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Rhythms of relief: perspectives on neurocognitive mechanisms of music interventions in ADHD

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Attention-deficit/hyperactivity disorder (ADHD) is a prevalent neurodevelopmental disorder characterized by multiple neurocognitive deficits. Research suggests that music interventions, both active and passive, may be an effective complementary method of addressing ADHD challenges. This narrative review discusses seven potential neurocognitive mechanisms through which music interventions may help mitigate or alleviate ADHD symptoms, including executive function enhancement, timing improvement, arousal regulation, default mode network modulation, neural entrainment, affective management, and social bonding facilitation. Our study synthesized evidence from ADHD-specific studies and examined parallels to other populations to identify possible pathways through which music therapy could exert its effect. The paper also discusses the implications of individualized music interventions tailored to specific neurocognitive profiles in ADHD, advocating additional research to refine and optimize these approaches. Overall, music therapy has substantial potential as a complementary treatment for ADHD, offering new avenues for addressing the psychosocial and cognitive aspects of this condition.

KEYWORDS

ADHD, music intervention, neurocognitive mechanism, executive function, brain activity, social bonding

1 Introduction

Music engages various aspects of brain activity. As an analogy of brain activity to music composition with music as a conductor, the conductor can adjust the pitch (i.e., neurotransmitters; Chanda and Levitin, 2013), shape the melody (i.e., brain regional activation; Tramo, 2001), and fine-tune the harmony (i.e., brain interregional coupling; Alluri et al., 2012). With this impact, 'music as medicine' is increasingly recognized as a therapeutic tool for neurological and psychiatric conditions (Sihvonen et al., 2017; Yinger and Gooding, 2014).

Recently, this therapeutic potential has been applied to attention-deficit/hyperactivity disorder (ADHD). ADHD is a neurodevelopmental condition characterized by core symptoms of inattention, hyperactivity, and impulsivity [American Psychiatric Association (APA), 2013]. It affects approximately 5% of youths worldwide, with a roughly two-to-one male-to-female ratio, and persists into adulthood in about two-thirds of cases (Faraone et al., 2021). The condition often impairs academic, social, and occupational functioning and has high comorbidity with other psychiatric disorders (Faraone et al., 2021). Decades of neurocognitive research have highlighted the mechanisms underlying ADHD (Faraone et al., 2021), guiding the development of new therapies. Music therapy, the professional use of music to optimize quality of life, may have a unique position in helping individuals with ADHD by targeting brain pathways that frontline interventions (e.g., stimulant medications and cognitive Behavioral therapy) do not effectively reach (Martin-Moratinos et al., 2023).

This narrative review contributes to the growing interest in music therapy for ADHD by examining its potential neurocognitive mechanisms. While previous studies have systematically reviewed the effects of music interventions on ADHD (e.g., Martin-Moratinos et al., 2023) or narrowly focused on specific neurocognitive mechanisms (Slater and Tate, 2018; Nigg et al., 2024), this review adopts a broader perspective. By mapping multiple possible mechanisms, it aims to inform the development of more mechanistic interventions in this emerging area.

The review is organized around the following considerations. First, it focuses on specific neurocognitive mechanisms through which music therapy may benefit individuals with ADHD. These mechanisms are all supported by a general mechanism: activity-dependent neuroplasticity, the ability of the brain to reorganize its structure, function, and connections in response to intrinsic or extrinsic stimuli (Ganguly and Poo, 2013). This brain property explains why music interventions address brain disorders (Sihvonen et al., 2017). Secondly, we discuss mechanisms based both on direct evidence (studies of music therapy in ADHD) and indirect evidence (studies of music therapy in other populations). Third, we adopt the broad definition of music therapy, distinguishing between active (or creative) therapy, passive (or receptive) therapy, and mixed therapy. Active therapy involves participation in music-making, such as musical improvisation with a therapist. Passive therapy involves listening to existing music. Mixed therapy combines elements of both.

2 Possible mechanisms

2.1 Executive function enhancement

A hallmark of neurocognitive deficits in ADHD lies in executive functions (EF), an umbrella term encompassing inhibitory control, working memory, and cognitive flexibility (Diamond, 2013). Compared to individuals with typically developing peers, those with ADHD usually perform less well on EF tasks (Cortese et al., 2012; Rubia, 2018). Many prevailing theories, such as the cognitive-energetic model (Sergeant, 2005) and the dual pathway model (Sonuga-Barke, 2005), highlight the role of EF deficits in causing ADHD symptoms, positioning EF as a key target in ADHD therapies. Music interventions align with this by engaging brain regions involved in EF, such as the prefrontal cortex, through rhythm-based tasks and auditory stimuli, potentially enhancing EF and thus mitigating ADHD symptoms.

Several preliminary studies suggest that music interventions can improve EF, particularly inhibitory control, in individuals with ADHD. Rickson (2006) found that active music interventions (instructional and improvisational activities, 30–45 min per session, 1 session per week for 8 weeks) significantly improved inhibitory control and ADHD symptoms in adolescents with ADHD. Jamey et al. (2024) reported improved inhibitory control in children with ADHD through an active music intervention (gamified rhythmic training, 30 min per session, 5 sessions per week, 2 weeks). Similarly, Dursun et al. (2021) reported improving inhibitory control in adolescents with ADHD using a passive music intervention (listening to filtered Mozart music and relaxing Turkish chants, 2 h per session, 5 sessions per week, 6 weeks). However, these promising findings are limited by experimental design: the first two studies used small and unblinded samples prone to bias, and the third was a case report lacking causal rigor. These limitations highlight the need for well-controlled trials to validate the efficacy of music interventions in improving EF in ADHD.

Further evidence of the beneficial effects of music interventions on EF is provided by behavioral and neuroimaging studies derived from other populations. EF was improved in typically developing children after active therapy, such as vocal and instrumental-based musical improvisation training (Bugos et al., 2022) and rhythmic movement-based activities (Bentley et al., 2023), as well as passive therapy, such as aural training (Frischen et al., 2019; Moreno et al., 2011), or active combined with passive therapy (Jaschke et al., 2018). The effect of music interventions on EF has also been reported in various clinical populations, including autism (Janzen and Thaut, 2018), dementia (Zhang et al., 2023a), and traumatic brain injury (Thaut et al., 2009). Neuroimaging studies also suggest that musical interventions can improve brain regional or network activities underpinning EF (Colombo et al., 2020; Koshimori and Thaut, 2019; Loui, 2020). It should be noted that music interventions appear to affect the subcomponents of EF in different ways. Among children, music interventions have a particularly profound impact on inhibitory control (Rodriguez-Gomez and Talero-Gutiérrez, 2022) which is a hallmark of ADHD (Sergeant, 2005; Sonuga-Barke, 2005). In contrast, among adults, music interventions appear more impactful on "hot" EF (Frischen et al., 2022). "Hot" EF refers to executive function performance in contexts influenced by emotions, rewards, or motivation, such as self-control during delayed gratification or social interactions (Salehinejad et al., 2021). In contrast, cold EF involves performance in neutral, emotion-free contexts, with hot EF primarily linked to the medial/orbital prefrontal cortex and cold EF to the lateral prefrontal cortex (Salehinejad et al., 2021).

2.2 Timing improvement

An alternative explanation for ADHD symptoms is the timing deficit hypothesis (Sonuga-Barke, 2005). The deficit manifests in multiple domains, including motor timing, perception timing, and temporal foresight, affecting tasks requiring synchronization, delay discounting, and duration discrimination, resulting in ADHD symptoms (Noreika et al., 2013). Meanwhile, timing is fundamental in music activities for controlling sound duration, coordinating rhythms, and conveying expressive content. Its broad involvement enables music interventions to provide an unparalleled opportunity to exercise timing deficits in ADHD.

The effect of music interventions on timing is supported by both direct and indirect evidence. One proof-of-concept study reported that rhythm-based active interventions improved motor and perceptual timing in children with ADHD, where longer training sessions were associated with greater improvements in timing abilities (Jamey et al., 2024). Indirect evidence comes from studies on movement disorders. A narrative review highlights that passive music interventions (e.g., listening to personalized music or rhythmic auditory cues) appear to enhance perceptual timing by increasing sensitivity to external physical cues, active interventions (e.g., engaging in rhythmic movement) appear to enhance motor timing through improved motor-perceptual coordination (Devlin et al., 2023). The increased behavioral performance may be attributed to various changes in the brain, including larger activation of perceptual and motor brain regions, increased connectivity between perceptual and motor regions, and greater alignment between internal brain rhythm and external rhythmic cues (Devlin et al., 2023). Molecularly, music interventions may affect timing by affecting dopamine. In general, dopamine serves as a reward prediction error signal that regulates the neural circuits of timing (Paton and Buonomano, 2018). Music is often characterized by predictable patterns (e.g., repetitive melodies), as well as surprises (e.g., sudden tempo changes), all of which boost dopamine release (Gold et al., 2019). It should be noted that previous studies mainly examined the role of music interventions in perceptual and motor timing. Future studies may examine whether music interventions can improve motivational timing in ADHD, given the role of dopamine in motivationally related timing (e.g., delayed gratification).

2.3 Arousal regulation

The above two mechanisms address the task-related deficits associated with ADHD. Several models propose that ADHD symptoms are due to a non-task-related deficit: brain underarousal. According to the optimal stimulation model, ADHD is characterized by a lower arousal state, leading individuals to seek additional stimulation to compensate for the lower arousal (Zentall and Zentall, 1983). ADHD symptoms can therefore be understood as stimulus-seeking behavior driven by lower brain arousal (Strauß et al., 2018; Zhang et al., 2018, 2019). A similar explanation is found in the cognitive-energetic model (Sergeant, 2005), which proposes that low arousal levels in ADHD disrupt the brain's ability to allocate mental resources effectively, causing difficulties with attention and executive function. These models form the basis for music interventions to manage ADHD symptoms. Music, with its rhythmic and engaging nature, provides a structured form of stimulation that enhances arousal, achieving a more optimal arousal state and improving ADHD symptoms.

Abikoff et al. (1996) and Pelham et al. (2011) reported that passively listening to music (e.g., playing background music during learning activities) helped children with ADHD focus on monotonous tasks (e.g., homework). These results can be explained by increased arousal based on the optimal stimulation model. Monotonous tasks are less stimulating environments, leading children with ADHD to seek additional stimulation to compensate for their low-level arousal, thus limiting their ability to behave properly in these tasks. In contrast, when monotonous tasks are accompanied by music, the auditory stimuli increase their arousal, reducing the need to seek additional stimulation to compensate for the lower arousal, resulting in better task focus. Notably, the optimal stimulation model can also predict that passive listening is not always beneficial - music may be detrimental to ADHD in engaging tasks in which ADHD does not need additional stimulation. However, this prediction has not been examined. Similar to the behavioral findings, a case study using EEG demonstrated that listening to classical music shifted the brain into a more alert state, suggesting that the music intervention increased arousal (Kiran, 2020).

Research from other populations supports the effect of music interventions on modulating arousal through both the autonomic nervous system (ANS) and the central nervous system (CNS). In Parkinson's patients, a passive music intervention (Neurologic Music Therapy, 3 times per week for 5 weeks) increased the arousal of the primary motor and auditory cortexes and their coupling (Buard et al., 2019). Similarly, in patients with minimally conscious states, a passive music intervention (listening to live, previously preferred music, 5 times per week for 4 weeks) induced changes in the ascending reticular activation system, indicating higher CNS arousal (Xiao et al., 2023). This study also found increased ANS arousal, which aligns with a study involving a passive music intervention (a single session of listening to clinician-selected rhythmic musical excerpts) in a healthy population (McPherson et al., 2019). It should be noted that McPherson et al. (2019) also used an active music intervention (a single session of improvisational expressive music making), which in contrast reduced ANS arousal, suggesting different impacts of music interventions on ANS arousal. Another study examining the effect of a mixed music intervention (singing and body percussion, and rhythmic music listening within one session, 1 session per week for 6 weeks) on arousal through questionnaires found that patients with substance use disorder and post-traumatic stress disorder reported increased arousal (Hakvoort et al., 2020).

2.4 Default mode network modulation

Deficits in the default mode network (DMN) represent another non-task-related deficit in ADHD. Most metabolic energy in the brain is expended on spontaneous activity. This activity follows an identifiable pattern involving a large-scale brain network, including the medial prefrontal cortex, posterior cingulate cortex, and parietal cortex (Raichle, 2015). While DMN is typically involved in self-directed thinking during rest, its proper deactivation is crucial for goal-directed performance (Raichle, 2015). ADHD often exhibits abnormal DMN activity, such as weakened connectivity within the DMN and failure to deactivate it during tasks, leading to difficulties in maintaining task engagement and regulating attention (Sutcubasi et al., 2020). Thus, interventions that address DMN deficits might benefit ADHD.

Neuroimaging studies highlight the role of music in modulating DMN activity. Taruffi et al. (2017) reported that sad music enhanced self-referential thought processes by strengthening DMN connectivity. Gould Van Praag et al. (2017) found that listening to naturalistic music shifted DMN activation patterns, promoting stress reduction. Similarly, Alluri et al. (2012) showed that naturalistic music dynamically engaged DMN regions through its rhythmic and tonal features. Furthermore, Belden et al. (2020) demonstrated that classical musicians exhibited enhanced DMN connectivity, reflecting long-term neuroplastic adaptations from music training.

Although there has been no research on ADHD, several studies have demonstrated that music interventions can improve DMN in other clinical populations. Mixed interventions (e.g., frequency discrimination plus music listening) have been shown to increase DMN activity, particularly in the posterior cingulate cortex, to improve tinnitus symptoms (Krick et al., 2017) and decrease hyperconnected DMN activity within sensory regions in individuals with traumatic brain injury (Martínez-Molina et al., 2021). Studies only involving a passive music intervention also reported increased DMN activity in the posterior cingulate cortex in individuals with fibromyalgia pain (Usui et al., 2020) and schizophrenia (Yao et al., 2020). This pattern of results raises questions about whether the effects observed in mixed music interventions can be attributed to the passive intervention component. There has been no research examining the influence of active music interventions alone on DMN. Moreover, one study found that individualized music selection can enhance the effect of music interventions on a range of brain connectivity (Wu et al., 2019). Future research should investigate whether this applies to those ADHD.

2.5 Neural entrainment

Atypical brain oscillations have been associated with ADHD symptoms and cognitive deficits (e.g., Zhang et al., 2017a, 2017b). Addressing these atypical brain oscillations has emerged as a promising approach for developing alternative ADHD treatments (Holtmann et al., 2014). Neural entrainment, the brain's ability to synchronize its neural oscillations with the rhythmic patterns of external stimuli, provides a powerful mechanism for targeting these irregularities (Thaut et al., 2015). Music interventions can leverage this phenomenon by using rhythmic elements to elicit brain oscillations that support desired cognitive functions (Thaut et al., 2015; Vuilleumier and Trost, 2015). For example, individuals with ADHD often exhibit reduced fast oscillations, which are closely linked to deficits in cognitive functioning (Zhang et al., 2017a, 2017b). Music interventions can employ rhythms that match the frequency of these fast oscillations, enhancing them through neural entrainment and thereby improving cognitive functioning.

The evidence supporting neural entrainment comes primarily from passive music interventions conducted in non-ADHD populations. An MEG study in a normal population found that when musical rhythms were played at frequencies below 8 Hz, brain oscillations also displayed that specific frequency and its harmonics for perceiving and decoding musical units (Doelling and Poeppel, 2015). Besides influencing music processing, this study also found that neural entrainment affected general cognitive processes based on the same brain oscillations. A second line of evidence comes from neurological disorders. Researchers used a specific passive music intervention – Neurologic Music Therapy – to elicit desired brain oscillations via neural entrainment (Thaut et al., 2015; Braun Janzen et al., 2022).

2.6 Affective management

Affective states are also difficult to manage for ADHD (Mulraney et al., 2016; Sandstrom et al., 2021). Affect consists of emotions and moods; emotions are intense, short-lived emotional responses to specific events or stimuli, while moods are diffuse, longer-lasting emotional reactions that are not necessarily tied to a particular event or stimulus. Both affective states are often dysregulated in ADHD. Emotional dysregulation is frequently observed throughout the lifetime of those with ADHD, significantly contributing to its psychosocial impairments (Shaw et al., 2014). Mood disorders are separate diagnoses in the DSM-5 [American Psychiatric Association (APA), 2013]. Those with ADHD are predisposed to mood disorders, such as disruptive mood dysregulation disorder (Mulraney et al., 2016) and bipolar disorder (Sandstrom et al., 2021). Drug therapies appear less effective at addressing affective dysregulation in ADHD (Lenzi et al., 2018), highlighting the need for alternative interventions to address affective difficulties. Music has long been known to moderate affective states and may serve as a unique stimulus to address affective dysregulation in ADHD.

Several systematic reviews have discussed how music interventions impact affective regulation in populations other than ADHD (e.g., Gold et al., 2009; Koelsch, 2014; Moore, 2013), and interested readers can refer to these sources for broader findings. Here, we focus specifically on the evidence related to ADHD. A study on adults with ADHD demonstrated that one-session listening to Mozart's music led to a decrease in negative mood (Zimmermann et al., 2019). The positive effect of a passive music intervention (listening to relaxing music, 15 min before and 30 min during each CBT session, 12 weekly sessions) on improving emotion was also found in a preliminary case report (Zemestani et al., 2023). Another study provided more nuanced insights into the effects on affective regulation in ADHD, highlighting that a mixed music intervention (improvisation and passive receptive listening to music, 50 min per session, 2 sessions per week, 12 weeks). alter neurophysiological processes relevant to affective regulation, such as 5-HT, cortisol, blood pressure, and heart rate (Park et al., 2023). Given these promising results, future research may explore how different types of music interventions (e.g., active vs. passive) impact specific aspects of affective regulation (e.g., emotional reactivity and mood stabilization) and their lasting impact on psychosocial functioning.

2.7 Social bonding

The inherent synchrony of music has historically served as a coalition signaling system that fosters social cohesion and trust among individuals - the social bonding theory of music (Savage et al., 2021). Meanwhile, social bonding poses another challenge for those with ADHD. Deficient social cognition involving prosody perception and the theory of mind is often observed in ADHD (Bora and Pantelis, 2016; Uekermann et al., 2010), leading to poor prosocial skills, aggressive conduct problems, and compromised quality of life (Arango-Tobón et al., 2023; Hay et al., 2010; Velő et al., 2021). Drawing on the social bonding perspective of music, it is plausible that music interventions could serve as an effective medium for cooperative learning, enabling individuals to align their intentions with group actions and potentially mitigating social impairments in ADHD.

A preliminary study using a pre-post design found that an active music intervention (group-based music movement to music and improvisation, 50 min per session, 1 session per week, 5 weeks) improved a range of social skills in ADHD (Gooding, 2011). Research from other populations lends further support to the effect of music interventions on social bonding. A recent review explored the influence of passive music interventions on prosocial behavior in typically developing populations (Grimani et al., 2024). This synthesis suggests that carefully designed music interventions, for example, focusing on factors like lyrics and the emotional effects of the music, can effectively promote prosocial behavior (e.g., donating money and volunteering). The second line of evidence comes from substantial autism research. It has been shown that active music interventions can enhance social bonding through multiple mechanisms, such as increasing social engagement (Thompson et al., 2014), increasing joint attention (LaGasse, 2014), improving social skills (Mössler et al., 2019), and fostering theory of mind (Silarat, 2022).

3 Discussion

This narrative review summarizes seven mechanisms by which music interventions can address neurocognitive deficits in ADHD, based on emerging studies and substantial research from other populations. Multiple components are often involved in music interventions. For example, an intervention could include both active and passive components, with each component further comprising multiple elements. As a result of this complexity, it might be possible for music interventions to simultaneously influence ADHD via multiple mechanisms (e.g., Jamey et al., 2024). On the other hand, the complexity also calls for future studies to isolate the causal effects of specific music components on ADHD.

Future studies should further tailor music interventions based on ADHD characteristics. Previous studies have used general music interventions to treat ADHD. In the meantime, research shows that certain rhythmic stimuli, such as white noise (Nigg et al., 2024) and binaural beats (Basu and Banerjee, 2023) can help to reduce ADHD symptoms and improve cognitive functioning. The rhythmic stimuli alone are not considered music, but they may be carefully incorporated into music interventions to enhance their effectiveness. Another approach to tailoring music interventions for ADHD is to prescribe interventions based on individual deficit profiles. The review revealed that music interventions may address several neurocognitive deficits. It should be noted that these neurocognitive deficits were mainly identified through group-level analyses. It is typical of ADHD to display heterogeneity in these deficits (Faraone et al., 2021). As a result of this heterogeneity, those with ADHD may respond differently to different treatments (e.g., non-pharmacological interventions; Zhang, 2023; Zhang et al., 2023b). Thus, music interventions may be tailored based on individual deficit profiles to achieve larger effects.

Overall, music interventions for ADHD are still in their infancy. In this review, we discuss potential mechanisms for studying the effects of music interventions on ADHD in the future. A more tailored approach to music interventions is necessary given the nature of neurocognitive deficits in ADHD.

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 authors.

Author contributions

ZL: Conceptualization, Writing – original draft, Writing – review & editing. D-WZ: Conceptualization, Writing – original draft, Writing – review & editing.

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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.2025.1476928/full#supplementary-material

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