweet message tones in subsamples by popularity and sample source.

contrast between these samplings is the inclusion of the performers' username. At all levels, BTS were @ed in roughly a quarter of Tweets using the #Sowoozoo hashtag, often with a slew of popular hashtags appended to the main text. During PTD on Stage, the more widely circulated Tweets caught in the Stream sample rarely mentioned this official account, however it was often in Tweets that were never retweeted.

Figure 6 also shows a strong trend by popularity across the two samplings: the prominence of embedded media in more popular posts. Less than 10% of either concert's top Retweets were all text, and the proportion drops across tiers of popularity. Maybe by design, the Hashtag sampled Tweets had higher rates of media inclusion at all levels of popularity. The particular value of different media types is harder to assess as so many had been taken down by the time of assessment. That surviving stills were substantially more popular than video in the later Stream sample may have been another strategic choice after fans saw their retweeted material disappear from previous concerts.

The tone of Tweets show distinct trends by popularity and sampling method. Direct expressions of affection were less common in the most widely shared posts (red bars of Figure 7), however intensity cues differed by popularity only in the Hashtag sample. Posts do not need to be staid in their expression to be popular, fandom-typical superlatives do not stop materials from being shared, however those who are posting may be strategic in choosing a more respectable tone for messages tagged for external visibility.

Included with the tone codes is also the frequency of Shout Tweets. These short and media-less Tweets rarely get to circulate after an initial posting, and they are more common in the Stream sample. This is consistent with the assumption that fans cheering online this way are more interested in expressing themselves in the moment than having these messages be heard by an official ear.

Figure 8 shows the relative frequency of topics with two prominent distinctions by popularity and one obvious difference between samplings. Around half of the most popular Tweets (Top RT) within the Hashtag sample are sharing practical information about the concert. Carrying privileged details like set lists with accurate track names and translations that could differ or be missing from the broadcast, these widely shared posts seemed to keep to the facts without affectionate or intensity tone markers. Such examples of fan labor are intentionally given hashtags to facilitate strangers finding the posts and making use of the work.

Tweets that mention the user posting (Self) shift in both samples by popularity. While there are a few widely Retweeted posts that use phrases such as "I am thankful," the posts in the low to no Retweet range are much more likely to explicitly mention the user's own feelings and experiences. This could be a consequence of their networks: it is much less costly to share personal feelings on accounts with a smaller numbers of followers (medians in Table 2). At the same time, explicit mentions of ARMY or even vague communal terms for the attending audience were not particularly common under any circumstances.

The principle difference in topic between the two samplings was how often BTS band members were the subject of Tweets in the Stream sample. At the higher levels of popularity, the majority of Tweets in this sample featured concert stills or video with a focus on individual members. Given the frequent use of Intensity tone cues, Tweets of shocked admiration, gregarious thirst, and overwhelming adoration for BTS dominated the popular range of the Stream sample. These forms of appreciative content were typical on Kpop Twitter, however they were generally not intended to be seen by the people being described. This distinction between sampling methods underlines how many of the Tweets and Retweets accompanying these concerts are materials and messages exclusively for other fans. In contrast, Tweets in the Stream sample

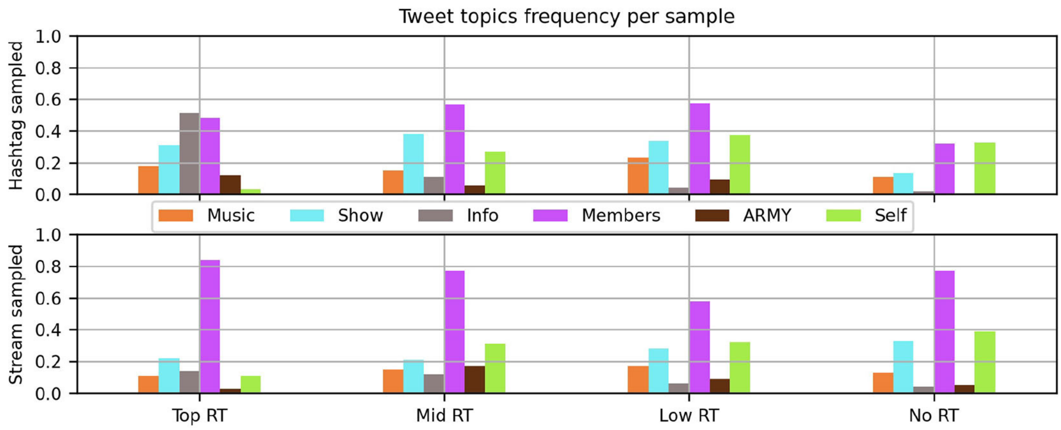

FIGURE 8
Frequency of coded topics per subsample, by popularity and sample source.

that seemed instead addressed to members, text starting with BTS's username, did not get retweeted at all.

While the posting rates and interaction timing made clear that these Twitter users tended to be very interested in the music performances of these live streamed concerts, it was not so frequently a topic of discussion, between 10 and 22% of each subset. Slightly more common were comments related to production choices (shown in Figure 8) particularly in the Retweeted hashtagged subsamples.

The most surprising absence from the content of these Tweets were mentions of the pandemic lockdown conditions that initially made live streamed concerts necessary. The first round of coding on half the Sowoozoo subsamples did not identify themes related to COVID-19 pandemic, performance restrictions, or the like because it never came up. A second search through the full databases of Tweet texts using a few keywords (virtual, pandemic, COVID, lockdown, and restriction) found only around 1,000 Tweets across posts during all concerts. The highest concentration were from Permission to Dance in LA, a show that had a face-to-face audience as well as those attending the live stream. About 0.5% of that concert's dataset included these keywords, wherein the majority were direct quotes of BTS member RM stating "Fuck COVID!" on stage.

7 Discussion

Much of the research on remote audiences has used concerts and audiences of a very different character than observed here: genres of music that rarely call for audience interaction, free concerts consumed more casually than an expensive in-person shows, new and unfamiliar broadcasting technologies, and small artificially constructed audiences. Here, instead, is captured unprompted activity from an extremely large (100, 000) paying audience attending highly anticipated performances for a community with a strong culture of active engagement during performances, extensive experience with live streaming, and access to an established networked space for live and near-synchronous fan-fan interaction. This dataset shows how a resourceful audience can extend and enrich their live stream concert experience with actions not supported by existing broadcasting platforms. Taken in combination, patterns in this distinct collection of fan Tweets during live streamed concerts have implications for how we understand what audience members add to concert performances, their own experiences and each others', and why so many went outside of the live stream platform to act and interact.

7.1 The audience's interest in the audience

For many fans of BTS, live stream concerts are as close as they will ever come to seeing the group perform live. Around the world, fans bought tickets and arranged their schedules to watch the concerts, some waking before dawn for the chance to see these seven on stage. And yet the rates of Likes and Retweets reported in our analysis of Tweet Timing demonstrate that many audience members were checking their Timelines during these broadcasts. Given the apparent value of these performances, why would so many be turning their attention away from the concert live stream to look at social media?

Social connectedness is an important motivation for attending concerts face-to-face (Kjus and Danielsen, 2014; Brown and Knox, 2017). The livechats on many broadcasting platforms allow some of this mutual awareness, a narrow channel over which everyone can shout to each other. When chat postings are in the hundreds, say Facebook Live streams of classical music concerts, participants can feel empowered by the chance to express their experience (Nguyen, 2018), however interactions are few and far between (Vandenberg and Berghman, 2023). On platforms with more active livechat practices, receiving direct acknowledgment of a comment is even more technically difficult because of the rapid rate of postings, and exchanges with people they know off-stream seem to be more social rewarding than responses from strangers (Vandenberg, 2022). And while people who comment frequently and in detail are more likely to feel like their feelings are shared with other live stream audience members (secondary analysis, Swarbrick, 2021), those willing to be so active are relatively few (1 in 5). Audience-audience interaction over live stream livechats seems more limited and onerous than many concertgoers want.

Already a proven point of access to both BTS's ARMY mutuals and interested strangers (Park et al., 2021a), Twitter offered these audience members an interesting alternative space for chat-like actions. Instead of dropping their comments in a churning live stream chatroom, thousands of audience members opted to prioritize "interpersonal communication" (Kjus and Danielsen, 2014) by shared Tweets where these would be shown to people they know. Whether in realtime or some minutes later, Twitter's array of engagement options then granted their followers a chance to acknowledge such Tweets directly with as little effort as clicking a heart icon or as much as writing a reply. Though we cannot say for certain what exactly each Like or Retweet action might mean (Park et al., 2021b), these engagements confirmed that someone else had seen the user's post and wanted the user to know it. Like eye-contact in a crowd, such light direct interactions may foster *ittaikan* between remote audience members (Tarumi et al., 2017).

The timing of Twitter engagement speaks to a negotiation of attention between what was happening on stage, sharing their own experiences (Original Tweet posting rates), and tracking what was happening in the audience (Retweet rates and estimated Like rates). There were inevitable time lags between posting a Tweet and seeing engagement from other users, particularly when the music called users' attention back to the concert live stream. However, asynchrony was always part of this social media platform. With an interface that only jumped to the latest material upon request, users were familiar with interpreting material presented as from the (recent) past. In contrast to busy livechats, the window of opportunity for engagement on any given Tweet extended for minutes, hours, even days after posting. This persistence of Tweets allows shared feeling and social connectedness between audience members to be reinforced well after the concert. The burst Twitter activity after the end of the concert stream looks a lot like the excited conversations between seat neighbors after an in-person show, even when much of the content being passed around was posted earlier, like in Figure 2.

The varied use of hashtags across these performances highlights these concert attendees' complex communication goals. In a livechat, any message would be broadcast to all watching the chat and potentially retained by the broadcasting platform. On a platform like Twitter, these online concert attendees could at least partially control the visibility of their comments. If they were only interested in the performers, their engagement would have been entirely focused on official accounts. Instead, filtering out Retweets of and Replies to official accounts only decreased these samplings by at most 20% of posts and 25% of unique users. Socially connected fans could also coordinate to share their concert excitement over more private channels. The public Twitter activity studied in this paper is the result of fans choosing to commune with a more manageable number of friends and strangers, as they would at a face-to-face show.

Still, the content posted can be intended for specific segments of the audience. Small accounts might use a hashtag to find wider engagement and build on their online community. Large accounts may instead be more selective of which posts carry hashtags, as these also invite scrutiny, both to the legality of the material being shared and to the tone and topics of discussion. Topics and tones of content that fans want to exchange with likeminded users without the risk of exposure to the performers or judgement by unsympathetic strangers. In-person, these reactions can be shared in the moment without permanent records. Online, fans still manage with the help of mitigating strategies like specialized terminology and the avoidance of keywords.

7.2 Audiences online vs. in-person

One of the most widely used tools for audiences at Kpop concerts is the camera phone. Fans use these both like opera glasses to zoom in and focus on action on a big stage and like cameras to preserve these precious moments from a "first-person aesthetic" (Glitsos, 2018), fulfilling the desire of a "possessive spectator" (Mulvey, 2006) with clips to be revisited. In an online broadcast, Retweets of extracted stream footage function very similarly. The work of capturing and processing live stream video takes technical resources and skills well beyond hitting a phone's record button. However, reblogging excerpts from fans capable of performing this work is easy and yields very similar results: a catalog of favorite moments to be reviewed and shared at will.

The Retweeting of information, like translations and set lists, is much like how audience members turn to their seat neighbors to ask what is happening and passing the news onto their accompanying friends. This kind of mutual support is especially important in multilingual and multi-cultural communities like Kpop fandom. A substantial amount of teaching is needed to help *baby ARMYs* (BTS fans who are new to the fandom) adapt to the extensive traditions of this subculture.

Of course, audiences at these shows are also accustomed to expressing intense excitement and joy, and the Shout Tweets demonstrate how strongly they desire to share these feelings, jumping to secondary platforms to scream as best they can with their followers and (using hashtags) with strangers too. Doing so on Twitter enabled their virtual screams to be "heard" (Charron, 2017) during and after the fact. Given the high flow of postings through these concerts, some Shout Tweets may pass without a chance to be liked. However, the resulting wall of Tweets shouting the same song title is easy to recognize as a parallel to the screams of fans at in-person concerts to the opening bars of favorite tracks (and to the collective rush of livechat crowdspeak.)

This virtual shouting also aligned with the patterns of behavior observed on the social music platform SoundCloud. A qualitative analysis of comments left by users on individual tracks, Hubbles et al. (2017) found these to be primarily short and positive toward the song or the artist while the use of Reply function was minimal. They characterized the purpose of such comments as a potential stand-in for mildly interactive experiences, creating a sense of social presence even without direct synchronous interaction (Ducheneaut et al., 2006). Posting on persistent platforms can also satisfy fans desire to demonstrate their worship of the artists, like being seen at the venue and sharing photos after the fact (Brown and Knox, 2017).

While this study cannot address the subjective experience of audience members during these live-stream performances, their observed activity suggests a great potential for rewarding expression and direct mutual recognition with friends and strangers, with just a little more asynchrony than is possible face-to-face.

7.3 Beyond Livechat

On live streaming platforms like Twitch.TV, or Kpop-oriented VLive (now part of Weverse), most of the strategies to coordinate commenting behavior are structured around communications from the audience to the performer (Jodén and Strandell, 2022). Topics are encouraged with repetition and the success of the communication is marked by a change of content in the live stream. During these concerts, as with other highly-produced live streamed concerts (Rendell, 2021), the performers being live streamed were not attending to the livechat in realtime. Other than a quick greeting before or after the show, there was no suggestion of attention from the performers to the audience's activity in this space. As such, the chat was left for the audience to interact with each other, without the coordinating influence of performer feedback or the cultivated shared culture built around popular streamer channels. Some of the audience used this broadcast platform feature during the performance, and it may have satisfied their need to express themselves, be seen, and feel like their experience was shared with a larger group of like-minded people. However, the technical impediments to social connection on this medium are numerous. The audience members' activity observed on Twitter during these shows suggests that a substantial number of saw a benefit to moving their interactions to a more hospitable space.

Besides offering convenient direct near- or a-synchronous interaction with mutuals and strangers, Twitter as a platform allowed for richer materials to be posted than a livechat. Much of what was most widely shared fit with the content tweeted from face-to-face shows (Bennett, 2014; Kjus and Danielsen, 2014): images and videoclips of the performances, privileged information like setlists, as well as more personal and affective reactions to the events. As is common for live-tweeted events, the number of accounts making original posts was much smaller than the network of users Retweeting and Liking what was share. However, unlike live Tweets from most face-to-face music performances, Twitter engagements appears to have been coming from users who were also attending the show. By propagating concert material and related fan commentary in a public networked social space, these twitter users are satisfying a branch of common concert audience activities unsupported by livechat.

While concert feed material like video excerpts were highly prized during and after these concerts, many of these Tweets were soon removed and some posting users suspended for uploading copyrighted material. For those capturing and sharing live stream concert footage, a sanctioned mechanism or channel could alleviate concerns around illicit distribution and heighten their sense of ownership and participation in the concert. Additionally, those who are only able to attend online (or "offline" after the performance) may get a more immersive experience from the first-person perspectives and feel more embedded in the audience. As many BTS fans will come for the realtime performance experience either way, even watching together the same tour show over multiple rebroadcasts, we question the financial risk of letting fans hold onto their favorite moments with personal clips.

The range of audience-to-audience interactions within broadcast platforms could be expanded in many ways, from recommending moments to friends and fans to sharing reactions big and small. Fans want to hear each other cheer and to feel heard by having their experiences acknowledged and mirrored in the people around them. This two-way connectivity needs to be fast, negotiable, and of a manageable scale. Fans want to choose when to attend to the stage or when to attend to their neighbors with a chance for low effort mutual recognition. Allowing concert attendees to find each other in the virtual crowd, attenuating the "roar" of the crowd, and to "capture" concert moments could greatly improve the audience experience. As this research shows, if the audience doesn't like the options for interaction within a broadcasting platform, they can and will seek it elsewhere.

8 Conclusions

Online concerts were embraced by many artists during the initial COVID-19 pandemic response, and fans around the world have tuned into these to see their favorite artists perform in realtime. Through analyses of Twitter data across four live stream BTS concerts, we found audiences members acting and interacting online throughout the shows. These fans leveraged their existing social networks on Twitter to recreate many common in-person audience behaviors such as posting Shout Tweets to cheer at the start of songs and capturing records of their favorite concert moments. Audience members shifted their attention between the concert streams and their curated view of other audience members reactions with less Twitter activity during music sets and big increases in posting activity when BTS was off stage. We also observed distinct patterns in what content audience members shared with a priority to Tweets carrying high quality information (translations and set lists) and edited video and stills from the concert feed. Lastly, these concert attendees were strategic in how they used the hashtags, dropping easily-searched markers from Tweets with content intended only for other fans to see.

This audience reconstructed a concert experience denied to them by geography and a pandemic by finding each other outside of the official online venue. Twitter, now X.com, may not always function as a reliable platform for this community, however it served to demonstrate how live stream concerts can still satisfy audiences' interest in expressions of excitement, mutual recognition, the capture of precious memories, and extending their celebration of collective fannish devotion well past the end of the broadcast.

Data availability statement

Reduced versions of the datasets presented in this study can be found in an online repository and with the open analysis Github repository: https://doi.org/10.6084/m9.figshare.24260452, https://github.com/finn42/Concert_Twt_Open/.

Ethics statement

Ethical approval was not required for the studies involving humans because this public social media activity was collected through licensed use of the Twitter Streaming API, in accordance with the platform's terms of service. The studies were conducted in accordance with the local legislation and institutional requirements. Written informed consent for participation was not required from the participants or the participants' legal guardians/next of kin in accordance with the national legislation and institutional requirements because this form of data collection was consented to in the user agreements. Additional steps to de-identify user accounts were taken before reporting and public release, further reducing risk to participants.

Author contributions

FU researched the literature, performed the analyses after data collection, and wrote the first draft of the manuscript. JL supported the data collection, research the literature, and contributed to the Sections 2 and 7 of the paper. SP researched the literature and contributed to the Sections 2 and 7 of the paper. FU, JL, and SP collaborated on the conceptualization of this study, edited the manuscript, and approved the final version of the manuscript. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fpsyg.2024.1214930/full#supplementary-material

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