TYPE Original Research
PUBLISHED 07 January 2025
DOI 10.3389/feduc.2024.1502396

Check for updates

OPEN ACCESS

EDITED BY
Daniel H. Solis,
Instituto Politécnico Nacional, Mexico

REVIEWED BY
Ana María Botella Nicolás,
University of Valencia, Spain
Ronnie Alejandro Videla,
Santo Tomás University, Chile
Alfonso Garcia De La Vega,
Autonomous University of Madrid, Spain

*CORRESPONDENCE
Serafina Pastore
serafina.pastore@uniba.it

RECEIVED 26 September 2024
ACCEPTED 20 December 2024
PUBLISHED 07 January 2025

CITATION
Eramo G, Pastore S, De Tullio M, Rossini V, Monno A and Mesto E (2025) The sound of science: a sonification learning experience in an Italian secondary school.
Front. Educ. 9:1502396.
doi: 10.3389/feduc.2024.1502396

The sound of science: a sonification learning experience in an Italian secondary school

Giacomo Eramo[1], Serafina Pastore[2]*, Mario De Tullio[1], Valeria Rossini[3], Alessandro Monno[1] and Ernesto Mesto[1]

[1]Department of Earth and Geoenvironmental Sciences, University of Bari Aldo Moro, Bari, Italy,
[2]Department of Research and Humanities Innovation, University of Bari Aldo Moro, Bari, Italy,
[3]Department of Education, Psychology, Communication, University of Bari Aldo Moro, Bari, Italy

Introduction: The present article reports on a case study aimed at improving STEAM education in secondary schools. It discusses the use of sonification as a teaching strategy to integrate music into science learning, using different approaches from data audification to parameter mapping into aural models and to the rewriting of song lyrics based on STEM topics.

Methods: A qualitative research study has been performed in a secondary school in the school district of Bari (South of Italy). More specifically, students' and experts' perceptions of experienced sonification activities have been collected through six rounds of focus group interviews.

Results: While there was a good improvement in student achievement in science, it is worth noting how musical activities also led to some benefits for students involved in the sonification workshops. The integration of music with STEM disciplines has promoted more cooperation and empathy among the students. Additionally, musical inputs can help students discover and regain interest in music. However, the study also highlighted the differences in teacher training and content knowledge, suggesting the need for future research to consider broader samples and experimental designs.

Discussion: Results and implications for educational research and practice are discussed considering the recent literature on STEAM. Finally, this study demonstrates the importance of a robust instructional design for sonification activities, so that they can be more effective, aligned with the school curriculum, and integrated into the classroom teaching-learning process.

KEYWORDS

STEAM, sonification, student learning, education, secondary school

1 Introduction

Over the last few years, several processes (i.e., migration, climate change, environmental threats, economic crises, the COVID-19 pandemic, and wars) have deeply affected our society. In this challenging scenario, the value of science has been strengthened as an expression of interconnected knowledge between the environment, society, economy, art, and policy institutions. Conceived as necessary for sustainable development and active and inclusive citizenship, mathematical, technical, and scientific competences are recognized as fundamental to develop and apply logical thinking, solve a range of problems in everyday situations, and explain the natural world through observation and experimentation (Hogan and O'Flaherty, 2022; Lederman and Lederman, 2019; Smith and Watson, 2019). Although the interest in STEM (Science, Technology, Engineering, Mathematics) has widely spread, becoming an "almost universal preoccupation" (English, 2016), the recent inclusion of Arts disciplines (e.g., humanities, social sciences, and fine arts) has emphasized the importance of creativity in students' development (Aguilera and Ortiz-Revilla, 2021).

Despite STEAM education being considered a priority in educational policies, there are still difficulties in teaching STEAM at school. These difficulties include low attractiveness of STEAM subjects for students, a strong gender bias in the approach to these subjects and in the development of academic scientific careers, effective inclusion of students with a disadvantaged background, a lack of evidence on students' learning outcomes in STEAM education, and low or ineffective preparation of teachers (García-Carmona, 2020). More specifically, as pointed out by Bautista et al. (2018), the prevailing educational model in schools continues to be the disciplinary model, where curriculum subjects are taught independently and in isolation. Recent studies, instead, confirm the inseparable link between teacher learning and student learning within STEAM education (Jiang et al., 2024).

Still today, one of the fundamental barriers toward STEAM is teachers' low level of preparation in designing and delivering integrated curricula (Kelley and Knowles, 2016). Furthermore, female students and students with special learning needs in scientific careers are often not effectively included (Moote et al., 2020; Mujtaba and Reiss, 2016). Nowadays, STEAM education research streams aim to:

- Attract more students and teachers to STEAM education;
- Break down the barriers between different subjects to integrate school curriculum and vocational guidance;
- Foster a deeper collaboration with universities and industry to develop STEAM teachers' skills;
- Develop teacher training activities to improve the quality of STEAM education;
- Reduce inequalities in access of scientific studies and carriers for women, ethnic minorities, and people with disabilities.

From this perspective, the present article reports a case study conducted within a broader research project aimed at enhancing STEAM education in secondary schools in Italy. More specifically, the research project, titled "The Sound of Science" focused on designing, developing, and implementing an innovative teaching strategy based on sonification. The goal was to incorporate music into science learning.

In the sections that follow, we first review the literature on STEAM education, which lays out the foundation for the framework adopted in the research project. Then, we describe how music can support the process of teaching and learning in science. Secondly, we illustrate the case study and analyze the perceptions of students and experts regarding the proposed STEAM activities (specifically, sonification). Finally, we discuss the implications for educational research and provide some suggestions for educational practice.

2 Conceptual framework and background

This study draws upon STEAM education and sonification concepts. Moreover, with the aim of investigating experts' and students' perceptions of sonification, the study is grounded in the literature on conceptions of teaching and learning activities.

2.1 STEAM education

Although a consensus has not been reached on the disciplines included within the STEM domain (Li et al., 2020), the term STEM education refers to the integrated and connected teaching of scientific-technological disciplines (Science, Technology, Engineering and Mathematics) through the use of real-world issues (Martín-Páez et al., 2019; Sanders, 2009) in contexts that allow students to make connections between school, community, work and business in order to develop the ability to compete in the new economy (Queiruga-Dios et al., 2019). While Rosicka (2016) pointed out how definitions in the literature cover a broad spectrum (from a mix-and-match or continuum approach, inter-and multi-disciplinary, through to a fully integrated view of STEM education) the recent literature on STEM education focused on four major themes:

- Teachers' competences;
- Integration of STEM disciplines;
- Active learning, and
- Student engagement and participation.

The main purpose of STEM education, from this perspective, is to improve the learning outcomes of students who will continue in careers associated with science or technological competence. Against the backdrop of Dewey (1934) epistemological perspective, STEM education represents a form of integrated education where learning is student-centered and based on real-life and authentic activities. Teaching fundamental skills and providing students with the knowledge needed to be active members of a democratic society are the main educational aims.

During the past decade, a more complex form of integration has emerged in the transition from STEM to STEAM. The difference between STEAM and STEM lies in the inclusion of the A for arts (Martín-Páez et al., 2019). The structured use of arts (A) in STEM is indicated as STEAM, which is a contextual curriculum in which the links between science, technology, engineering, math, and art subjects and the actual world are made to reinforce each other. The arts serve as a bridge between various concepts, as well as between the research world and society. Additionally, students are encouraged to use both hard and soft skills to solve challenges in STEAM courses (Quigley et al., 2019; Yakman, 2008). Indeed, some evidence supports how the inclusion of artistic processes in science can promote students' conceptual understanding and attitude toward science, involve them more actively in learning science and allow for a more realistic transdisciplinary learning experience.

The combination of art and STEM education can promote not only the coordination of various disciplines, but also the students' creativity and innovation ability and strengthen their artistic edification and their backgrounds in the humanities. In fact, STEAM education can be successfully integrated into ESD (Education for Sustainable Development), as in the Arts and Humanities (Hsiao and Su, 2021).

However, an agreed understanding of the nature and definition of STEAM does not exist.

The construct of STEAM education has been diversely conceptualized over the years. While some authors consider STEAM simply as a movement in search of innovative pedagogical experiences (Colucci-Gray et al., 2019), or as integrative classroom practices focused on solving real-world problems (Korea Foundation for the Advancement of Science and Creativity [KOFAC], 2017); others confer STEAM a higher status, defining it as an integrated teaching approach (Martin-Gordillo, 2019; Zamorano et al., 2018) or as a full-fledged educational model (Carmona-Mesa et al., 2019; Quigley et al., 2019; Yakman and Lee, 2012). Despite the ambiguity of the acronym, the proponents of STEAM education agree with the need for pedagogical innovation that breaks down boundaries between disciplines. From this perspective, teaching and learning activities that address problems in innovative and responsible ways should allow students to understand, assess, and successfully handle techno-scientific issues that arise in everyday life (Bautista, 2021).

With its halo of an ideal approach, the STEAM movement has rapidly extended within the education debate (García-Carmona, 2020). If, on one hand, in some educational systems (e.g., South Korea), it represents a core-curriculum aspect (Hong, 2016), on the other hand, STEAM education is considered more as a political objective (Domènech-Casal, 2018), rather than a pedagogical or didactic approach as such. Given this diversity of perspectives, Colucci-Gray et al. (2019) argue that STEAM constitutes a boundary object, that is, a construct shared by different communities and networks, each with a different understanding of its meaning (Bautista, 2021). Compared to traditional teaching methods, which are often teacher-centered and fragmented, the key component of STEAM education, instead, is integration. In fact, STEAM aims to connect disciplinary contents, promoting innovative student-centered settings and problem-based activities. Anyway, integration is something different from interdisciplinarity: STEAM pedagogy does not integrate the different fields in a way that they are not distinguishable anymore, but it makes the nature of those fields more explicit to students, connecting them through a relevant and wider context. So, an interdisciplinary approach helps recognize the concepts and processes which are typical of different fields (Andreotti and Frans, 2019). Additionally, some authors introduce the term transdisciplinarity to underline the further move toward the opportunity to decouple the specific language of a discipline from its original context, opening new possibilities for viewing and experiencing the same phenomenon from a different position (Burnard et al., 2022).

This kind of teaching fosters collaboration between educational practice and educational research. Spreading the culture of inclusion and social justice, STEAM promotes equity and enhances the differences between students in terms of personal and professional identity development.

Incorporating the benefits of scientific and artistic creativity (Lehmann and Gaskins, 2019; Silverstein and Layne, 2010), STEAM education practice is characterized by the promotion of students' convergent (common in STEM disciplines) and divergent thinking (common in the Arts) (Yakman and Lee, 2012). Providing students with an active, constructive, and critical role in their learning, STEAM education fosters collaborative work (Chien and Chu, 2018; Thuneberg et al., 2018). Moreover, STEAM seeks to encourage students' self-efficacy, confidence, and motivation toward techno-scientific learning (Clapp and Jimenez, 2016; Hong, 2016).

Although there is no consensus on the benefits of arts in terms of scientific learning outcomes, students who participate in arts learning experiences often improve their achievement even in other domains of learning and life. Arts nurture motivation to learn by emphasizing students' active engagement, disciplined and sustained attention, persistence, and provide diverse opportunities for communication and expression. More specifically, within the STEAM field, musical training in rhythm emphasizes proportion, patterns, and ratios expressed as mathematical relations. Using music in STEAM teaching, therefore, facilitates learning since the activation of cognitive and metacognitive processes is strongly encouraged. Moreover, the use of music improves memorization and learning through the participants' emotional and kinesthetic involvement. Some studies have shown that participation in music, especially in an instrumental way, is important for supporting academic achievement (Guhn et al., 2020). Students who participate in music-based activities enjoy the practices, their interest in music increases, they gain awareness that music could be used effectively in different fields (Dignam, 2024; Greenstein and Nita, 2023; Özer and Demirbatır, 2023).

The following section reports on how music supports student science learning.

2.1.1 STEM education, music, and sonification

As recalled by Nobel laureate Giorgio Parisi (Frova, 2014), music represents a high-dimensional information carrier. As an example, the amount of information contained in about 20 s of music stored in an mp3 file is equivalent to that of a novel like War and Peace. This feature has a great potential to be exploited in order to analyze, interpret, and communicate data (Sawe et al., 2020; Vines et al., 2019).

From this perspective, sonification is defined as the encoding of data into nonspeech sounds organized by an algorithm that ensures an objective, systematic, reproducible, and repeatable output (Hermann, 2008). Several techniques have been developed in the last decades, thanks to the increasingly sophisticated use of software and hardware, to create and process digital sounds (Grond and Hermann, 2012; Truax and Meelberg, 2016; United Nations, 2023). Moreover, digital sound synthesis and organization maximize both human and computer interactivity, creativity, and interpretability.

Although the First International Conference for Auditory Display (ICAD) in 1992 generally represents the birth of sonification as a structured knowledge field (Hermann, 2008), the idea of using musical analogies in connection with the description of natural phenomena has attracted several scientists over time. The analogy between sounds and planetary orbits, for example, dates back to Pythagoras (ca. 580–495 B.C.) (Godwin, 1992) and was later adopted by Kepler (1571–1630) and Copernicus (1473–1543). In this analogy, the Sun represents the fundamental sound of a series of sounds in mathematical relation that identify the planets (Gentner et al., 1997; Stephenson, 2016). A further example can be found in the studies of chemist John Newlands (1838–1898), who, in his theoretical elaboration of data on the recursiveness of properties of elements, proposed an interesting parallel between musical octaves and the similarities between the characteristics common to different elements, even before the formalization of Mendeleev's Periodic Table of Elements (Scerri, 2019).

On the other side, we can recall the work of Hindemith (1895–1963) (Bruhn, 2005), or the music references to chemistry, as in the case of Ionization by French composer Varèse (1883–1965) (Shreffler, 2006), or the motion of the planets, as in Cosmic Pulses by Stockhausen (1928–2007) (Stockhausen, 1989). While the use of mathematics as a tool to shape (tuning) and organize (texture and form) sounds is known from antiquity (Godwin, 1992), it is with the advent of the different types of atonal, serial, and electronic music that it became systematic (Iddon, 2023; Xenakis, 1992).

Recent sound representations of scientific phenomena include, for example, the sound of the microbiome as part of the Biota Beats project at MIT Boston (Kim et al., 2020), or sonifications of cosmic phenomena (Bank and Scafetta, 2022). To the same category belongs the sonification of a spider web (Su et al., 2020), of DNA (Plaisier et al., 2021; Temple, 2017), of earthquakes (Bloch et al., 2023), of gravitational waves (Valle and Korol, 2022), of silent epileptic seizures (Parvizi et al., 2018), or that of crystals (Monno et al., 2016). Moreover, the inverse use of sonification has been proposed as a tool to design new molecules, starting from the assumption that in music, like in materials, there is a hierarchical assembly of building blocks (Franjou et al., 2019; Mahjour et al., 2023; Milazzo et al., 2021; Wong et al., 2012). All these examples demonstrate the multidisciplinary nature of sonification work, where researchers, musicians, educators, and science communicators are engaged for three main aims: (1) scientific research; (2) outreach and education; and (3) artistic purposes (United Nations, 2023). These different aims provide a great array of sonification to represent various natural phenomena both in science and art, increasingly narrowing the gap between these two domains.

In the last decades, several studies have also reported the use of sonification strategies as aids for visually impaired or blind people (Abu Rass et al., 2023; Ahmetovic et al., 2023; Cavaco et al., 2013; Daunys and Lauruska, 2009; Presti et al., 2019).

The efforts made to sonify data of different nature may only result in curiosities without further meaning. This is exemplified by the attempts to obtain music from plants using electrodes to measure electrical potential differences applied to leaves and translating them into sounds (www.plantwave.com). In contrast, recent studies have explored the intriguing possibility that plants can use sounds as signals of their physiological status (Khait et al., 2023). Some of the "suggestive" sonifications, while interesting, have limitations in conveying information that can be utilized in education and outreach activities. However, if sonification is used as a means to access data that can reveal potentially significant signals for further investigation, it cannot replace rigorous mathematical analysis and modeling in scientific research. As reported in Hermann (2008), the systematic classification of available sounds reveals a complexity and potential that is not fully utilized. Hermann maintains that sound classification consists of Organized Sound and Unorganized Sound, with Organized Sound being intentionally organized by sound/interface developers. Organized sounds include music and functional sounds, which are complex structured signals organized on various levels. In Figure 1 a more inclusive definition of music is considered, in line with that proposed by Berio: "music is everything you listen to with the intention of listening to music" (Berio and Dalmonte, 2015, p. 7). Berio also acknowledges that unintentional sounds can be perceived as music. The poetics of John Cage represents a clear example of this definition, which includes silence, unintentional sounds, and randomness in Western music, traditionally considered an artificial and deterministic "time-object" (Kutnik, 1992).

Functional sounds are organized sounds that serve a specific function or goal, such as signal sounds in telephones or doorbells. Music can also serve functional aspects, such as demonstrating power (fanfare) or enhancing shopping mood (background music). Thus, sonification is a subset of functional sounds, serving communication, monitoring processes, or understanding data structure (see above). However, its result is not intended to be music. Musification can be considered a further subset in which musical representations of data are found, using higher-level musical elements like polyphony and tone modulation to captivate the listener (Coop, 2016; Gresham-Lancaster, 2012; Williams, 2016). The artistic intention of the musification may not meet all the requirements for sonification in scientific research (Bonet et al., 2016; Grond and Hermann, 2012).

Among the most common uses of music in STEM education we have the (re)writing of song lyrics to improve memorization (Crowther, 2012) or the use of rhythm for learning mathematical concepts (Bianchi et al., 2015; Upson, 2002). The creation of the Sonic Pi app in 2013 was oriented to facilitate the teaching of programming within schools by combining coding with music making (Aaron, 2016; Aaron et al., 2016). It was observed that Sonic Pi can foster positive attitudes toward programming, thanks to the enjoyment of making music with code and the gratification from listening to the result of coding (Banut, 2023; Petrie, 2022).

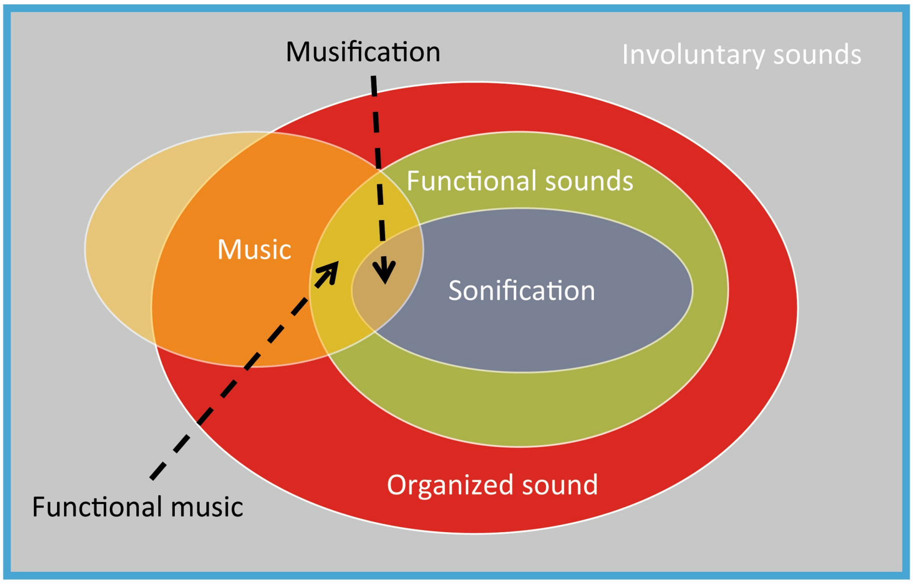

FIGURE 1
Map of sound discussed in text. Figure modified after Hermann (2008).

When considering sonification, relations with major theories of learning can be drawn. Emphasis on active engagement with information, using prior experiences and knowledge as a foundation, is a distinctive trait of constructivist learning theory (Fox, 2001) and aligns with the exploration of data in an active, multisensory way, engaging both auditory and cognitive faculties allowed by sonification. It also supports scaffolding and personal meaning-making, allowing students to interpret and re-interpret sounds based on their evolving understanding.

Sonification also supports contextual learning (Johnson, 2002), making abstract concepts more tangible and allowing students to connect new information with familiar sounds and experiences. Experiential learning theory (Kolb, 1984) emphasizes learning through concrete experiences, reflection, conceptualization, and experimentation. From this vein, sonification represents a precious tool in multimodal learning theories (Picciano, 2009) and complements situated learning theory (Lave and Wenger, 1991), providing insights for fields where sounds directly inform practice (e.g., physics, medicine, engineering).

Several sonification strategies are documented in STEM education (Ballora et al., 2018; Ezquerro and Simón, 2019; Sawe et al., 2020; Scaletti et al., 2022; Supper, 2012; Zanella et al., 2022).

Basically, all these strategies imply the use of digital sound and computer aided output (Supper, 2015) although the use of body percussion and instrumental performance of sonification is also attested (Romero-Naranjo, 2013; Fabra-Brell and Romero-Naranjo, 2017).

Aligning with this debate, the Sound of Science project used sonification as an education strategy to foster science learning performance of secondary school students in Italy.

Although it is not possible to establish a causal link between music training and the positive effects of music on learning in other disciplines (Sala and Gobet, 2020), individuals who have learned to play an instrument show increased ability to concentrate, memorization, and psychophysical benefits (Hallam, 2010). In addition, a music approach to STEM education could help solve the cognitive and social problems associated with digitization (Spitzer, 2014).

Incorporating sonification and the arts into STEM education can make learning more dynamic, inclusive, and enjoyable, ultimately contributing to the development of well-rounded and engaged learners (Izadi, 2017; Ruppert, 2006; Yakman, 2008). A more inclusive learning environment, accommodating students with visual impairments or learning disabilities, is a relevant short-term achievement of the STEAM approach. In addition, the two contexts (scientific and artistic) reinforce each other, and the transfer of knowledge may accumulate over time, revealing its effectiveness in multiple ways (Burton et al., 2000; Ruppert, 2006; United Nations, 2023).

2.2 Students' and experts' conceptions: a standpoint for practice analysis

What people believe (i.e., their conceptions) makes a difference to the strategies they might use in their practice. Conceptions work as a framework through which professionals see, analyze, and act within a specific life context. Conceptions also guide decision-making and help, for example, people to process new information and, accordingly, frame new situations. Several studies have highlighted how the focus on conceptions is relevant to understanding the dynamics involved in our lives. The growing research body spans multiple disciplines, fields (e.g., education, school actors, social workers, professionals, etc.), theoretical paradigms (e.g., phenomenography, hermeneutics), and methodological approaches.

Investigations of conceptions (e.g., leadership, power, governance, values, etc.) shed light on educational practices that sometimes cannot easily be analyzed in the real context. Despite the lack of consensus on an exact definition or their degree of explicitness, conceptions provide a meaningful lens through which to identify predictors and shaping factors of human behavior. However, conceptions represent a challenging research object because they are complex, hierarchical, multidimensional, and nested with individuals' values, formative and experiential background. While some studies report personal intentions or goals, beliefs about what others think and a sense of power to fulfill one's intentions shape behavior (Ajzen, 2011), other studies address how human social behavior is driven by implicit attitudes and other unconscious mental processes (Aarts and Dijksterhuis, 2000; Uhlmann and Swanson, 2004).

Continuing this last tradition, the present study has tried to describe students' and experts' conceptions of STEAM education and sonification workshops performed in the context of a secondary school in Italy.

3 The present study

The Sound of Science project, realized in 2022–2023, aimed to promote an engaging and active scientific learning experience for students by experimenting with a creative approach that combines music and science through sonification (Eramo et al., 2022; Eramo et al. 2018). More specifically, the research team has designed, developed, and delivered a creative approach to support secondary school students in the study of Biology, Chemistry, and Physics.

A working group, including the research team and two teachers specialized in Science and Physics, organized the workshops and defined the following subjects to implement the sonification strategies:

- Atomic structure and Periodic Table organization;
- Chemical bonds and compounds;
- Thermodynamic universe;
- Different aspects of entropy;
- Mitosis and meiosis;
- Genetic code.

Seven workshops of three hours were planned. Each workshop included a warm-up/introduction section (half an hour) aimed at recapping the scientific topic to be covered. Then, experts provided an explanation of the adopted sonification strategy (half an hour) and proposed drill and practice activities to students (two hours).

The first session performed was a sort of seminar with a presentation on human perception, symmetry, taxonomy of organized sounds, and sonification. During the drill sessions, students were encouraged to use their own musical instruments, although their practical tasks were mainly carried out through body percussion, singing, or using musical software like Sonic Pi (sonic-pi.net) and

Sibelius ©. An electric piano and a guitar were always present in the classroom to create a musical environment.

Various sonification techniques were employed in the various exercises. More specifically, audification of data was used to listen for variations in the properties of chemical elements. Parameter mapping, instead, was used for the sonification of crystals, proteins and thermodynamic transformations. Although it was not initially considered among the techniques to be used, in agreement with the students involved in the sonification workshops, it was decided to use a famous pop song to rewrite its lyrics on the subject of chemical bonds.

3.1 Study design and research method

This study, realized within The Sound of Science research project, is included in the qualitative research paradigm (Creswell, 2014). More specifically, a qualitative case study was performed as it allowed us to explore the sonification phenomenon at a micro-level (Werang and Leba, 2022). In contrast to an experimental research design, which seeks to test a specific hypothesis through deliberate manipulation of the environments, we have tried to capture rich, contextualized information that would be examined within the scope of the project. From this perspective, we checked the feasibility of the research project and provided comprehensive insights into the sonification. The case study design (Yin, 2019) has indeed been used to investigate the perception of participants (students and experts involved in the sonification workshops). This methodological perspective, therefore, allowed the authors to understand and interpret the reality of sonification as understood by its players (students and experts).

Through an in-depth analysis of the discourse, conceptions, points of view, and perceptions, this case study aimed to:

- Collect students' and experts' feedback about the sonification workshops;
- Understand participants' perceptions, as well as their expectations about the teaching-learning process in the STEM domain;
- Use students' feedback to instigate experts' reflection and revision of the sonification model

3.2 Participants

Data were collected through six focus-group interviews undertaken, respectively, with students ($N = 35$) and experts ($N = 6$) involved in the sonification workshops. More specifically, five focus groups collected the views and experiences of students from one secondary school in the school district of Bari, the chief town of the Apulia region (South of Italy). All participants were informed of the purposes of the study; anonymity and confidentiality of their responses were assured. They voluntarily consented to participate in the study.

3.3 Instruments

The focus-group interview track for students and experts comprised six questions divided into three main sections:

- Their perceptions of the sonification workshops in the process of learning science (difficulties, hindrances, drivers);
- The teaching-learning practice in the science domain;
- The feedback about the experience of the sonification workshops (what worked, what did not work).

The interviews, guided by the research questions, were unstructured enough to allow the discovery of new ideas and themes. The choice of the semi-structured interview allowed for a deep discussion with study participants (Bazeley, 2013; Strauss and Corbin, 1998). The interview scheme was modified as data collection proceeded to further refine questions that were not eliciting the intended information and to reflect the categories and concepts that required further development (Strauss and Corbin, 1998).

3.4 Data analysis

The focus group interviews were arranged in person.

The interviews were recorded as audio in order to perform an exhaustive analysis of the information collected. The information was then transcribed and analyzed. A numerical code was used to identify each focus group participant. In this way, the privacy of the participants was guaranteed. The content analysis (Neuendorf, 2002) considered the provisional categories defined in the track interview. Researchers used these categories to identify topics, coding, and categorize information. The process was reiterated until new concepts, ideas, and perceptions related to the research topics ceased to emerge (Table 1).

To endow the study with methodological qualitative rigor the following criteria were considered: dependency criterion; credibility; transferability; and auditability (or confirmability).

Results consider each of the following categories:

- Students' perceptions of STEAM;
- Students' and experts' feedback about the sonification workshop;
- STEAM activities (and sonification workshop) barriers for students and experts.

4 Main results

4.1 Students' perceptions of STEAM

When prompted to share their thoughts and conceptions about science, the relationship between science and music, and the effects of this relationship on their learning, students demonstrate plural points of view. Most of the interviewed students report different definitions of science. They move from very simplistic and scholastic definitions to more sophisticated ones:

> *Science is a way to know the world* [St_42]
>
> *Through science we can understand the world, the laws, the models that rule our world and how we have developed over time* [St_44]

Some students enthusiastically perceive the science-music connection they have experienced in the sonification workshops. In

TABLE 1 Coding scheme for semi-structured interviews with students and experts.

Category	Topics
Students' feedback	Positive and negative aspects of the sonification workshops experience Unexpected elements in the sonification workshops experience Differences between science lesson and sonification workshops Usefulness of sonification workshops experience for learning science What worked What did not work
Students' conceptions	How science and art are connected Usefulness of music in learning science contents Conceptions about learning science Differences and bias in student performance
Experts' feedback	Positive and negative aspects in the sonification workshops experience What worked What did not work Required revisions
Experts' conceptions	Sonification teaching potential Effectiveness of STEAM in teaching Students' perceptions of the usefulness of the sonification workshops experience.

this case, students stress how music makes the scientific content knowledge (e.g., the periodic table of elements) more interesting for them and, more specifically, how music offers different and new lenses through which science can be learned:

> *(The science-music connection) is very close to us adolescents. It allows us to understand how science is important for us* [St_25]
>
> Music allows student involvement and participation in the learning process [St_3]

Music makes science more interesting and appealing; it facilitates students' understanding of complex concepts. However, sometimes, students have a more instrumental vision of the relationship between science and music. Some of them, for example, reported how music can be considered only as a memorization strategy:

> *I noticed that I remember more things even though I have not taken notes* [St_33]
>
> *Music can help to memorize science contents, those that are difficult to remember* [St_36]

However, among our students, there are some who have a more skeptical perspective:

> *I don't think that music relates to science, so music can lead to developing an interest in science… but then, if you study science and you realize that you don't like it, music will not change this.* [St_40]

Other students, instead, point out how music can be used as an instrument of communication and dissemination of scientific discoveries:

> *With music and sounds you can easily understand science and communicate it* [St_37]

When asked to reflect on the relationship between the gender gap and learning achievements in science, interviewed students have very different perceptions. On one hand, students, contrary to the wide research evidence on this topic, affirm that they do not see this problem in their school. On the other hand, some students report experiences of teachers' assessment malpractices, such as teachers' stereotypes and biases. However, in both cases, music is not considered an effective solution to the gender gap problem.

4.2 Students' and experts' feedback about the sonification workshop

Students' active involvement is the most frequently positive aspect of the sonification experience reported by our interviewees. Students have appreciated how experts have explained and shared with them the learning goals and the rationale of the proposed learning activities. Consequently, students report:

> *There was no anxiety for assessment, and this was a positive aspect* [St_21]
>
> *It was different (from the teacher's lesson) because, generally, in the classroom teachers ask us to work alone and not in a group* [St_30]

Students, furthermore, point out the time they have had to talk to each other share and confront their ideas:

> *It was not the traditional way of studying science using textbooks* [St_3]

Experts' competence and passion for science was another aspect addressed by students who always refer to the astonishing nature of the sonification activities. Students correlate well-being, involvement, teamwork, and pleasure in learning science. Most of them remark how they were positively surprised by the sonification experience and how they developed a new, different, idea of science.

Aligned with this perspective, the focus group interview with experts confirms how the sonification workshops allowed students to experience school in a freer way.

Experts stress how the playful activities have been perceived by students as very engaging:

> *They don't want to go back home!* [Exp_2]
>
> *I think these teaching activities can represent an antidote to the risks of excessively using technologies. Dealing with the learning task students have been called to reactivate their knowledge and capacities* [Exp_4]

> *We have taught science in a different way!* [Exp_6]
>
> *What was crystal clear was the great desire of students to live school in terms of social experience (…) they want to live school as a place where they are recognized for what they are able to do* [Exp_5]

Although experts acknowledge the validity of the sonification workshop in terms of content knowledge, instructional strategies, and student involvement, they also highlight some difficulties. These difficulties include issues with warm-up activities and the initial skeptical behavior of students. However, this initial negative reaction was counterbalanced by the increasing interest that students demonstrated during the sonification process.

> *Then, some students were curious about the sonification of new science contents* [Exp_5]
>
> *At the end they were able to understand when they have to use the body percussion without my presence or my prompts* [Exp_4]

4.3 Sonification workshop barriers

When invited to reflect on the main hindrances or criticalities related to the sonification workshop, all students report the same two aspects: the duration of the proposed activities and the unbalanced proportion of theory and practice. In the first case, students criticize the fact that sonification activities were scheduled in the afternoon, after the school day.

> *I have to be honest, at some point I realized I was sleeping* [St_24]
>
> *Staying there, after more than two hours was hard for us* [St_25]
>
> *I think that if they (the experts) had been more concise and left more room for practice, it would have been better* [St_26]
>
> *I would change only one thing: not the fact that there was a theoretical part, but its length. Because, in the end, it was very interesting* [St_3]

Reflecting on the main difficulties in the implementation of the sonification activities, experts stressed students' initial prejudice about the proposed activities. According to the experts, students initially considered the sonification workshop as an additional activity focused more on socialization and entertainment.

> *They come to the workshop without notebooks, as if they have to spend their time in leisure* [Exp_5]

One of the reasons is represented by the modality in which the sonification workshop was presented to students by the school teachers. For this reason, the experts recognize the need to better align their activities with the school's curriculum design and teachers' learning goals. A closer collaboration with school teachers should/would ensure that the sonification is perceived as a learning activity and not just a socialization opportunity. Furthermore, the organization of the sonification would be more responsive to students' learning needs, especially in terms of the length of time for the activities or the learning spaces.

> *We should have been at school since the introduction teachers made of the sonification. In this way it would have been clear that this activity was the result of a university-school partnership and not an extemporary event* [Exp_1]

A better synergy between STEAM activities like sonification and curricular activities is needed. In this perspective, experts confirm that the lack of assessment of student learning during sonification is a negative aspect. Although during the school semester, teachers registered a good improvement in student achievement in science, without specific measures of learning related to the sonification experience, a correlation is not possible. Another important aspect to consider in redesigning sonification activities is the issue of students' music literacy. Having students with different levels of music literacy can be challenging for experts and discriminatory for students. Therefore, the activities must be carefully planned and developed.

5 Discussion

The positive aspects generally ascribed to STEAM education are all recalled by the interviewed students. Music and sonification have helped them not only to memorize some challenging contents (e.g., chemical nomenclature), but have also fostered the activation of their cognitive and metacognitive abilities in the learning process (Bertrand and Namukasa, 2020; Lehmann and Gaskins, 2019; Silverstein and Layne, 2010). The sonification experience, for most of the participants, has instigated a reflection on their learning transfer modalities and stimulated a revision of their learning strategies to maximize their cognitive efforts and achievement. Moreover, music theory rudiments and musical examples provided during drills allowed students to access art music which is generally considered less attractive by younger people (Eisentraut, 2012).

Students have realistically experienced inquiry-based learning and developed a creative, unusual, scientific approach during the sonification workshops. Their previous perceptions of science as something rigorous, with rigid cognitive structures (Prengaman, 2019), have been challenged through the sonification experience, which has demonstrated how it is possible to incorporate the benefits of scientific and artistic creativity in the learning process (Lehmann and Gaskins, 2019). In the first phase of the sonification workshops, students have had to shift from the dichotomic categories of science (logic, rigor, objectivity) and art (illogic, creativity, subjectivity) to a pluralistic approach that recognizes cross-discipline contamination. The awareness of existing multiple intelligences (Gardner, 1999) in each human being is an added value on a personal and social level. Group music activities, in fact, promote synchronization, coordination, cooperation, and empathy (Clayton et al., 2020; Hatfield et al., 1993; Romero-Naranjo, 2013).

This aspect represents an important result in terms of innovation within the context of the Italian secondary school, which is generally perceived by students as an unengaging and unmotivating learning environment focused solely on the repetition of traditional content knowledge. The adoption of new educational approaches, such as sonification, which introduces new forms of collaboration between STEM and artistic disciplines, has been perceived as a disruptive teaching and learning activity. However, students have gradually become aware of this over time through the various sonification workshops that have been conducted. As a result, students have acknowledged that initially, they were more interested in the social and interpersonal aspects of the sonification workshops. Over time, however, they recognized these activities as formal learning experiences within the school, specifically designed to achieve specific learning objectives aligned with the school curriculum.

The appealing effect of STEAM education represents a powerful lever to be used in school contexts characterized by traditional, passive, and teacher-centered instruction. However, as the results of the present case-study confirm, the risk of misunderstanding the rationale of proposed STEAM activities has to be carefully considered to avoid identifying this teaching innovation only in terms of leisure moments or diversionary practices. The experts' feedback and reflections confirm, indeed, how it is important to systematically design the STEAM activities aligning them with the school curriculum and the teachers' instructional practices within the classroom.

6 Conclusions, limitations, and implications

Caution needs to be exercised in interpreting the findings of this case study. The sample was small and not necessarily representative of the general secondary school student population in Italy. Future research should attempt to consider broader samples, as well as different research designs, such as experimental ones. Using quantitative measures such as pre-and post-tests to assess students' learning outcomes would allow for a more systematic evaluation of the impact of sonification on learning. Furthermore, the effects of different variables would be effectively detected (e.g., students' gender, different targets of students, different groups of schools).

It is worth noting, furthermore, that for this study, an urban secondary school in the Apulia school district was selected. This scientific teaching and assessment context can differ dramatically from schools in other settings across the country.

Finally, the proposed STEAM activities, and more specifically, the sonification workshops, have been conducted by experts (in this case, university faculty members) rather than school teachers. The differences in teacher training, content knowledge, and pedagogical content knowledge can vary significantly. Therefore, future research should consider teacher professional development and training initiatives aimed at preparing teachers for STEAM education. Promoting real changes in teaching and learning calls for a greater range of strategies on the importance of STEAM education. Among the more strategic investments of resources, teacher education (both pre-and in-service) could be an effective lever to rethink policy to favor STEAM as an integral part of educational innovation.

Music's approach to STEM subjects in the classroom provides beneficial effects on both an individual and interpersonal level. Musical inputs to students may give them the opportunity to discover art music, in some cases probably unattainable otherwise. Another individual benefit may be the renewed interest in music in students who have studied a musical instrument in the past but then stopped. Group musical activities, in this case based on sonification, are recognized to have great potential to generate an affective dimension and reinforce social bonds, promoting social inclusion.

Despite variability in definitions, theoretical foundations, and methodological approaches of STEAM education, our study participants are convinced of the value and potential of STEAM education. Further research is needed in this field. To move toward a more effective understanding of STEAM effectiveness, a focus on teaching and learning strategies is required. At the same time, a detection of teachers' and students' conceptions, such as the study reported above, can be helpful in shedding light on contextual and cultural aspects that affect STEAM education.

Data availability statement

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

Ethics statement

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. Written informed consent for participation in this study was provided by the participants' legal guardians/next of kin.

Author contributions

GE: Funding acquisition, Investigation, Resources, Supervision, Visualization, Writing – original draft, Writing – review & editing. SP: Formal analysis, Investigation, Methodology, Supervision, Writing – original draft, Writing – review & editing. MD: Conceptualization, Investigation, Writing – original draft. VR: Investigation, Writing – original draft. AM: Conceptualization, Investigation, Writing – original draft. EM: Conceptualization, Investigation, Writing – original draft.

Funding

The author(s) declare that financial support was received for the research, authorship, and/or publication of this article. The research was financially supported by the University of Bari Aldo Moro with the research program "Horizon Europe Seeds." Project title "The Sound of Science(s): suoni per la didattica STEAM e la comunicazione scientifica" (SOSTEAM, S65).

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.

Generative AI statement

The authors declare that no Generative AI was used in the creation of this manuscript.

Publisher's note

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

References

Aaron, S. (2016). Sonic pi – performance in education, technology and art. *Int. J. Perf. Art Dig. Med.* 12, 171–178. doi: 10.1080/14794713.2016.1227593

Aaron, S., Blackwell, A. F., and Burnard, P. (2016). The development of sonic pi and its use in educational partnerships: co-creating pedagogies for learning computer programming. *J. Mus. Tech. Educ* 9, 75–94. doi: 10.1386/jmte.9.1.75_1

Aarts, H., and Dijksterhuis, A. (2000). Habits as knowledge structures: automaticity in goal-directed behavior. *J. Pers. Soc. Psych.* 78, 53–63. doi: 10.1037/0022-3514.78.1.53

Abu Rass, S., Cohen, O., Bareli, E., and Portnoy, S. (2023). Comparing performance and preference of visually impaired individuals in object localization: tactile, verbal, and sonification cueing modalities. *Technologies* 11:127. doi: 10.3390/technologies11050127

Aguilera, D., and Ortiz-Revilla, J. (2021). STEM vs. STEAM education and student creativity: a systematic literature review. *Educ. Sci.* 11:331. doi: 10.3390/educsci11070331

Ahmetovic, D., Avanzini, F., Baratè, A., Bernareggi, C., Ciardullo, M., Galimberti, G., et al. (2023). Sonification of navigation instructions for people with visual impairment. *Int. J. Hum Comp. Stud.* 177:103057. doi: 10.1016/j.ijhcs.2023.103057

Ajzen, I. (2011). The theory of planned behaviour: reactions and reflections. *Psychol. Health* 26, 1113–1127. doi: 10.1080/08870446.2011.613995

Andreotti, E., and Frans, R. (2019). The connection between physics, engineering and music as an example of STEAM education. *Phys. Ed.* 54:045016. doi: 10.1088/1361-6552/ab246a

Ballora, M., Roman, C., Pockalny, R., and Wishner, K. (2018). Sonification and science pedagogy: preliminary experiences and assessments of earth science data presented in an undergraduate general education course. *Proc. Int. Conf. Aud. Disp.* 213–218. doi: 10.21785/icad2018.004

Bank, M. J., and Scafetta, N. (2022). Scaling, Mirror symmetries and musical consonances among the distances of the planets of the solar system. *Front. Astron. Spa. Sci.* 8:758184. doi: 10.3389/fspas.2021.758184

Banut, M. (2023). Using the sonic pi application for educational purposes. A literature review. *Educatia* 21, 108–119. doi: 10.24193/ed21.2023.26.12

Bautista, A. (2021). STEAM education: contributing evidence of validity and effectiveness. *J. Stud. Educ. Dev./Infancia Aprendizaje* 44, 755–768. doi: 10.1080/02103702.2021.1926678

Bautista, A., Toh, G. Z., Mancenido, Z., and Wong, J. (2018). Student-centered pedagogies in the Singapore music classroom: a case study on collaborative composition. *Aust. J. Teach. Educ.* 43, 1–25. doi: 10.14221/ajte.2018v43n11.1

Bazeley, P. (2013). Qualitative data analysis: Practical strategies. London: Sage.

Berio, L., and Dalmonte, R. (2015). Intervista sulla musica. Bari: Giuseppe Laterza & Figli Spa.

Bertrand, M. G., and Namukasa, I. K. (2020). Steam education: student learning and transferable skills. *J. Res. Innov. Teach. Learn.* 13, 43–56. doi: 10.1108/JRIT-01-2020-0003

Bianchi, A., Cuomo, C., Curti, G., Lentini, D., Magnani, N., and Vagni, R. (2015). Doremat, la Musica della Matematica. Insegnare e imparare la Matematica con la Musica. Digital Index Editore. Available at: https://www.digitaldocet.it/le-collane-di-digital-docet/21-risorse-didattiche-digitali/46-doremat-la-musica-della-matematica-il-testo (Accessed December, 27, 2024).

Bloch, W., Metzger, S., Schurr, B., Yuan, X., Ratschbacher, L., Reuter, S., et al. (2023). The 2015-2017 Pamir earthquake sequence: foreshocks, main shocks and aftershocks, seismotectonics, fault interaction and fluid processes. *Geophys. J. Int.* 233, 641–662. doi: 10.1093/gji/ggac473

Bonet, N., Kirke, A., and Miranda, E. (2016). 'Sonification of Dark Matter: Challenges and Opportunities', Proceedings of the Sound and Music Computing Conference. Available at: https://pearl.plymouth.ac.uk/sc-research/4 (Accessed December, 27, 2024).

Bruhn, S. (2005). The musical order of the world: Kepler, Hesse. Hindemith: Pendragon Press.

Burnard, P., Colucci-Gray, L., and Cooke, C. (2022). Transdisciplinarity: re-visioning how sciences and arts together can enact democratizing creative educational experiences. *Rev. Res. Ed.* 46, 166–197. doi: 10.3102/0091732X221084323

Burton, J. M., Horowitz, R., and Abeles, H. (2000). Learning in and through the arts: the question of transfer. *Stud. Art Educ.* 41, 228–257. doi: 10.2307/1320379

Carmona-Mesa, J. A., Arias-Suárez, J., and Villa-Ochoa, J. A. (2019). "Formación inicial de profesores basados en proyectos para el diseño de lecciones STEAM" in Revolución en la Formación y la Capacitación para el Siglo XXI. ed. E. Serna, vol. *1. 2nd* ed (Editorial Instituto Antioqueño de Investigación), 483–492.

Cavaco, S. J., Henriques, T., Mengucci, M., Correia, N., and Medeiros, F. (2013). Color sonification for the visually impaired. *Proc.Tech.* 9, 1048–1057. doi: 10.1016/j.protcy.2013.12.117

Chien, Y.-H., and Chu, P.-Y. (2018). The different learning outcomes of high school and college students on a 3d-printing STEAM engineering design curriculum. *Int. J. Sci. Math. Educ.* 16, 1047–1064. doi: 10.1007/s10763-017-9832-4

Clapp, E. P., and Jimenez, R. L. (2016). Implementing STEAM in maker-centered learning. *Psychol. Aesthet. Creat. Arts* 10, 481–491. doi: 10.1037/aca0000066

Clayton, M., Jakubowski, K., Eerola, T., Keller, P. E., Camurri, A., Volpe, G., et al. (2020). Interpersonal entrainment in music performance: theory, method, and model. *Music. Percept.* 38, 136–194. doi: 10.1525/mp.2020.38.2.136

Colucci-Gray, L., Burnard, P., Gray, D., and Cooke, C. (2019). A critical review of STEAM (science, technology, engineering, arts, and mathematics). *Oxf. Res. Encycl. Educ.* 1-22. doi: 10.1093/acrefore/9780190264093.013.398

Coop, A. D. (2016). Sonification, Musification, and synthesis of absolute program music. *Proc. Int. Conf. Audit. Disp.* 177–183. doi: 10.21785/icad2016.030

Creswell, J. W. (2014). Research design: Qualitative, quantitative. Sage, London: And Mixed Methods Approaches.

Crowther, G. (2012). Using science songs to enhance learning: an interdisciplinary approach. *CBE Life Sci. Educ.* 11, 26–30. doi: 10.1187/cbe.11-08-0068

Daunys, G., and Lauruska, V. (2009). "Sonification system of maps for blind: alternative view" in Universal access in human-computer interaction. Intelligent and ubiquitous interaction environments. UAHCI 2009. Lecture notes in computer science. ed. C. Stephanidis, vol. *5615* (Berlin, Heidelberg: Springer).

Dewey, J. (1934). Art as experience. London: George Allen and Unwin LTD.

Dignam, C. (2024). Harmonies on the string: exploring the synergy of music and STEM. *Intern. J. Tech. in Ed. Scien. (IJTES)* 8, 491–521. doi: 10.46328/ijtes.571

Domènech-Casal, J. (2018). Aprendizaje basado en proyectos en el marco STEM: Componentes didácticas para la competencia científica. *Ápice. Rev. Educ. Cient.* 2, 29–42. doi: 10.17979/arec.2018.2.2.4524

Eisentraut, J. (2012). The accessibility of music: Participation, reception, and contact. Cambridge: Cambridge University Press.

English, L. D. (2016). STEM education K-12: perspectives on integration. *Int. J. STEM Educ.* 3, 1–8. doi: 10.1186/s40594-016-0036-1

Eramo, G., Monno, A., Mesto, E., Ferilli, S., and De Tullio, M. (2018). Aural structures: music as a tool to describe crystals and their origin. *EDULEARN18* Proceedings, 4098–4105. doi: 10.21125/edulearn.2018.1036

Eramo, G., Rossini, V., Pastore, S., Muschitiello, A., Monno, A., Mesto, E., et al. (2022). The sound of science (S): a sound-based project for inclusive STEAM education and science communication. *EDULEARN22 Proc*, 7130–7134. doi: 10.21125/edulearn.2022.1673

Ezquerro, L., and Simón, J. L. (2019). Geomusic as a new pedagogical and outreach resource: interpreting geoheritage with all the senses. *Geoheritage* 11, 1187–1198. doi: 10.1007/s12371-019-00364-3

Fabra-Brell, E., and Romero-Naranjo, F. J. (2017). Body percussion: social competence between equals using the method bapne in secondary education (design research). *Proc. Soc. Behav. Sci.* 237, 1138–1142. doi: 10.1016/j.sbspro.2017.02.168

Fox, R. (2001). Constructivism Examined. *Oxf. Rev. Ed.* 27, 23–35. doi: 10.1080/03054980125310

Franjou, S. L., Milazzo, M., Yu, C.-H., and Buehler, M. J. (2019). Sounds interesting: can sonification help us design new proteins? *Ex. Rev. of Prot.* 16, 875–879. doi: 10.1080/14789450.2019.1697236

Frova, A. (2014). Armonia celeste e dodecafonia. Milano: Rizzoli.

García-Carmona, A. (2020). STEAM, ¿una nueva distracción para la enseñanza de la ciencia? *Ápice. Rev. de Educ. Cien.* 4, 35–50. doi: 10.17979/arec.2020.4.2.6533

Gardner, H. (1999). Intelligence reframed: Multiple intelligences for the 21st century. New York: Basic Books.

Gentner, D., Brem, S., Ferguson, R., and Wolff, P. (1997). "Analogy and creativity in the works of Johannes Kepler" in Creative thought: An investigation of conceptual structures and processes (Washington DC: American Psychological Association), 403–459.

Godwin, J. (1992). The harmony of the spheres: The Pythagorean tradition in music. Simon and Schuster, Rochester.

Greenstein, S., and Nita, G. B. (2023). The harp project: collective learning at the intersection of the mathematical and musical arts. *Primus* 34, 284–301. doi: 10.1080/10511970.2023.2282547

Gresham-Lancaster, S. (2012). Relationships of sonification to music and sound art. *AI Soc.* 27, 207–212. doi: 10.1007/s00146-011-0337-3

Grond, F., and Hermann, T. (2012). Aesthetic strategies in sonification. *AI Soc.* 27, 213–222. doi: 10.1007/s00146-011-0341-7

Guhn, M., Emerson, S. D., and Gouzouasis, P. (2020). A population-level analysis of associations between school music participation and academic achievement. *J. Educ. Psyc.* 112, 308–328. doi: 10.1037/edu0000376

Hallam, S. (2010). The power of music: its impact on the intellectual, social and personal development of children and young people. *Int. J. Mus. Educ.* 28, 269–289. doi: 10.1177/0255761410370658

Hatfield, E., Cacioppo, J. T., and Rapson, R. L. (1993). Emotional contagion. Current directions. *Psych. Sci.* 2, 96–100. doi: 10.1111/1467-8721.ep10770953

Hermann, T. (2008). Taxonomy and definitions for sonification and auditory display. Proceedings of the 14th international conference on auditory display (ICAD2008). International Community for Auditory Display. Available at: http://hdl.handle.net/1853/49960 (Accessed December, 27, 2024).

Hogan, D., and O'Flaherty, J. (2022). Exploring the nature and culture of science as an academic discipline: implications for the integration of education for sustainable development. *Inter. J. Sust. High. Ed.* 23, 120–147. doi: 10.1108/IJSHE-06-2021-0236

Hong, O. (2016). STEAM education in Korea: current policies and future directions. *Asian Res. Pol.* 8, 92–102.

Hsiao, P.-W., and Su, C.-H. (2021). A study on the impact of STEAM education for sustainable development courses and its effects on student motivation and learning. *Sust.* 13:3772. doi: 10.3390/su13073772

Iddon, M. (2023). The Cambridge companion to serialism. Cambridge (UK): Cambridge University Press.

Izadi, D. (2017). Arts in science education. *Canad. J. Phys.* 95:xliii–xlvi. doi: 10.1139/cjp-2016-0590

Jiang, H., Chugh, R., Zhai, X., Wang, K., and Wang, X. (2024). Longitudinal analysis of teacher self-efficacy evolution during a STEAM professional development program: a qualitative case study hum. *Soc. Sci. Com.* 11:1162. doi: 10.1057/s41599-024-03655-5

Johnson, E. B. (2002). Contextual teaching and learning: what it is and why It's Here to stay. London: SAGE Publications.

Kelley, T. R., and Knowles, J. G. (2016). A conceptual framework for integrated STEM education. *Int. J. Sci. Math. Educ.* 3. doi: 10.1186/s40594-016-0046-z

Khait, I., Lewin-Epstein, O., Sharon, R., Saban, K., Goldstein, R., Anikster, Y., et al. (2023). Sounds emitted by plants under stress are airborne and informative. *Cell* 186, 1328–1336.e10. doi: 10.1016/j.cell.2023.03.009

Kim, C., Guo, A., Salhotra, G., Sprinkhuizen, S., Shetty, K., and Kong, D. S. (2020). Sonifying data from the human microbiota: biota ceats. *Comp. Mus. J.* 44, 51–70. doi: 10.1162/comj_a_00552

Korea Foundation for the Advancement of Science and Creativity [KOFAC] (2017). Concept and definition of STEAM. Available at: https://steam.kofac.re.kr/?page_id=11269 (Accessed December 27, 2024).

Kolb, D. A. (1984). Experiential learning experience as the source of learning and development. NJ, Prentice Hall: Englewood Cliffs, NJ.

Kutnik, J. (1992). John cage: towards a poetics of interpenetration and non-obstruction. *Stu. Angl. Posn.* 24, 67–78.

Lave, J., and Wenger, E. (1991). Situated learning: Legitimate peripheral participation. Cambridge: Cambridge University Press.

Lederman, N. G., and Lederman, J. S. (2019). Teaching and learning nature of scientific knowledge: is it déjà vu all over again? *Discipl. Interdiscipl. Scien Ed. Res.* 1, 1–9. doi: 10.1186/s43031-019-0002-0

Lehmann, J., and Gaskins, B. (2019). Learning scientific creativity from the arts. *Palg. Commun.* 5. doi: 10.1057/s41599-019-0308-8

Li, Y., Wang, K., Xiao, Y., and Froyd, J. E. (2020). Research and trends in STEM education: a systematic review of journal publications. *Int. J. Sci. Math. Educ.* 7:11. doi: 10.1186/s40594-020-00207-6

Mahjour, B., Bench, J., Zhang, R., Frazier, J., and Cernak, T. (2023). Molecular sonification for molecule to music information transfer. *Dig. Discov.* 2, 520–530. doi: 10.1039/D3DD00008G

Martin-Gordillo, M. (2019). STEAM(E). Escuela. Available at: http://maculammg.blogspot.com/2019/10/steame.html (Accessed December, 27, 2024).

Martín-Páez, T., Aguilera, D., Perales-Palacios, F. J., and Vílchez-González, J. M. (2019). What are we talking about when we talk about STEM education? A review of literature. *Sci. Educ.* 103, 799–822. doi: 10.1002/sce.21522

Milazzo, M., Anderson, G. I., and Buehler, M. J. (2021). Bioinspired translation of classical music into de novo protein structures using deep learning and molecular modeling. *Bioinspir. Biomim.* 17:015001. doi: 10.1088/1748-3190/ac338a

Monno, A., Eramo, G., Mesto, E., and Tullio, M. D. (2016). The music of molecules: novel approaches for stem education. *Edulearn16 Proceedings*, 7442–7449. doi: 10.21125/edulearn.2016.0623

Moote, J., Archer, L., DeWitt, J., and MacLeod, E. (2020). Science capital or STEM capital? Exploring relationships between science capital and technology, engineering, and maths aspirations and attitudes among young people aged 17/18. *J. Res. Sci. Teach.* 57, 1228–1249. doi: 10.1002/tea.21628

Mujtaba, T., and Reiss, M. (2016). Girls in the UK have similar reasons to boys for intending to study mathematics post-16 thanks to the support and encouragement they receive. *Lond. Rev. Educ.* 14, 66–82. doi: 10.18546/LRE.14.2.05

Neuendorf, K. A. (2002). The content analysis guidebook. Thousand Oaks, CA: Sage Publications.

Özer, Z., and Demirbatır, R. E. (2023). STEAM based music activity example for gifted students: I design my instrument with scratch and Makey Makey. *LUMAT* 11, 1–24. doi: 10.31129/LUMAT.11.4.1993

Parvizi, J., Gururangan, K., Razavi, B., and Chafe, C. (2018). Detecting silent seizures by their sound. *Epil.* 59, 877–884. doi: 10.1111/epi.14043

Petrie, C. (2022). Programming music with sonic pi promotes positive attitudes for beginners. *Comp. Educ.* 179, ISSN 0360-1315,:104409. doi: 10.1016/j.compedu.2021.104409

Picciano, A. G. (2009). Blending with purpose: the multimodal model. *JALN* 13, 7–18.

Plaisier, H., Meagher, T. R., and Barker, D. (2021). DNA sonification for public engagement in bioinformatics. *BMC Res. Not.* 14:273. doi: 10.1186/s13104-021-05685-7

Prengaman, E. (2019). Lessons in process: similarities between scientific and artistic creative practice. *Steam J.* 4, 1–6. doi: 10.5642/steam.20190401.11

Presti, G., Ahmetovic, D., Ducci, M., Bernareggi, C., Ludovico, L., Baratè, A., et al. (2019). "Watch out: obstacle sonification for people with visual impairment or blindness" in Proceedings of the 21st international ACM SIGACCESS conference on computers and accessibility (ASSETS'19) (New York, NY, USA: Association for Computing Machinery), 402–413.

Queiruga-Dios, M. Á., Ojeda, M., and Saiz-Manzanares, M. (2019). Análisis de la apreciación sobre la implicación y desempeño y las dificultades y aprendizajes en la realización de proyectos STE(A)M atendiendo al género en alumnos de secundaria. In *Innovación Docente e Investigación en Ciencias de la Educación*. ed. M. C. Pérez-Fuentes. 989–997. Dykinson.

Quigley, C. F., Herro, D., and Baker, A. (2019). "Moving toward transdisciplinary instruction: a longitudinal examination of STEAM teaching practices" in STEAM education: Theory and practice. eds. M. S. Khine and S. Areepattamannil (Cham: Springer International Publishing), 143–164.

Romero-Naranjo, F. J. (2013). Science and art of body percussion: a review. *J. Hum. Sport Exer.* 8, 442–457. doi: 10.4100/jhse.2012.82.11

Rosicka, C. (2016). From concept to classroom. Translating STEM education research into practice. Australian Council for Educational Research. Available at: https://research.acer.edu.au/cgi/viewcontent.cgi?article=1010&context=professional_dev (Accessed December 27, 2024).

Ruppert, S. S. (2006). Critical evidence: how the arts benefit student achievement (p. 24). NASAA. Available at: https://nasaa-arts.org/product/critical-evidence-arts-benefit-student-achievement/ (Accessed December 27, 2024).

Sala, G., and Gobet, F. (2020). Cognitive and academic benefits of music training with children: a multilevel meta-analysis. *Mem. Cogn.* 48, 1429–1441. doi: 10.3758/s13421-020-01060-2

Sanders, M. (2009). STEM, STEM education, STEMmania. *Tech. Teac.* 68, 20–26.

Sawe, N., Chafe, C., and Treviño, J. (2020). Using data sonification to overcome science literacy, numeracy, and visualization barriers in science communication. *Front. Com.* 5:45. doi: 10.3389/fcomm.2020.00046

Scaletti, C., Rickard, M. M., Hebel, K. J., Pogorelov, T. V., Taylor, S. A., and Gruebele, M. (2022). Sonification-enhanced lattice model animations for teaching the protein folding reaction. *J. Chem. Ed.* 99, 1220–1230. doi: 10.1021/acs.jchemed.1c00857

Scerri, E. (2019). The periodic table: Its story and its significance. Oxford: Oxford University Press.

Shreffler, A. C. (2006). "Varèse and the technological sublime; or, how ionisation went nuclear" in Edgard Varèse: Composer, sound sculptor, visionary. eds. Z. Heidy and M. Felix (Suffolk: The Boydell Press), 290.

Silverstein, L. B., and Layne, S. (2010). What is arts integration?: Explore the definition. Washington, DC: The Kennedy Center ArtsEdge. Available at: https://artsedge.kennedy-center.org/educators/how-to/arts-integration/what-is-arts-integration#explorethe-definition. (Accessed December 27, 2024).

Smith, C., and Watson, P. (2019). Does the rise of STEM education mean the demise of sustainability education? *Austral. J. Envir. Ed.* 35, 1–11. doi: 10.1017/aee.2018.51

Spitzer, M. (2014). Information technology in education: risks and side effects. *Tren. Neur. Ed.* 3, 81–85. doi: 10.1016/j.tine.2014.09.002

Stephenson, B. (2016). The music of the heavens: Kepler's harmonic astronomy. Princeton: Princeton University Press.

Stockhausen, K. (1989). Towards a cosmic music. *Elements*. Shaftesbury.

Strauss, A., and Corbin, J. (1998). Basics of qualitative research: Techniques and procedures for developing grounded theory. *2nd* Edn. London: Sage.

Su, I., Qin, Z., Saraceno, T., Bisshop, A., Mühlethaler, R., Ziporyn, E., et al. (2020). Sonification of a 3-D spider web and reconstitution for musical composition using granular synthesis. *Comp. Mus. J.* 44, 43–59. doi: 10.1162/comj_a_00580

Supper, A. (2012). *Lobbying for the ear: the public fascination with and academic legitimacy of the sonification of scientific data*. [Doctoral Thesis, Maastricht University]. Datawyse / Universitaire Pers Maastricht. doi: 10.26481/dis.20120606as

Supper, A. (2015). Sound information: Sonification in the age of complex data and digital audio. *Infor. Cult.* 50, 441–464. doi: 10.7560/IC50401

Temple, M. D. (2017). An auditory display tool for DNA sequence analysis. *BMC Bioinform.* 18:221. doi: 10.1186/s12859-017-1632-x

Thuneberg, H. M., Salmi, H. S., and Bogner, F. X. (2018). How creativity, autonomy and visual reasoning contribute to cognitive learning in a STEAM hands-on inquiry-based math module. *Think. Sk. Creat.* 29, 153–160. doi: 10.1016/j.tsc.2018.07.003

Truax, M. C., and Meelberg, B. (2016). The Routledge companion to sounding art. Abingdon: Routledge.

Uhlmann, E., and Swanson, J. (2004). Exposure to violent video games increases automatic aggressiveness. *J. Adol.* 27, 41–52. doi: 10.1016/j.adolescence.2003.10.004

United Nations. (2023). Sonification: a tool for research, outreach and inclusion in space sciences [special report]. United Nations Office for Outer Space Affairs. Available at: https://www.unoosa.org/oosa/en/ourwork/space4personswithdisabilites/index.html (Accessed December, 27, 2024).

Upson, R. (2002). Educational sonification exercises: Pathways for mathematics and musical achievement. Proceedings of the 2002 international conference on auditory display. Available at: https://www.hdl.handle.net/1853/51358 (Accessed December, 27, 2024).

Valle, A., and Korol, V. (2022). For LISA. A piano-based sonification project of gravitational waves (arXiv:2202.04621). *arXiv*. doi: 10.48550/arXiv.2202.04621

Vines, K., Hughes, C., Alexander, L., Calvert, C., Colwell, C., Holmes, H., et al. (2019). Sonification of numerical data for education. *Open Lear.* 34, 19–39. doi: 10.1080/02680513.2018.1553707

Werang, B. R., and Leba, S. M. R. (2022). Factors affecting student engagement in online teaching and learning: a qualitative case study. *Qual. Rep.* 27, 555–577. doi: 10.46743/2160-3715/2022.5165

Williams, D. (2016). Utility versus creativity in biomedical musification. *J Creat. Mus. Syst* 1:1. doi: 10.5920/jcms.2016.02

Wong, J. Y., McDonald, J., Taylor-Pinney, M., Spivak, D. I., Kaplan, D. L., and Buehler, M. J. (2012). Materials by design: merging proteins and music. *Nan. Tod.* 7, 488–495. doi: 10.1016/j.nantod.2012.09.001

Xenakis, I. (1992). Formalized music: Thought and mathematics in composition. Hillsdale: Pendragon Press.

Yakman, G. (2008). STΣ@M education: an overview of creating a model of integrative education. Paper presented at the pupils' attitudes towards technology (PATT-19) conference: Research on technology, innovation, design and engineering teaching, Salt Lake City, Utah: USA. Available at: http://www.steamedu.com/2088_PATT_Publication.pdf (Accessed December 27, 2024).

Yakman, G., and Lee, H. (2012). Exploring the exemplary STEAM education in the US as a practical educational framework for Korea. *J. Kor Ass. Scien. Educ.* 32, 1072–1086. doi: 10.14697/jkase.2012.32.6.1072

Yin, R. K. (2019). Case study research: Design and methods. London: Sage.

Zamorano, T., García, Y., and Reyes, D. (2018). Educación para el sujeto del siglo XXI: principales características del enfoque STEAM desde la mirada educacional. *Contextos* 41, 1–21. (Accessed December 27, 2024).

Zanella, A., Harrison, C. M., Lenzi, S., Cooke, J., Damsma, P., and Fleming, S. W. (2022). Sonification and sound design for astronomy research, education and public engagement. *Nat. Astron.* 6, 1241–1248. doi: 10.1038/s41550-022-01721-z