Journal of the Brazilian Computer Society, 202X, XX:1, doi: 10.5753/jbcs.202X.XXXXXX

Roll Like Thunder: Expert Validation and Refinement of a Design Process to Convey Emotions in Music Visualizations

Caio Nunes [**Federal University of Ceará** | ***caioeduardo@alu.ufc.br***]
Ticianne Darin [**Federal University of Ceará** | ***ticianne@virtual.ufc.br***]

Received: DD Month YYYY • **Accepted:** DD Month YYYY • **Published:** DD Month YYYY

Abstract. Music evokes complex emotions and enhances engagement across interactive media. Music visualizations — graphical representations of sound — have gained relevance in games, virtual environments, and digital art. Yet, many existing approaches fail to convey emotional nuance, focusing instead on structural or reactive aspects of sound. To support the creation of emotionally engaging visualizations, we previously introduced Thunder, a design process grounded in a Research Through Design (RtD) approach. While its initial application showed creative potential, it also highlighted opportunities to improve structural clarity, enhance guidance for designers, and increase adaptability across varied contexts. In this paper, we present a refined version of Thunder, developed through an expert review with specialists in Human-Computer Interaction, Music, and Computing. The updated process is organized into three core phases – Conceptualization, Prototyping, and Evaluation – each offering clearer support for emotional, aesthetic, and musical decision-making. Implementation is now framed as an external and adaptable step, allowing flexibility across technical scenarios. The new refined Thunder offers an improved foundation and design guidance for creating emotionally resonant music visualizations in diverse contexts.

Keywords: Music Visualization Design, Emotional Communication, User Experience, UX, Player Experience, PX, Design Process, Expert Review, Audio Design, Audio Assessment, Well-being, Hearing Accessibility, Human-Computer Interaction (HCI), Affective Computing, Iterative Design, Evaluation Metrics, Immersive Audio

1 Introduction

Music is a powerful way of expression in human culture. It goes beyond the limits of cultures, geographies, and societies [Munteanu, 2012; Pokharel, 2020], evokes emotions, and conveys complex moods [Pouris and Fels, 2012; Koelsch, 2015]. The literature has shown how the influence of music on our emotions brings up its uses in several fields. For example, music has been found helpful as an intervention in enhancing emotional well-being and associated with benefits for people with clinical depression and anxiety [Hallam and MacDonald, 2013; Kamioka *et al.*, 2014]. Because it can serve as a mechanism for regulating mood [Koelsch, 2010; Reybrouck and Eerola, 2017], and is also associated with the release of dopamine and oxytocin, which are linked to pleasure and social bonding[Chanda and Levitin, 2013].

With its strong emotional appeal, music naturally applies to interactive applications, especially within the entertainment domains [Pereira and Chambel, 2023; Stewart *et al.*, 2010], which include video games, virtual environments, interactive art, and storytelling, to name a few. Much more than simple background sound, music can deeply impact user experience (UX) by deepening immersion [Hassenzahl, 2008; Cuny *et al.*, 2015], affective engagement [Hassenzahl, 2008; Hwang and Oh, 2020], and the feelings of aesthetic experience [Cuny *et al.*, 2015]. It has also been associated with a stronger behavioral intention and a more positive perception towards a target interactive application [Hwang and Oh, 2020].

In this context, music visualization has gained much attention as a field for applications in entertainment, education, art, and commerce, incorporating elements of music, digital audio, image processing, and virtual reality [Tian, 2007]. Music visualization can be defined as the practice of translating musical elements – such as rhythm, melody, harmony, and dynamics – into graphical representations that enhance perception, analysis, and engagement with music [Pouris and Fels, 2012; Lima *et al.*, 2021; Chen *et al.*, 2023]. These representations take various forms, including dynamic animations [Lee and Fathia, 2016], color-based patterns [De Prisco *et al.*, 2018], and interactive visual effects that react in real-time to sound [bea, 2019]. Beyond their artistic and aesthetic appeal, music visualizations serve practical purposes, such as improving accessibility and understanding, especially for individuals with hearing or cognitive disabilities [Fourney and Fels, 2009; Pouris and Fels, 2012].

Despite these advantages, effectively designing music visualizations presents several challenges. While existing approaches successfully capture structural components of music, they often fall short in conveying the emotional nuances that define a musical experience [Fourney and Fels, 2009; Mori and Fels, 2009]. To bridge this gap, visualizations must go beyond technical accuracy and integrate expressive elements that enhance immersion and audience engagement. Achieving this, however, requires intricate processes of audiovisual synchronization, composition, and animation [Abreu *et al.*, 2018], which demand both artistic intuition and computational precision. Additionally, the labor-intensive nature of high-quality visualization production poses a barrier for many creators [Liu *et al.*, 2023]. The manual synchronization of visuals with music involves complex decision-making across multiple artistic and technical domains [Abreu *et al.*, 2018], making the process time-consuming and resource-intensive [Chen *et al.*, 2023]. Consequently, there is a growing need for tools that streamline this workflow, allowing designers to focus on creative and narrative aspects without sacrificing technical quality.

Beyond the technical challenges, integrating musical visualizations into digital narratives presents additional difficulties. The balance between auditory and visual stimuli must be carefully managed to ensure coherence and effectiveness. Users often struggle to interpret the association between graphically represented sounds and the overarching narrative [Siu *et al.*, 2022], which can lead to cognitive overload or disengagement. This issue is exacerbated by the subjective nature of emotional perception in music, as different listeners may interpret the same musical passage in distinct ways. To mitigate these concerns, designers must approach the creation of musical visualizations with a deep understanding of emotional triggers, ensuring that visuals and sound work synergistically to evoke the intended affective response.

To address these issues, we previously proposed Thunder, a design process focused on supporting the creation of emotionally engaging music visualizations [Nunes *et al.*, 2024]. First presented in the Innovative Ideas and Emerging Results track at the XXIII Brazilian Symposium on Human Factors in Computing Systems (IHC'24), Thunder built upon the process by Almeida *et al.* (2021), which was grounded in design thinking principles for animated visualization prototyping. Thunder introduced a more emotion-oriented structure, consisting of four stages – Conceptualization, Prototyping, Implementation, and Evaluation – and was applied in developing two visualizations for the song "The Sixth Station," composed by Joe Hisaishi. These visualizations were positively received in user evaluations and communicated the intended emotional atmosphere.

Despite its positive results, a key limitation emerged. Thunder was entirely defined and refined within the scope of a single design project. While the outcomes were promising, the process itself had evolved in parallel with the production of the visualizations, without undergoing a more systematic or external validation. Rooted in a Research Through Design (RtD) approach [Zimmerman and Forlizzi, 2014], the construction of Thunder was intrinsically tied to practical experimentation, which – although methodologically valuable – highlighted opportunities to enhance its clarity, broaden its applicability, and strengthen its relevance across diverse creative and technical contexts.

To address this gap, in this work we present an enhanced version of Thunder resulting from an expert review involving three specialists in HCI, Music, and Computing. Our goal was to assess Thunder's structure, terminology, and clarity, as well as to understand how well its steps could be generalized beyond the specific use case in which it was conceived. Based on this critical feedback, we reviewed and refined the process steps, the inputs and outputs, and the level of detail, enhancing its conceptual structure while emphasizing emotional communication.

In this work, we present the refined version of Thunder, now structured into three core phases, instead of four: Conceptualization, Prototyping, and Evaluation. Each phase encompasses decisions that span musical analysis, visual language definition, emotional intent, and iterative assessment. Moreover, we introduce an external and flexible perspective about implementation, which allows designers to adapt Thunder's outcomes to various development contexts without compromising its expressive goals.

Our work thus provides a more thorough approach to designing musical visualizations, aiming to facilitate effective communication of music's emotional subtleties. We anticipate Thunder will significantly enhance user experiences across diverse contexts, including interactive media, virtual environments, games, digital art, multimedia installations, and entertainment applications.

2 Background

In this section, we present a background on the influence of music on human emotions and discuss the process involved in creating a visualization that represents the essence of music through selected components.

2.1 Music and Emotions

The relationship between music and emotions has fascinated researchers across various disciplines, including musicology, psychology, and neuroscience. Music is important in evoking emotions, creating a pleasant atmosphere, expressing inner feelings, and enhancing creative behaviors [Prisco *et al.*, 2017]. Music can also be used to encode emotional information; for instance, a movie soundtrack can set the mood of a scene and affect the emotional perception of the audience[Lipscomb and Kendall, 1994]. Take, for instance, the iconic, minimalist theme from "Jaws," a simple alternation of E and F notes. As Matessino points out (1999), many North American adults instantly associate it with a lurking shark and impending doom, even outside the context of the film.

Expanding on this understanding, Cowen *et al.* (2020) investigated the subjective experiences associated with Western and Chinese music, examining whether these experiences transcend cultural boundaries. Their findings revealed 13 distinct dimensions of subjective experience linked to music across both cultures: "amusing," "annoying," "anxious/tense," "beautiful," "calm/relaxing/serene," "dreamy," "energizing/pump-up," "erotic/desirous," "indignant/defi ant," "joyful/cheerful," "sad/depressing," "scary/fearful," and "triumphant/heroic." This comprehensive mapping underscores the diverse emotional palette music can elicit.

The emotional power of music derives from a very complex interaction of auditory stimuli and cognitive processing. Contributory factors in such expressiveness lie in the structural elements of music: tempo, melody, harmony, and dynamics. These elements combine and interact with listeners' cognitive and affective systems to elicit responses, which may be individual or shared. Manipulating these musical elements can raise targeted emotional responses.

Psychology and neuroscience research prove that music provokes physiological and neural responses, laying concrete proof of its impact on our bodies. Koelsch (2014) highlights functional neuroimaging studies demonstrating music's ability to modulate activity in brain regions intrinsically linked to emotions, such as the amygdala and hypothalamus. It translates into physiological and autonomic and endocrine changes; motor expressions are expressed through a smile or a frown, and action tendencies mean tapping your feet or hitting the dance floor. Music can stir real emotions beyond mere subjective feelings because it can affect the roots of emotional responses.

2.2 Music Visualization

Visualizations encompass a range of techniques and methods for creating graphics, images, and animations to communicate information effectively [Zhang *et al.*, 2018]. Music visualizations, a subset of this field, merge music and visual elements to produce synchronized and immersive experiences that enhance the viewer's engagement with the music [Schmidt, 2018]. Moreover, music visualizations offer an accessible way to experience music, particularly for the deaf, deafened, and hard of hearing (D/HH) communities, who seek to access music from mainstream hearing culture [Pouris and Fels, 2012]. Music poses significant challenges for individuals who are D/HH, as they often encounter obstacles when attempting to engage with music designed for hearing audiences [Fourney and Fels, 2009]. Furthermore, partial and total hearing loss can hinder the ability to comprehend and enjoy music, even with hearing aids, which may distort the quality of the music [Chasin, 2003].

Music visualizations can be broadly categorized based on their purpose and representation approach. A common classification found in literature divides them into augmented score visualizations and performance visualizations [Hiraga *et al.*, 2002; Lima *et al.*, 2021]. Augmented score visualizations enhance traditional music notation by incorporating additional graphical elements such as color-coded pitch mapping, animated note representations, and interactive score interfaces [Ciuha *et al.*, 2010; Miller *et al.*, 2019]. These visualizations are particularly useful in educational settings, allowing learners to develop a deeper understanding of music theory and composition.

Performance visualizations, on the other hand, focus on capturing and analyzing expressive aspects of music, such as dynamics, articulation, phrasing, and tempo variations [Hiraga *et al.*, 2002; Khulusi *et al.*, 2020]. These representations can be used to track interpretative differences between performers, visualize the evolution of a musical piece over time, or provide insights into the performer's expressive intent. Some performance visualizations employ real-time tracking of physical gestures and movements of musicians, mapping these actions into dynamic visual representations [Hiraga *et al.*, 2002].

Beyond this fundamental classification, music visualizations can also be categorized by their technical approach. Audio-driven visualizations process raw sound data to generate visual outputs, relying on frequency analysis and amplitude detection to create dynamic animations [Fourney and Fels, 2009]. MIDI-based visualizations, in contrast, use symbolic representations of music to provide structured graphical depictions, such as piano rolls or harmonic grids [Bergstrom *et al.*, 2007]. Advances in generative design and artificial intelligence have further expanded the possibilities for creating sophisticated real-time visual representations of music [Graf *et al.*, 2021].

2.3 Music Visualization in Digital Interactive Systems

Music visualizations have come a long way, especially in artistic areas, such as operas, ballets, and movies [Hiraga *et al.*, 2002]. For instance, the film "Fantasia" [fan, 1940] developed by Disney in 1940 was produced using artistic interpretations of selected musical works. Through various degrees of abstract and literal art in the form of visual animation, "Fantasia" effectively communicates emotion, entertainment, and other music properties [Fourney and Fels, 2009]. Another early use of electronics to visualize music through art occurred with the release of the Atari Video Music system [ata, 1976]. Designed to connect to a television set, this console allowed users to either create their own visual effects or place the system in automatic mode where the visuals responded dynamically to the music [Brown, 1978]. These displays were precursors to modern software-based music player visualizations [Fourney and Fels, 2009]. Furthermore, with the advance of technologies, music players such as Windows Media Player and iTunes started to use software algorithms to automatically extract key music data, such as frequency and time, from digital music files, translating this data into visualizations.

The use of music visualizations in digital systems currently far transcends music players. It has become a vital component within some kinds of interactive systems and gaming environments. This integration not only enriches user and player experiences but also introduces innovative engagement methods. Modern game engines like Unity and Unreal Engine offer extensive libraries and tools for creating sophisticated audio-reactive environments. For instance, games like Gris use minimalist, watercolor-inspired visuals that shift dynamically in color palette and intensity in line with the melancholic and hopeful emotional arc of the soundtrack, reflecting the emotional journey of the protagonist through grief. Likewise, games like Sayonara Wild Hearts use bright, stylized graphics in synchronization with its high-energy synth-pop soundtrack to heighten the sensations of thrill and liberation expressed through the music. Beat Saber is another example of a rhythm game that uses synchronized visual feedback and particle effects to enhance the game's immersive nature further, tying the player's actions directly to musical rhythms.

Besides gaming, interactive art installations are commonly applied in music visualization methods to create dynamic and captivating experiences. These installations may rely on sensor information, such as the proximity or movement of participants, to modify the visual reaction to music and produce an adaptive and personalized artwork. Interactive art installations are also making use of AI-generated visuals to convert sensitive emotional undertones in music into form, color, and texture abstractions. Such installations can use machine learning algorithms trained on large datasets of art and music to create mappings between specific musical qualities, for example, dissonance or consonance, and corresponding visual representations that evoke feelings of discomfort or harmony. Projects like *The Treachery of Sanctuary* by Chris Milk, while focused on physical movement, demonstrate the potential to create deeply emotional audiovisual experiences that resonate with the viewer on an inherent level.

Furthermore, innovations in virtual reality (VR) and augmented reality (AR) technologies have opened the door to new opportunities for immersive music visualization, allowing listeners to explore musical environments and interact with sound in new and intuitive ways. Virtual reality experiences are being designed that enable users to become fully immersed in abstract, affectively laden worlds and music and sounds play a central role here. Through the music they are listening to, users establish an intensely personal and synesthetic exchange between visual and musical stimuli. Rez Infinite is a VR remastered version of the classic rail shooter, Rez, and it's the "Area X" section exemplifies this application. The music in Area X is deliberately designed to be emotionally evocative. It often shifts between moments of serene beauty and intense, energetic euphoria, and the visuals directly mirror these emotional shifts.

The examples given above, such as video games, interactive installations, and virtual reality environments, point to the more sophisticated application of music visualization in digital systems. Yet regardless of the ever-changing technologies that provide opportunities to make visually engaging and technologically impressive presentations, the basic issue is still to express the emotional content of music into a visual system that engages listeners on a deep level. In that way, such experiences will not only be visually appealing but also intensely emotionally evocative.

3 Thunder as Initially Proposed

In our previous study [Nunes *et al.*, 2024], we presented the construction of Thunder, a design process developed to support the creation of emotionally expressive music visualizations. Thunder emerged through a Research through Design approach [Zimmerman and Forlizzi, 2014], grounded in the practical challenges faced during the design of two visualizations for the song The Sixth Station, from the film Spirited Away. This piece had previously been evaluated in a live concert setting, where the accompanying visualization – produced independently of our research – failed to convey the intended emotional tone of the music. While the soundtrack evoked feelings of sadness, loneliness, and melancholy, the audience reported predominantly positive emotions, revealing a disconnection between the music and its visual representation.

This observation motivated us to explore whether an alternative design approach could better support the expression of these emotional nuances. We selected The Sixth Station as a case study and set out to produce two new visualizations intended to improve the emotional alignment between sound and visualization. Our initial intention was to follow the design process proposed by Almeida *et al.* (2021), which proposes inspiration, ideation, and prototyping phases inspired by design thinking. However, as we engaged more deeply with the emotional, aesthetic, and interactive demands of the visualization, we identified the need for a more detailed structure.

Throughout the development of the two alternatives, we progressively reorganized and refined the stages of the original process. These refinements led to the definition of a new design process, which we named Thunder (see Figure 1). Thunder is composed of four main stages:

1. **Conceptualization**: In this stage, designers define the emotional goals of the visualization, select the music to be represented, and establish the visual and aesthetic direction that will guide the entire project.
2. **Prototyping**: This stage involves the creation of medium- and high-fidelity prototypes, which are iteratively refined through structured feedback to ensure alignment between emotional intent, visual elements, and musical structure.
3. **Implementation**: At this point, the final prototype is translated into an interactive visualization, coded to dynamically respond to the selected music—whether prerecorded or performed live.
4. **Evaluation**: Integrated across the previous stages, this phase includes feedback sessions with designers, laboratory testing with users, and field validation of the implemented version to assess emotional expressiveness, engagement, and overall user experience.

Each stage was articulated based on practical needs that emerged during the creative process, a characteristic of Research through Design, and focused on supporting emotional expressiveness as a central design concern. This iterative, practice-based approach, fundamental to RtD, allows for a deep understanding of user needs as they are revealed through the design itself. However, because Thunder was formulated within a single project context and was primarily guided by the empirical experience of the designers involved, a gap remained in its external validation. This exemplifies a common challenge in RtD: while deeply insightful, findings require further rigorous evaluation to verify their broader applicability. By engaging with RtD, we gained valuable situated knowledge. This knowledge, however, must be complemented by more formal research methods to ensure the robustness and generalizability of the design principles uncovered. To bridge this limitation and strengthen the Thunder's robustness, we conducted an expert review followed by a refinement, detailed in Section 4

Still, the benefits of adopting the RtD approach for the proposal of Thunder [Nunes *et al.*, 2024] were significant. It helped us fostering innovation by embracing experimentation and learning from failures. Because of that, Thunder design decisions was grounded in real-world contexts. Furthermore, RtD generated valuable research insights that informed our design efforts, creating a virtuous cycle of knowledge production and practical application, as is the intent of applying an RtD approach.

4 Methodology

In order to refine Thunder, we conducted an expert review with specialists in HCI, Music and Computing. This evaluation aimed to (i) assess the clarity and feasibility of the pro-

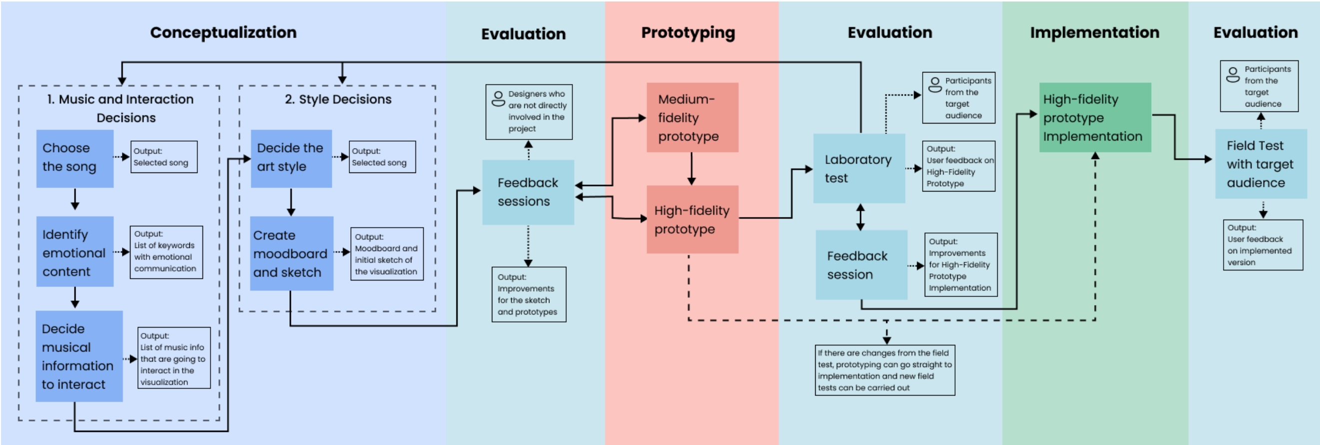

Figure 1. Version of the Thunder design process presented in our previous work, developed prior to refinement based on expert feedback (zoom in for a more detailed view).

cess, (ii) identify strengths and areas for improvement, and (iii) ensure that Thunder effectively supports the design of emotionally expressive music visualizations.

When developing a new process, it is critical to ensure its robustness, clarity, and alignment with intended outcomes. Incorporating expert reviews helps identify key insights, potential challenges, and opportunities for refinement [Armstrong, 2001; Rubio *et al.*, 2003]. Although expert feedback inherently carries subjectivity and potential biases [Rubio *et al.*, 2003], it significantly helps reduce the necessity for future revisions and optimizes resource usage, complementing additional validation methods.

4.1 Participants

The literature does not establish a specific minimum number for implementing this method. Armstrong (2001) states that expert groups should consist of approximately 5 to 20 members, depending on the availability of experts and the nature of the desired feedback. Smaller panels may be more suitable when seeking in-depth insights, while larger panels may be preferable if the goal is to gather a variety of opinions. Meanwhile, Lazar *et al.* (2017) notes that to obtain in-depth insights from domain experts, a large number of participants is not necessary; only two or three motivated experts can be recruited.

For this stage of the research, we decided to recruit a minimum of three experts, selected by convenience, to participate in the evaluation. The experts will be invited to participate through email invitations. The inclusion criteria were:

- The person must be at least 21 years old;
- The person must hold a postgraduate degree;
- The person must work or have worked in the fields of Computing, Music, Design, or HCI.

The exclusion criteria for this stage were:

- People under 21 years old or over 59 years old;
- People without a postgraduate degree;
- People who have never worked in the fields of Computing, Music, Design, or HCI.

4.2 Procedure

Experts received two documents via email: one detailed the Thunder process comprehensively – including its four initial phases (Conceptualization, Prototyping, Implementation, and Evaluation) and illustrative diagram – while the other optional document presented the preliminary application of Thunder in the creation of the two alternative visualizations, serving as a practical reference. Following document review, participants completed an online survey to assess Thunder.

The review questionnaire was designed to assess Thunder's methodological clarity, feasibility, and effectiveness in structuring music visualizations. It comprised two sections: the first collected demographic and professional background data, including age, gender, academic field, experience level, and prior exposure to music visualizations.

The second section evaluated Thunder as a whole and it's four phases: Conceptualization, Prototyping, Implementation, and Evaluation. In Conceptualization, participants assessed the clarity of emotion identification methods, the effectiveness of free word association and Cowen et al.'s emotional mapping, and the role of mood boards and sketches in defining artistic direction. Prototyping was evaluated in terms of fidelity distinctions, iterative refinement, and the clarity of instructions for developing prototypes. Implementation focused on technical feasibility, flexibility for adjustments, and the adequacy of suggested tools and libraries. Finally, Evaluation examined the effectiveness of feedback sessions, structured testing methods, and the integration of qualitative and quantitative user experience metrics.

Each section included open-ended fields for additional feedback, allowing experts to highlight challenges and suggest refinements.

4.3 Data Analysis

Quantitative responses from closed-ended survey questions were analyzed using descriptive statistics to measure consensus regarding Thunder's clarity, methodological coherence, and practicality. Qualitative feedback underwent thematic analysis, identifying recurrent suggestions and critiques to understand Thunder's strengths and limitations comprehensively.

Both quantitative and qualitative data informed Thunder's refinement. Initial analyses guided a series of structured discussions with the research team, in which we critically reviewed the findings, interpreted ambiguous feedback, and weighed the implications of each suggested change. These reflective sessions enabled iterative adjustments to the process, ensuring that modifications were not only aligned with expert input but also coherent within the design rationale of Thunder.

Each major revision was validated through these collaborative reviews, strengthening the theoretical foundation and practical consistency of the final version. This layer of critical reflection and validation added rigor to the refinement process and increased confidence in the applicability of Thunder for future studies and design scenarios.

5 Results

In the following sections we describe the results obtained from the expert review.

5.1 Participants Profile

Three participants took part in the expert evaluation, each bringing complementary academic and professional backgrounds. Table 1 summarize information on each participant involved in the study, including their age group, gender, academic background, field of work, years of experience, and their prior involvement with musical visualizations.

Overall, the group of experts has solid academic backgrounds – all hold doctoral degrees – and works in interdisciplinary fields, primarily Design, Computing, HCI, and Music. Two of them have over a decade of experience on projects merging computing and music, and all have been involved with musical visualizations – whether by creating multimedia tools, studying performative approaches, or conducting musical analyses.

Their ages range from 30–49 years, reflecting perspectives that span more academic viewpoints to practical software applications. Regarding gender, two males and one female participated, ensuring diverse experiences and analysis methods. Although each expert's focus differs (Design, Computing, HCI, Music), this blend of complementary perspectives enables a broad understanding of the requirements and possibilities in the field, adding conceptual depth alongside Thunder's creative and technical applications.

5.2 Quantitative Analysis

The quantitative evaluation of Thunder was divided into five sections: overall process, conceptualization, prototyping, evaluation, and implementation. The results are presented in the following sections.

5.2.1 Overall Assessment

Regarding the overall process assessment, as depicted in Figure 2, the results indicate that Thunder is well-structured and demonstrates strong potential for application across different contexts, with experts highlighting its clarity and flexibility.

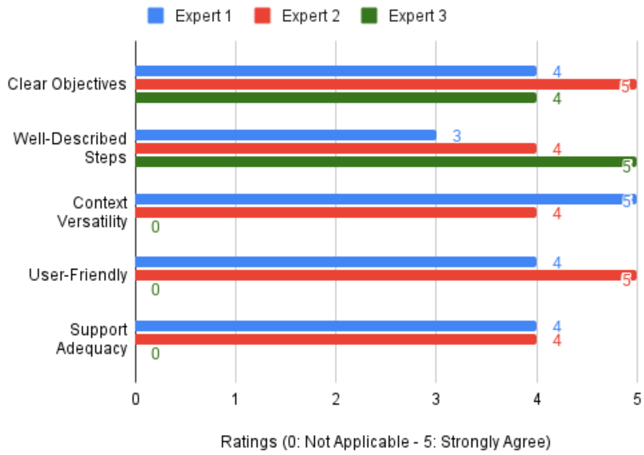

Figure 2. Overall process assessment

The clarity of Thunder's objectives received positive ratings (4, 5, and 4), confirming that its purpose is well-defined. Similarly, the comprehensibility of its steps was positively evaluated (3, 4, and 5), indicating that while the process is detailed and systematic, some aspects could be further emphasized to enhance clarity. One expert pointed out that the evaluation phase could be more distinctly differentiated from the core stages of Thunder, as its recurrence might lead to misunderstandings. This suggests an opportunity to refine how the iterative nature of evaluation is communicated within the process.

The applicability of Thunder across different contexts was well-rated by most experts (5, 4), who acknowledged its versatility. The process's broad scope was seen as a strength, allowing it to be used in different scenarios. Given its flexibility, its ability to accommodate various approaches to mapping visual and sonic representations was particularly noted, reinforcing its relevance across disciplines. Similarly, the user-friendliness was also positively evaluated (4, 5), with experts acknowledging its structured methodology. The results indicate that Thunder provides a solid approach for guiding professionals through the process while allowing room for adaptation. Experts also recognized the model's approach to evaluating emotional content in music, particularly its consideration of how different emotional states can be represented within the process structure.

One expert rated several categories with a score of 0, particularly in context versatility, user-friendliness and support adequacy. According to the qualitative feedback, the rating of 0 on context versatility indicates that the process could benefit from a clearer differentiation regarding the intended application scenarios - whether it's just for musical visualizations or for broader artistic and interactive media. Similarly, the score of 0 in user-friendliness and support adequacy may stem from challenges related to the practical development of medium- and high-fidelity prototypes, where additional tools or guidelines could provide more effective assistance. These considerations highlight areas for refinement that could further strengthen Thunder's usability and accessibility, particularly by offering explicit resources to support prototype creation and validation processes.

Finally, the sufficiency of Thunder's resources for professionals received strong support (4, 4), affirming that it offers a comprehensive foundation for application. The evalu-

ID	Age Group	Gender	Academic Degree	Area of Expertise	Experience with Music Visualization
1	40–49	Male	PhD	Over 10 years of experience in Design, Computing, and HCI.	Developed a multimedia installation converting audio (via Fourier transforms) into real-time animations.
2	30–39	Female	PhD	3-5 years of experience in HCI.	Investigated performative aspects and attended live musical visualization performances.
3	40–49	Male	PhD	Over 10 years of experience in Music and Computing.	Focused on object-oriented methods for translating sonic structures (e.g., Bossa Nova rhythms) into visual forms.

Table 1. Expert Review Participants Profiles

ation also highlighted the importance of integrating different analytical criteria – both objective and subjective – to further strengthen the process, particularly in later stages where deeper assessments are conducted. Addressing these considerations could further reinforce Thunder's robustness as a design methodology.

5.2.2 Conceptualization Assessment

The Conceptualization phase received positive feedback from experts, as illustrated in Figure 3. The results indicate that the methods and activities in this phase were generally perceived as relevant and highly relevant, reinforcing their effectiveness in structuring the initial stages of music visualization design.

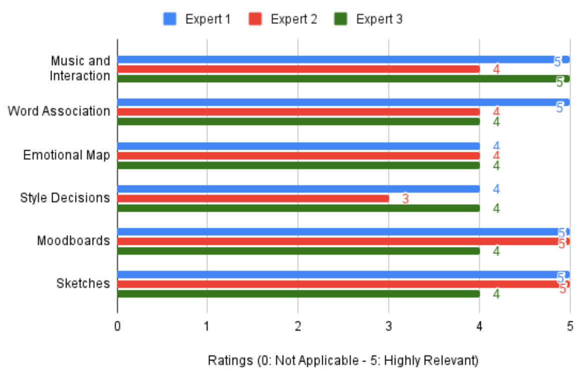

Figure 3. Conceptualization phase expert assessment

The identification of emotions evoked by the music was among the highest-rated aspects, with experts consistently classifying it as highly relevant. This suggests that the process effectively supports designers in establishing a strong emotional foundation for their creative decisions. Similarly, the use of free word association to capture emotional perceptions was well received, highlighting its suitability for facilitating intuitive and exploratory engagement with musical affect.

The application of Cowen *et al.* emotional map as a complementary method for identifying emotions was rated as relevant, with some variation in expert opinions. This suggests that while the tool is recognized as valuable, its effectiveness may depend on contextual factors such as familiarity with the model and its interpretability within different creative workflows.

Defining the artistic style based on the identified emotions received favorable evaluations, emphasizing its practical role in ensuring coherence between affective interpretation and visual representation. Additionally, the use of moodboards to consolidate emotions and artistic direction into cohesive visual references was widely acknowledged as a crucial step in maintaining consistency throughout the design process.

The use of initial sketches to translate conceptual ideas into early-stage visualizations also received strong support, with experts recognizing it as an effective bridge between conceptual exploration and later prototyping stages. Moreover, the overall coherence between the sub-steps of the conceptualization phase and their integration into the broader Thunder process was positively evaluated, indicating that the process successfully maintains logical continuity between its stages.

5.2.3 Prototyping Assessment

The Prototyping phase received positive feedback from experts, as illustrated in Figure 4. The results indicate that experts generally perceive these stages as valuable for refining and enhancing musical visualizations, with ratings consistently ranging from relevant to very relevant.

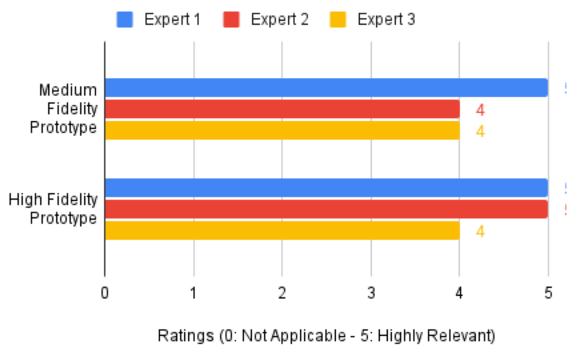

Figure 4. Prototyping phase expert assessment

Regarding the structuring of medium- and high-fidelity prototypes, the feedback was largely positive, demonstrating that the differentiation between these two levels of fidelity is clear for most evaluators. Additionally, the expected outcomes of this phase were deemed well-defined and achievable, reinforcing the effectiveness of Thunder's prototyping guidelines. Experts also highlighted that the connections between prototyping sub-stages and the overall process were coherent, further validating the integration of these steps within the broader methodology.

5.2.4 Evaluation Assessment

Figure 5 summarizes the results of the evaluation phase assessment, highlighting its effectiveness in refining musical visualizations through structured feedback loops and validation methods. Experts rated the iterative feedback sessions, laboratory tests, and field tests as highly relevant, reinforcing the importance of these steps in improving the final design.

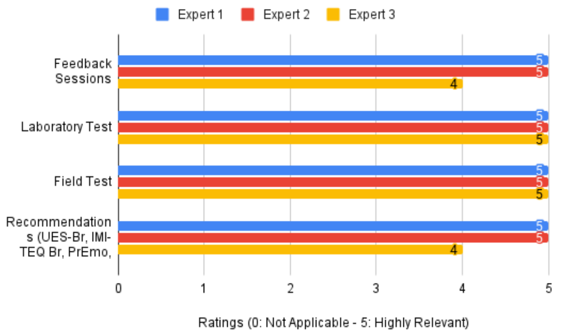

Figure 5. Evaluation phase expert assessment

The structured feedback sessions were well-rated (4, 5), confirming their usefulness in guiding design adjustments. Experts recognized the clarity of post-conceptualization feedback sessions and the transition between mid- and high-fidelity prototypes, though some suggested minor refinements to improve clarity. Similarly, the integration of audience feedback into final adjustments was seen as practical and well-documented.

Laboratory testing methods received strong support (5, 5), validating their structure and appropriateness for assessing user experience. However, one expert rated the field test description lower (1), possibly indicating a need for more detailed guidance on its implementation and its role in evaluating emotional impact in real-world scenarios.

The combination of quantitative and qualitative suggested methods was generally seen as sufficient (5, 5), yet one expert marked this aspect as “Not Applicable” (0), which may suggest uncertainty about its direct applicability in some cases. This highlights an opportunity to clarify how these methods integrate into Thunder’s broader evaluation strategy.

5.2.5 Implementation Assessment

The assessment of the implementation phase highlights its role in translating the designed visualizations into functional applications. Experts provided mixed feedback, with most aspects receiving positive evaluations while some areas indicate opportunities for refinement.

The connections between implementation and previous stages were well-rated (4, 5), suggesting that the process ensures coherence throughout development. The flexibility for technical adjustments was recognized as a strength (3, 5), demonstrating that the process accommodates refinements without compromising the final experience. Similarly, the suggested tools and libraries were considered suitable for different contexts (4, 5), supporting the adaptability of the implementation phase.

However, one expert rated certain aspects significantly lower (0, 1), particularly regarding the clarity of execution guidelines, technical recommendations, and expected outcomes. This suggests that the implementation phase may require additional documentation or practical examples to enhance its applicability. Moreover, the diversity of approaches to producing musical visualizations raises questions about whether implementation should remain an integral part of Thunder. Given the wide range of technologies, platforms, and artistic directions that can influence implementation, maintaining it as a separate, adaptable phase could allow Thunder to focus more effectively on the design of visualizations rather than prescribing specific technical pathways.

5.3 Qualitative Analysis

A qualitative thematic analysis of expert feedback identified key themes related to Thunder’s clarity, adaptability, process structuring, evaluation strategies, and practical implementation (see Table 2). These insights guided refinements in the process, ensuring a more structured and user-friendly approach while maintaining its flexibility. The following sections synthesize the main findings and the corresponding changes incorporated into the refined version of Thunder.

5.3.1 Enhancing Coherence and Process Transparency

Experts recommended making clearer which elements – particularly sound, but also visual and emotional – are addressed at each stage to enhance comprehension and prevent the process from appearing overly generic. To address this, we incorporated icons into the process activities to specify these elements explicitly, ensuring that designers can easily identify which components are relevant at each phase.

Additionally, some experts recommended integrating the suggested evaluation methods (e.g., PrEmo, UES-Br, IMI-TEQ Br) directly into the process diagram. However, we opted against this to maintain Thunder’s adaptability, as evaluation methods should be selected based on the emotional communication objectives rather than being predetermined. Instead, we integrated the DECIDE framework as the laboratory test and field test sub-activities, offering structured guidance to help users define objectives, select relevant methods, and analyze results while maintaining adaptability.

Further concerns were raised regarding the differentiation of Thunder’s phases, particularly the evaluation phase. Experts highlighted that the workflow needed clearer distinctions between iterative assessments and the transition between conceptualization, prototyping, and testing. To improve this, we included a header section with objective descriptions for each stage, outlining their purpose and the participants involved. Additionally, decision-making elements – such as conditional statements – were introduced to enhance logical structuring, and assessment activities were broken down into sub-activities to provide greater clarity.

Table 2. Classification of Expert Feedback

Category	Description	Comment Count
Enhancing Coherence	Suggestions to improve the overall clarity and unity of the Thunder process.	3
Process Transparency	Requests for clearer documentation or rationale behind decisions and steps.	4
Refining Process Structure	Suggestions to restructure steps, add substeps, or clarify phase distinctions.	6
Designer Preparation	Points related to the skills, training, or background the designer needs to apply the method.	2
Expand Theoretical Foundation	Requests to include or consider relevant theoretical or scientific literature.	4
Future Research Directions	Proposals that extend beyond the current process, suggesting tools or new research.	3

5.3.2 Refining Process Structure and Adaptability

Experts highlighted concerns regarding the relationship between time and visual representation. To address this, we incorporated a mapping sub-stage to establish a structured correlation between musical time and visual elements. This sub-activity has been integrated into the conceptualization and prototyping phases, enhancing clarity in the translation of the multiple emotional contexts in music into visuals.

Additionally, the implementation phase was widely discussed, leading to significant refinements in Thunder's structure. Based on both qualitative and quantitative feedback, we decided to remove implementation from the core workflow of Thunder. Given the diversity of approaches in creating musical visualizations – ranging from different technologies and platforms to artistic directions – it would be impractical to define a single implementation pathway within a dedicated stage. Instead, we adopted a black-box approach where, after laboratory testing, the process moves into implementation and later returns for field testing. This decision preserves Thunder's flexibility while allowing users to integrate their own implementation strategies tailored to their specific needs.

5.3.3 Strengthening Designer Preparation and Knowledge Accessibility

Experts emphasized the importance of ensuring that designers receive adequate preparation before applying Thunder. Many highlighted that effective use of the process requires prior knowledge of evaluation methodologies, emotional mapping, and prototyping approaches. To address this, we will provide a set of suggested resources within a supplementary artifact, offering designers the necessary background knowledge to apply the process effectively. This material will include curated academic articles, videos, and practical examples of music visualizations.

5.3.4 Future Research Directions and Expanding Theoretical Foundations

One expert proposed exploring advanced modeling techniques such as decision trees or finite state machines to improve creative freedom and automation within prototyping. While these approaches hold potential, they are currently considered beyond the immediate scope of the project and will be examined in future studies.

Another area for future exploration involves accessibility and inclusivity in musical visualizations. Some experts emphasized the importance of considering accessibility, and artistic experiences. While these aspects are highly relevant, they fall beyond the current scope of Thunder and will be acknowledged as directions for future research. Future iterations of Thunder may explore methods for making musical visualizations more inclusive to diverse audiences, including users with sensory impairments.

6 Thunder: Key Improvements and Structured Process

Thunder is a structured and iterative design process developed to create music visualizations with a focus on emotional communication. The refined version builds upon the original user-centered approach, incorporating expert feedback to improve clarity, process structuring, and evaluation rigor. The most significant changes from the pre-refined version include:

- A restructured **Conceptualization phase**, now aimed at ensuring that songs with multiple emotional contexts are contemplated through mapping activities.
- The removal of **Implementation as a core phase**, allowing flexibility in execution and technological adaptation.
- More structured **feedback loops**, ensuring that refinements occur systematically based on external designers evaluations.
- The inclusion of **lists with specific criteria** that indicate to the designer when it is appropriate to move on to the next step.
- An expanded **Evaluation phase**, now incorporating the **DECIDE framework** to structure the planning of evaluation activities.

The refined Thunder process is structured into three main stages: **Conceptualization**, **Prototyping**, and **Evaluation**. Each stage ensures a rigorous approach to designing emotionally engaging music visualizations.

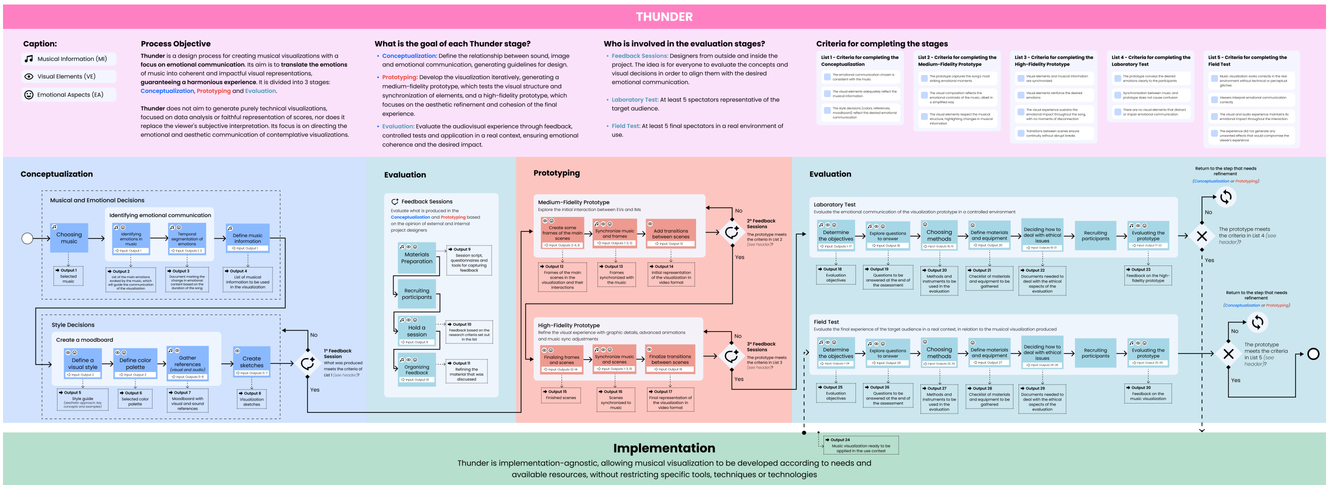

Figure 6. Thunder, a Design Process for Creating Music Visualizations focused in the Music's Emotional Communication (zoom in for a more detailed view).

6.1 Step 1 - Conceptualization: Defining the Emotional Communication

The first stage establishes the foundation for the visualization by defining its emotional intent and visual aesthetics. Unlike the pre-refined version, this stage now explicitly separates **Musical and Emotional Decisions** from **Style Decisions**, ensuring that the music's emotional communication drives aesthetic choices rather than occurring in parallel.

Musical and Emotional Decisions: Designers select a musical piece and analyze its emotional content. A key refinement in this version of Thunder is the explicit temporal mapping of emotions within the music. This ensures that multi-emotional contexts within a song are accurately represented in the visualization. By segmenting the music into emotional phases, designers can structure the visualization to reflect these shifts dynamically.

Style Decisions: With emotional mapping complete, designers move on to artistic choices, ensuring that the selected visual style reinforces the music's emotional message. The refined process provides clearer guidelines for building **moodboards and sketches**, aligning aesthetics with sound before moving to prototyping.

6.2 Step 2 - Prototyping: Iterative Refinement of the Visualization

The prototyping phase kept its basic structure divided into two levels: **Medium-Fidelity Prototyping** and **High-Fidelity Prototyping**

Medium-Fidelity Prototyping: serves as the initial animated representation of the visualization, incorporating key interaction points between music and animation. The first prototype features a simplified color palette, basic visual transitions, and an initial synchronization between the chosen musical elements and the visual representation. At this stage, an iterative feedback session is conducted with external designers who assess whether the prototype effectively conveys the intended emotions, whether the aesthetic choices facilitate comprehension, and whether the musical elements are successfully translated into visual interactions.

High-Fidelity Prototyping: The process progresses towards a polished visualization, incorporating adjustments from feedback. This version of the prototype includes full animation of the entire musical piece, improved visual refinement, and a clear definition of interactive elements. The high-fidelity prototype serves as the closest representation of the final product before implementation.

6.3 Step 3 - Evaluation: Assessing Emotional Impact and Design Coherence

Evaluation now plays a more structured role in the refined Thunder, ensuring that feedback is integrated throughout the process. The stage kept its original structure, divided into three activities: **Feedback Sessions**, **Laboratory Testing**, and **Field Testing**.

Feedback Sessions: These sessions occur after the conceptualization phase and during prototyping, and involve external designers. The goal is to assess the effectiveness of emotional communication, the coherence of aesthetic decisions, and the integration of musical and visual elements.

Laboratory Testing: This step evaluates the emotional response of users in a controlled environment and assesses the effectiveness of interactive elements. Unlike the pre-refined version, the refined Thunder incorporates the DECIDE framework as subactivities to ensure a well-structured evaluation planning, including participant selection, data collection, and analysis.

Field Testing: After implementation, the visualization undergoes real-world evaluation to validate emotional impact. The refined Thunder diagram now explicits this stage reiterations, meaning that unsatisfactory results may prompt refinements and further testing before finalizing the visualization. The DECIDE framework was also used as subactivities to ensure consistency in planning, execution, and assessment of results.

6.4 Implementation: A Flexible External Process

In the refined version of Thunder, implementation is no longer structured as a fixed internal stage, but rather conceptualized as an **external and adaptable step**. This decision stems from the understanding that implementation is highly dependent on technical, contextual, and logistical variables that differ substantially across design scenarios. Maintaining it as a prescriptive phase would reduce the process's versatility and potentially constrain designers working under diverse conditions.

By externalizing this step, Thunder allows the final visualization to be developed through a range of implementation strategies. Whether realized as a real-time system [Graf *et al.*, 2021], a rendered animation [fan, 1940], an audiovisual installation [Erdmann *et al.*, 2025], or a browser-based experience [Lee and Hong, 2025], the choice of implementation remains open to adaptation, ensuring the emotional and aesthetic intentions defined in the design process can be preserved regardless of platform or technology.

This flexibility reinforces Thunder's focus on emotional communication and expressive design, recognizing that the implementation phase often involves multidisciplinary collaboration and is shaped by factors such as available infrastructure, production timelines, and exhibition formats. Rather than prescribing a single mode of execution, Thunder encourages designers to treat implementation as a continuation of the design rationale—adjusted to context—thus broadening its applicability across both creative and technological landscapes.

7 Echoes of Thunder

Having presented the refined Thunder design process, this discussion brings a reflective critique of the essential challenges and insights arising from this context. We discuss the subjectivity inherent in designs for emotional engagement, the unexploited potential of music and visualization to promote psychological wellness, and the need to go beyond conventional metrics.

As we move through these reflections, we offer a few thought-provoking questions that we expect to serve as starting points for an innovative research agenda.

7.1 Strengthening Thunder: Insights from the Expert Refinement

The refinement of Thunder emerged from a clear need: to transform a process that had proven effective within a specific project into a more structured and widely applicable approach. While the original version of Thunder successfully supported the development of emotionally engaging music visualizations, its construction within the boundaries of a single design experience highlighted areas where the process could benefit from clearer guidance, broader applicability, and stronger methodological grounding.

Rather than viewing these early traits as limitations, we saw them as opportunities for intentional growth. One of the main strengths of the original version was its creative flexibility – phases could merge intuitively, and designers were free to improvise based on their understanding of the music and design goals. In the refined version, we sought to preserve this creative space, but now supported by clearer transitions between steps, structured decision points, and a more balanced relationship between openness and methodological clarity.

A particularly impactful refinement lies in how the conceptualization phase was reorganized. While the original version included emotional and aesthetic decision-making, the implicit simultaneity of these steps sometimes obscured the central role of emotional intent. Based on expert feedback, we refined this structure into two distinct but connected moments: the mapping of the emotional narrative of the music, followed by stylistic exploration guided by those emotional insights. This change reinforces emotional communication as the core driver of visual decisions and provides designers with a more intentional structure for aligning mood and style.

Another shift – also based on the expert feedback – was the removal of implementation as a fixed internal phase. Experts pointed out that technical execution often depends on contextual factors not foreseeable during early design, such as available tools, collaborators, or the intended format of presentation. By treating implementation as an adaptable continuation rather than a prescribed stage, Thunder is now better positioned to accommodate a range of technological environments while still preserving its expressive goals.

One of the most actionable insights from the expert review was the recognition that the process diagram alone, while helpful, does not fully capture the nuances and tacit knowledge embedded in each stage. In response, we are developing a complementary template that will accompany the Thunder diagram. This resource will include expanded explanations, practical examples, and methodological suggestions, offering clearer support for less experienced designers or multidisciplinary teams who may not be familiar with all aspects of emotional visualization design.

Overall, the expert review was not only instrumental in refining specific components of Thunder – it also validated the potential of the process while identifying concrete areas for enhancement. The feedback allowed us to articulate design rationales that were previously intuitive, clarify decision-making criteria, and better support designers in navigating the emotional and aesthetic dimensions of music visualization.

Ultimately, these refinements reinforce Thunder's foundational aim: to support the creation of emotionally resonant music visualizations. At the same time, they invite deeper reflections on how we approach affective design. As Thunder evolves into a more structured, and grounded method, we are also invited to reconsider the relationships between emotion, visualization, and design practice itself – shifting the focus from merely representing music to intentionally shaping the affective landscapes of digital experience.

To guide future investigations, we propose the following thought-provoking questions:

- How can design processes like Thunder maintain adaptability and creative openness while still offering the clarity and structure needed for reproducibility across diverse teams and contexts?

- Could Thunder evolve to support collaborative authorship – bringing together composers, psychologists, or even audiences – to co-design emotionally resonant music visualizations?

7.2 Dealing with the Subjectivity in Emotionally Resonant Music Visualization

Emotions are subjective individual experiences that are a function of the particular individual's history, culture, and personal preferences, such that different people interpret and react differently to the same stimulus [Juslin and Västfjäll, 2008; Cowen *et al.*, 2020]. This subjectivity makes selecting and synchronizing visual elements with musical elements very important.

Thunder addresses this complexity through the application of an iterative design process, which allows for ongoing refinement through user feedback and evaluation. In particular, the repeated testing of medium- and high-fidelity prototypes allows designers to match the visual elements to the desired emotional message progressively. Despite the advantages of iterative design, though, achieving universally consistent emotional responses continues to be a problem. Additional research must focus on comprehending and dealing with individual variations in emotional perception and reaction. This could involve integrating personalized features into visualizations or enabling users to personalize the visual experience in such a manner that it more closely aligns with their personal preferences.

Another critical aspect involves balancing aesthetic decisions with functional elements that interact meaningfully with the music. While the visual appearance is critical to audience engagement, it should not overwhelm the interactive elements that represent the musical components. This balance is particularly challenging during the high-fidelity prototyping phase of Thunder, where designers must ensure the visualization remains visually captivating and functionally informative. This aligns with findings from Holm and Siirtola (2012), who emphasized the need for harmony between visual and musical elements in their guidelines for music visualization systems. Furthermore, it is important to consider the excess of interactive elements competing within the visualization, a concern already noted in the literature as potentially affecting audience focus [Almeida *et al.*, 2021]. This aspect may be related to the lower scores of Focused Attention observed in the UES-Br applied to the initial visualizations (before applying Thunder), which suggests that a balance between visual richness and clarity is essential.

Still, another challenge in this context is the inherent subjectivity introduced when a single designer creates a visualization. The designer's personal, emotive perceptions and experiences can't help but filter through the visual elements and their synchronization with the music. This can result in a biased representation of the intended emotional impact. This could be why the emotional response some visualizations provoke might be distorted by the audience, as the feelings and sentiments of the designer would not align with the diversified emotional landscapes of different users. To decrease this type of subjectivity, in our process to develop Thunder, we included two designers and two researchers who were not part of the design process to collect feedback from different perspectives. We advocate that a multi-disciplinary team approach is necessary to design – where the psychology domain, musicology, visual arts, and user experience design come together to maximize the universality of emotional communication.

Addressing these design challenges requires a deeper investigation of the underlying mechanisms of emotional communication. To inspire future research in this area, consider the following provocative questions:

- Given the subjective nature of emotion, can we move beyond universal emotional mappings to create AI-driven visualizations that learn and adapt to *individual* affective profiles, minimizing negative impacts prior to their occurrence?
- What are the neurological mechanisms by which synchronized audio-visual elements create synergistic emotional responses? Can we use this knowledge to create algorithms that can produce engaging visuals on their own?

7.3 Fostering Well-being Through Intentionally Designed Music Visualizations

The complex interaction between well-being and emotions has been extensively documented across various academic fields, demonstrating the influence of emotions on human experiences and well-being [Ryan and Deci, 2001; Diener and Chan, 2011]. Emotional well-being is a key factor in mental health, influencing cognitive processes, behavior, and quality of life [Keyes, 2007; Huppert, 2009]. Understanding the mechanisms that underlie emotional responses and their effects on well-being can inform various applications.

Music plays a significant role in this dynamic as a powerful emotional stimulus. Its ability to evoke deep emotional responses and enhance well-being is well-established in research and practical contexts [Koelsch, 2014]. The structural elements of music – tempo, melody, harmony, and dynamics – interact with listeners' cognitive and affective systems to evoke a wide range of emotions, from joy and relaxation to sadness and tension [Juslin and Laukka, 2004; Salakka *et al.*, 2021].

Thunder is aligned with that perspective because it considers music's intrinsic emotional quality to help develop visualizations that enhance the emotional depth of interactive applications. This is supported by the Self-Determination Theory (SDT) [Ryan and Deci, 2017], a psychology theory widely used in HCI that focuses on intrinsic motivation, autonomy, and competence for well-being. Thunder can foster a sense of intrinsic motivation by creating immersive experiences that resonate deeply with users. It encourages users to engage with the visualizations out of genuine interest and enjoyment. This is particularly relevant in digital storytelling and artistic settings, where the effective integration of music and visuals can significantly enhance the story's emotional impact and help communicate an underlying message.

Furthermore, Thunder can be particularly beneficial to improving the sense of autonomy in contexts with limited access to music, such as for individuals with hearing impairments, contributing to their overall well-being and integration. Our research corroborates the work of Pouris and Fels (2012) and Fourney and Fels (2009), that highlight the importance of accessible music experiences for the deaf and hard-of-hearing communities. By enhancing the emotional expressiveness of music visualizations, Thunder offers an accessible way to experience the emotional content of music through visual stimuli, making the benefits of music more inclusive.

In order to find out how Thunder and music visualizations can promote well-being, we have to look closely at the ways they affect emotions. So, the following questions are to encourage future research:

- Can Thunder-designed visualizations be strategically applied therapeutically to encourage emotional processing in a way that allows users to engage and resolve negative emotions in the context of a safe and nurturing space?
- Beyond hearing-impaired accessibility, how could Thunder be made accessible to other forms of sensory and cognitive diversity, creating visualizations that are inclusively accessible and supportive of the well-being of all users regardless of ability or neurotype?

7.4 Going Beyond Engagement in Immersive Audio Experiences Evaluation

Sound is a potent force in shaping emotions and experiences within immersive environments, ranging from musical visualizations to games and virtual reality (VR). While it can enhance engagement, immersion, and well-being, it can also manipulate, induce anxiety, or divert attention for exploitative purposes. Recognizing this dual nature is crucial for responsible immersive experience design.

Applying SDT principles to audio design using Thunder suggests that catering to users' needs for autonomy, competence, and relatedness can enhance their engagement and well-being. For example, customizable sound settings, clear feedback mechanisms, and audio features that foster social interaction can all contribute to a more positive long-term user experience.

Generalizing research findings beyond specific application types, such as musical visualizations and VR experiences, helps mitigate potential biases and provides a more comprehensive understanding of the interplay between audio, user experience, and immersive design. Future research should employ mixed-methods approaches to measure and compare audio's impact on UX across diverse applications and contexts. This includes examining how audio interacts with UX in varying noise levels, distraction, immersion, and social interaction scenarios. Besides, research must consider a diverse range of participants with varying demographics, preferences, and experiences, including individuals with auditory sensitivities (e.g., misophonia, hyperacusis) or other pre-existing conditions that might influence their responses to audio stimuli. Statistical analysis can then be used to test hypotheses about the relationship between audio characteristics, UX, and well-being constructs, while also controlling for the potential influence of individual differences in auditory processing.

The relentless pursuit of engagement in various immersive experiences, from games to VR, often overshadows the critical role of user experience in promoting well-being. This focus on "engagement at all costs" can neglect long-term impacts. One step toward overcoming this scenario is a deeper understanding of how audio influences user emotions, behaviors, and mental states.

Audio is a powerful, though often overlooked, aspect of immersive experiences. It has the power to evoke strong emotional responses, influence people's sense of presence and realism, and can even impact cognitive processes. On the other hand, poorly designed audio can be distracting, irritating, and even harmful. Knowing how sound affects human beings is essential in creating experiences that are healthy and pleasant for users. This encompasses aspects of sound quality, spatial distribution of sound, using sound effects and music, and avoiding excessive noise. Properly crafting the sound enables creators to craft experiences that calm people down, concentrate them, and make them feel good, as opposed to stressing and annoying them. This thoughtful design must also consider the possibility that certain frequencies, soundscapes, or dynamic ranges will evoke negative reactions in certain individuals, and thereby produce overstimulating or anxiety-provoking spaces.

Hence, we must move beyond superficial metrics and evaluate UX through a lens that prioritizes both immediate enjoyment and long-term well-being. We hope that applying Thunder is a step in moving the design of musical visualizations toward being more holistic and beneficial.

Achieving this vision requires carefully considering our design priorities and investigating more about how sound affects users implicitly. However, a review of the literature on immersive audio assessment reveals that there are challenges in using common frameworks to mix measures in subjective data, such as self-reports, with the physiological effects of different sounds [Nunes and Darin, 2024], so further validation and frameworks are needed to understand such connections. This limited integration between subjective assessments and biometric data reduces the power to draw insightful conclusions.

To motivate future work that shifts the paradigm for audio visualization, we propose the following guiding questions:

- Beyond measuring emotional responses at the moment, how can we develop longitudinal evaluation frameworks that assess the sustained impact of audio visualizations on users, identifying and addressing any potential long-term harms?
- Can we develop intelligent audio visualization systems that adapt in real-time to a user's auditory sensitivities and cognitive state, dynamically adjusting parameters like sound intensity, complexity, and emotional valence to optimize their experience?
- What novel combinations of subjective (e.g., narrative accounts, focus groups) and objective (e.g., biometric sensors, behavioral tracking) evaluation techniques can

better capture the multi-faceted nature of the audio visualization experience?

8 Limitations

Thunder is a promising approach to designing emotionally appealing music visualizations but has some limitations. Firstly, emotional perception is subjective in nature and, therefore, is likely to vary from one individual to another on account of cultural background, experience, and taste. Hence, the process cannot guarantee the complete absence of discrepancies between the intended emotional communication and user experience.

Secondly, although Thunder was refined through an expert review, the inherently subjective nature of expert opinions presents a limitation. While this subjectivity is an inherent challenge in qualitative evaluations, our approach sought to mitigate its effects by selecting experts from diverse backgrounds in music, design, and human-computer interaction. This multidisciplinary perspective helped ensure a broader validation of Thunder's methodology. However, further expert reviews with a larger panel, including professionals from psychology, audiovisual production, and accessibility studies, could provide even greater depth in evaluating the process.

9 Conclusion

This paper introduced the refined version of Thunder, a structured design process focused on creating emotionally expressive music visualizations. Originally developed within a specific design scenario, Thunder showed promising results in supporting the emotional communication of music through visual language. However, its initial formulation revealed the need for broader methodological clarity and greater adaptability when applied beyond the specific context in which it was originally developed.

To address this, we conducted an expert review involving three specialists in Music, HCI, and Computing, whose feedback played a pivotal role in shaping the current version of the process. The new version features clearer phase distinctions, systematic evaluation points supported by the DECIDE framework, and increased flexibility through the externalization of implementation. These refinements strengthen Thunder's potential to be applied in diverse technical and creative scenarios while preserving its core emphasis on emotional communication. The process now balances creative freedom with structured guidance, making it more accessible to multidisciplinary teams and applicable across varying levels of design expertise.

Looking ahead, we plan to apply the refined Thunder in a new case study to validate its practical effectiveness and adaptability. Further research will explore its use in interactive and personalized visualizations, accessibility-driven contexts, and long-term emotional impact. These paths aim to extend Thunder's influence beyond static visualizations toward more dynamic, inclusive, and responsive design practices.

By presenting a process grounded in expert review and oriented toward real-world application, we hope Thunder can serve not only as a methodological contribution to music visualization, but also as a critical reflection on how emotional meaning is constructed, expressed, and experienced through design.

Declarations

Authors' Contributions

CN and TD conceived the study and designed the experiments. CN conducted the experiments, performed the primary data analysis, and drafted the initial manuscript. TD provided guidance on data collection and analysis, and critically reviewed and edited the manuscript for important intellectual content. Grammarly and Gemini were used as tools to improve the clarity and presentation of the text. These tools were used for editing and polishing, but not for generating original content. Both authors have read and approved the final manuscript and declare that they are responsible for all aspects of the work.

Competing interests

The authors declare that they have no competing interests.

Acknowledgements

This paper is a partial result of the project Digital Well-Being supported by CNPq (CNPq/MCTI Nº 10/2023 - UNIVERSAL) under grant number 404559/2023-9.

Availability of data and materials

The datasets generated and analysed during the current study will be made upon request.

References

(1940). Fantasia.

(1976). Atari video music.

(2019). Beat saber.

Abreu, R., dos Santos, J., and Bezerra, E. (2018). A bimodal learning approach to assist multi-sensory effects synchronization. In *2018 International Joint Conference on Neural Networks (IJCNN)*, pages 1–8. IEEE. DOI: https://doi.org/10.1109/IJCNN.2018.8489357.

Almeida, H., Cabral, G., and Moura, R. (2021). Design process and rapid prototyping of animated music visualizations. In *Anais do XVIII Simpósio Brasileiro de Computação Musical*, pages 114–120. SBC. DOI: https://doi.org/10.5753/sbcm.2021.19435.

Armstrong, J. S. (2001). *Principles of Forecasting A Handbook for Researchers and Practitioners*. International Series in Operations Research Management Science. Springer.

Bergstrom, T., Karahalios, K., and Hart, J. C. (2007). Isochords: visualizing structure in music. In *Proceedings of Graphics Interface 2007*, pages 297–304. DOI: https://doi.org/10.1145/1268517.1268565.

Brown, R. J. (1978). Audio activated video display. US Patent 4,081,829.

Chanda, M. L. and Levitin, D. J. (2013). The neurochemistry of music. *Trends in cognitive sciences*, 17(4):179–193. DOI: https://doi.org/10.1016/j.tics.2013.02.007.

Chasin, M. (2003). Music and hearing aids. *The Hearing Journal*, 56(7):36–38. DOI: https://doi.org/10.1097/01.HJ.0000292553.60032.c2.

Chen, C., Cao, N., Hou, J., Guo, Y., Zhang, Y., and Shi, Y. (2023). Musicjam: Visualizing music insights via generated narrative illustrations. *arXiv preprint arXiv:2308.11329*. DOI: https://doi.org/10.48550/arXiv.2308.11329.

Ciuha, P., Klemenc, B., and Solina, F. (2010). Visualization of concurrent tones in music with colours. In *Proceedings of the 18th ACM international conference on Multimedia*, pages 1677–1680. DOI: https://doi.org/10.1145/1873951.1874320.

Cowen, A. S., Fang, X., Sauter, D., and Keltner, D. (2020). What music makes us feel: At least 13 dimensions organize subjective experiences associated with music across different cultures. *Proceedings of the National Academy of Sciences*, 117(4):1924–1934. DOI: https://doi.org/10.1073/pnas.1910704117.

Cuny, C., Fornerino, M., and Helme-Guizon, A. (2015). Can music improve e-behavioral intentions by enhancing consumers' immersion and experience? *Inf. Manag.*, 52:1025–1034. DOI: https://doi.org/10.1016/j.im.2015.07.009.

De Prisco, R., Malandrino, D., Pirozzi, D., Zaccagnino, G., and Zaccagnino, R. (2018). Evaluation study of visualisations for harmonic analysis of 4-part music. In *2018 22nd International Conference Information Visualisation (IV)*, pages 484–489. IEEE. DOI: https://doi.org/10.1109/iV.2018.00090.

Diener, E. and Chan, M. Y. (2011). Happy people live longer: Subjective well-being contributes to health and longevity. *Applied Psychology: Health and Well-Being*, 3(1):1–43. DOI: https://doi.org/10.1111/j.1758-0854.2010.01045.x.

Erdmann, M., von Berg, M., and Steffens, J. (2025). Development and evaluation of a mixed reality music visualization for a live performance based on music information retrieval. *Frontiers in Virtual Reality*, 6:1552321. DOI: https://doi.org/10.3389/frvir.2025.1552321.

Fourney, D. W. and Fels, D. I. (2009). Creating access to music through visualization. In *2009 ieee toronto international conference science and technology for humanity (tic-sth)*, pages 939–944. IEEE. DOI: https://doi.org/10.1109/TIC-STH.2009.5444364.

Graf, M., Opara, H. C., and Barthet, M. (2021). An audio-driven system for real-time music visualisation. *arXiv preprint arXiv:2106.10134*. DOI: https://doi.org/10.48550/arXiv.2106.10134.

Hallam, S. and MacDonald, R. (2013). Introduction: Perspectives on the power of music.

Hassenzahl, M. (2008). User experience (ux): towards an experiential perspective on product quality. pages 11–15. DOI: https://doi.org/10.1145/1512714.1512717.

Hiraga, R., Watanabe, F., and Fujishiro, I. (2002). Music learning through visualization. In *Second International Conference on Web Delivering of Music, 2002. WEDELMUSIC 2002. Proceedings.*, pages 101–108. IEEE. DOI: https://doi.org/10.1109/WDM.2002.1176199.

Holm, J. and Siirtola, H. (2012). A comparison of methods for visualizing musical genres. In *2012 16th International Conference on Information Visualisation*, pages 636–645. DOI: https://doi.org/10.1109/IV.2012.107.

Huppert, F. A. (2009). Psychological well-being: Evidence regarding its causes and consequences. *Applied psychology: health and well-being*, 1(2):137–164. DOI: https://doi.org/10.1111/j.1758-0854.2009.01008.x.

Hwang, A. and Oh, J. (2020). Interacting with background music engages e-customers more: The impact of interactive music on consumer perception and behavioral intention. *Journal of Retailing and Consumer Services*, 54:101928. DOI: https://doi.org/10.1016/j.jretconser.2019.101928.

Juslin, P. N. and Laukka, P. (2004). Expression, perception, and induction of musical emotions: A review and a questionnaire study of everyday listening. *Journal of new music research*, 33(3):217–238. DOI: https://doi.org/10.1080/0929821042000317813.

Juslin, P. N. and Västfjäll, D. (2008). Emotional responses to music: The need to consider underlying mechanisms. *Behavioral and brain sciences*, 31(5):559–575. DOI: https://doi.org/10.1017/S0140525X08005293.

Kamioka, H., Tsutani, K., Yamada, M., Park, H., Okuizumi, H., Tsuruoka, K., Honda, T., Okada, S., Park, S.-J., Kitayuguchi, J., *et al*. (2014). Effectiveness of music therapy: a summary of systematic reviews based on randomized controlled trials of music interventions. *Patient preference and adherence*, pages 727–754. DOI: https://doi.org/10.2147/PPA.S61340.

Keyes, C. L. (2007). Promoting and protecting mental health as flourishing: a complementary strategy for improving national mental health. *American psychologist*, 62(2):95. DOI: https://doi.org/10.1037/0003-066X.62.2.95.

Khulusi, R., Kusnick, J., Meinecke, C., Gillmann, C., Focht, J., and Jänicke, S. (2020). A survey on visualizations for musical data. In *Computer Graphics Forum*, volume 39, pages 82–110. Wiley Online Library. DOI: https://doi.org/10.1111/cgf.13905.

Koelsch, S. (2010). Towards a neural basis of music-evoked emotions. *Trends in cognitive sciences*, 14(3):131–137. DOI: https://doi.org/10.1016/j.tics.2010.01.002.

Koelsch, S. (2014). Brain correlate of music-evoked emotions. *Nature reviews. Neuroscience*, 15:170–180. DOI: https://doi.org/10.1038/nrn3666.

Koelsch, S. (2015). Music-evoked emotions: principles, brain correlates, and implications for therapy. *Annals of the New York Academy of Sciences*, 1337(1):193–201. DOI: https://doi.org/10.1111/nyas.12684.

Lazar, J., Feng, J. H., and Hochheiser, H. (2017). *Research methods in human-computer interaction*. Morgan Kaufmann.

Lee, C. and Hong, J.-H. (2025). musicolors: Bridging sound and visuals for synesthetic creative musical experience.

Lee, Y. and Fathia, R. N. (2016). Interactive music visualization for music player using processing. In *2016 22nd International Conference on Virtual System & Multimedia (VSMM)*, pages 1–4. IEEE. DOI: https://doi.org/10.1109/VSMM.2016.7863205.

Lima, H. B., Santos, C. G. D., and Meiguins, B. S. (2021). A survey of music visualization techniques. *ACM Computing Surveys (CSUR)*, 54(7):1–29. DOI: https://doi.org/10.1145/3461835.

Lipscomb, S. D. and Kendall, R. A. (1994). Perceptual judgement of the relationship between musical and visual components in film. *Psychomusicology: A Journal of Research in Music Cognition*, 13(1-2):60. DOI: https://doi.org/10.1037/h0094101.

Liu, V., Long, T., Raw, N., and Chilton, L. (2023). Generative disco: Text-to-video generation for music visualization. *arXiv preprint arXiv:2304.08551*. DOI: https://doi.org/10.48550/arXiv.2304.08551.

Matessino, M. (1999). Letter in response to 'a study of jaws' incisive overture to close off the century'. Internet. [Accessed on March 4, 2009].

Miller, M., Bonnici, A., and El-Assady, M. (2019). Augmenting music sheets with harmonic fingerprints. In *Proceedings of the ACM Symposium on Document Engineering 2019*, pages 1–10. DOI: https://doi.org/10.1145/3342558.3345395.

Mori, J. and Fels, D. I. (2009). Seeing the music can animated lyrics provide access to the emotional content in music for people who are deaf or hard of hearing? In *2009 IEEE Toronto International Conference Science and Technology for Humanity (TIC-STH)*, pages 951–956. IEEE. DOI: https://doi.org/10.1109/TIC-STH.2009.5444362.

Munteanu, L. H. (2012). Musical culture, a finality of musical education. *Procedia-Social and Behavioral Sciences*, 46:4195–4199. DOI: https://doi.org/10.1016/j.sbspro.2012.06.225.

Nunes, C. and Darin, T. (2024). Echoes of player experience: A literature review on audio assessment and player experience in games. *Proc. ACM Hum.-Comput. Interact.*, 8(CHI PLAY). DOI: https://doi.org/10.1145/3677069.

Nunes, C., Reinbold, I., Castro, M., and Darin, T. (2024). Thunder: A design process to build emotionally engaging music visualizations. In *Proceedings of the XXIII Brazilian Symposium on Human Factors in Computing Systems*, pages 1–15. DOI: https://doi.org/10.1145/3702038.3702077.

Pereira, D. and Chambel, T. (2023). Enhancing emotional awareness and regulation in movies and music based on personality. *Proceedings of the 2023 ACM International Conference on Interactive Media Experiences*. DOI: https://doi.org/10.1145/3573381.3596462.

Pokharel, R. (2020). Exploring the different roles and aspects of music. *Molung Educational Frontier*, pages 125–133. DOI: https://doi.org/10.3126/mef.v10i1.34035.

Pouris, M. and Fels, D. I. (2012). Creating an entertaining and informative music visualization. In *International Conference on Computers for Handicapped Persons*, pages 451–458. Springer. DOI: https://doi.org/10.1007/978-3-642-31522-0$_6$8.

Prisco, R. D., Malandrino, D., Pirozzi, D., Zaccagnino, G., and Zaccagnino, R. (2017). Understanding the structure of musical compositions: Is visualization an effective approach? *Information Visualization*, 16(2):139–152. DOI: https://doi.org/10.1177/1473871616655468.

Reybrouck, M. and Eerola, T. (2017). Music and its inductive power: a psychobiological and evolutionary approach to musical emotions. *Frontiers in Psychology*, 8:242694. DOI: https://doi.org/10.3126/mef.v10i1.34035.

Rubio, D. M., Berg-Weger, M., Tebb, S. S., Lee, E. S., and Rauch, S. (2003). Objectifying content validity: Conducting a content validity study in social work research. *Social work research*, 27(2):94–104. DOI: https://doi.org/10.1093/swr/27.2.94.

Ryan, R. M. and Deci, E. L. (2001). On happiness and human potentials: A review of research on hedonic and eudaimonic well-being. *Annual review of psychology*, 52(1):141–166. DOI: https://doi.org/10.1146/annurev.psych.52.1.141.

Ryan, R. M. and Deci, E. L. (2017). *Self-determination theory: Basic psychological needs in motivation, development, and wellness*. Guilford publications.

Salakka, I., Pitkäniemi, A., Pentikäinen, E., Mikkonen, K., Saari, P., Toiviainen, P., and Särkämö, T. (2021). What makes music memorable? relationships between acoustic musical features and music-evoked emotions and memories in older adults. *PloS one*, 16(5):e0251692. DOI: https://doi.org/10.1371/journal.pone.0251692.

Schmidt, K. L. (2018). *Meaningful Music Visualizations*. PhD thesis, Purdue University.

Siu, A., S-H Kim, G., O'Modhrain, S., and Follmer, S. (2022). Supporting accessible data visualization through audio data narratives. In *Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems*, CHI '22, New York, NY, USA. Association for Computing Machinery. DOI: https://doi.org/10.1145/3491102.3517678.

Stewart, R., Kudumakis, P., and Sandler, M. (2010). Interactive music applications and standards. pages 20–30. DOI: https://doi.org/10.1007/978-3-642-23126-1$_2$.

Tian, Q. (2007). A survey on music visualization. *Computer Science*.

Zhang, Y., Pan, Y., and Zhou, J. (2018). Study on application of audio visualization in new media art. In *Journal of Physics: Conference Series*, volume 1098, page 012003. IOP Publishing. DOI: https://doi.org/10.1088/1742-6596/1098/1/012003.

Zimmerman, J. and Forlizzi, J. (2014). Research through design in hci. In *Ways of Knowing in HCI*, pages 167–189. Springer. DOI: https://doi.org/10.1007/978-1-4939-0378-8$_8$.