"We Musicians Know How to Divide and Conquer": Exploring Multimodal Interactions To Improve Music Reading and Memorization for Blind or Low Vision Learners

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ABSTRACT

Despite the potential of multimodal assistive technologies (MATs) to convey visual information, such as music notation, to blind or low-vision (BLV) individuals, we do not fully understand how MATs can be used to improve music reading and memorization. Through ideation and co-design workshops, we explored how modalities, such as sound and vibration, can improve music reading and memorization through hands-free timely interactions and reminders. Our design workshops presented a unique opportunity for BLV musicians and learners to collaborate and actively engage in the research and design process informed by their individual perspectives and lived experiences. We classified the complex challenges of reading and memorizing music into intrinsic (related to the cognitive aspects of music understanding) and extraneous (pertaining to external factors such as interaction and access) complexities and found that specific modalities are well suited to tackle particular problems. We conclude by outlining design implications and future research directions aimed at developing MATs that holistically improve music learning for BLV people.

CCS CONCEPTS

• **Human-centered computing → Accessibility**; • **Applied computing → Education**.

KEYWORDS

Blind and Low Vision Music Learning, Music Reading and Memorization, Vibrotactile Feedback, Multimodal Assistive Technologies, Cognitive Load Theory

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1 INTRODUCTION

Despite advancements in multimodal assistive technologies (MATs) that aid blind or low-vision (BLV) people in accessing visual information, the obstacles to learning music remain largely unresolved [1, 6, 26]. BLV music learners typically access new music by reading and feeling Braille music or by listening to audio recordings. However, each method presents unique difficulties that make the process slow, cumbersome and cognitively demanding [1, 6, 15, 26, 32, 34].

Commercially available aids have largely focused on software solutions that make music composition software screen-reader-friendly or convert music notation to Braille music in digital formats [47–49]. More recently, studies have focused on making music notation more accessible [17, 18, 21, 34]. Payne et al. created SoundCells, a browser-based system that outputs music notation in audio, print and Braille formats [33]. Relatedly, Lu et al. found that feeling timely variations in vibration intensities can provide contextual musical information while playing and performing music [27]. In parallel, music and HCI researchers have utilized sound, force feedback and vibration to aid musical instrument instruction for sighted learners [12, 25, 40, 41, 50, 52].

However, to our knowledge, no studies have investigated how MATs can holistically improve music reading and memorization for BLV musicians and learners. To address this gap, we conducted a two-part study to explore ideas for improving music reading and memorization utilizing multimodal interactions. To guide our approach, we pose two research questions:

- **RQ 1:** What are the primary challenges of music reading and memorization for BLV musicians and learners?
- **RQ 2:** How can multimodal interactions improve music reading and memorization?

Through these questions, we can examine the complexity of accessing and reading new music and understand the difficulties of music memorization. Furthermore, this enables us to pinpoint technological interventions that align specific modalities with particular challenges.

Our study comprised two phases involving nine participants: an ideation workshop and a co-design workshop. The first phase, the ideation workshop, featured open-ended discussions about the challenges and strategies related to music reading and memorization, where participants also developed design ideas beyond the constraints of current technologies. The second phase, the co-design workshop, combined sensory body storming with a Wizard of Oz exercise. We developed a proof-of-concept wearable haptic prototype, controlled by the facilitator, to manipulate a sample audio track to play, pause, stop, repeat and reset music in sync with vibrations. These vibrations communicated the tempo and changes in amplitude and provided timely musical reminders. Participants explored the independent and collective use of sound, vibration, and Braille music to enhance music reading and memorization.

Paper Contributions: First, we present findings that clarify the complex challenges of music reading and memorization, classifying key issues into *intrinsic* and *extraneous complexities*. Second, we introduce specific design ideas that tackle the challenges of music reading and memorization by pairing modalities with distinct needs. Third, we provide design considerations for designers and researchers to make MATs that holistically improve music reading and memorization for BLV musicians and learners.

2 RELATED LITERATURE

In this section, first, we discuss the challenges of reading and memorizing new music. After, we explore the intersection of multimodal assistive technology design and music learning. Lastly, we examine theoretical frameworks intended to reduce cognitive load during complex tasks. To provide context, we articulate definitions for commonly used music theory terms in Table 1.

2.1 Challenges of Reading and Memorizing New Music

There is a notable distinction between how sighted and BLV musicians read and memorize new music. While sighted musicians can simultaneously engage in reading, memorizing and learning to play music on their instrument, most BLV musicians separate these tasks into different stages of learning [15, 29]. For instance, a BLV musician might first listen to a new piece of music before deciding to learn it. Second, they would memorize the music line by line by either reading and feeling Braille music code or by listening to the music score, and finally, they would learn to play the piece of music on their instrument. Most BLV musicians and learners access new music by reading Braille music notation or hearing audio recordings. Both methods, however, present distinct challenges and limitations. Prior studies found that BLV musicians perceived Braille music code to be difficult to learn, time-consuming to read and costly to acquire [1, 6, 26, 32]. Goldstein added that the six-dot system of Braille is applied differently in Braille music notation compared to Braille for reading language [15]. For instance, the Braille symbol for the letter 'C' differs from the Braille music notation symbol for the musical note 'C'. Lu et al. highlighted an additional challenge, as Braille music requires musicians to take their hands off their instrument to read the notation before attempting to play the music on their instrument [26]. This is particularly taxing for pianists, who need to read music for each hand independently and then mentally merge these parts together when playing. Abramo and Pierce found that some BLV musicians avoided Braille music altogether and preferred accessing new music through hearing alone as it was quicker and more readily available [1]. This also presents a challenge for singers who need to read two lines of Braille simultaneously: one for lyrics and one for musical notes. [32].

However, Lu et al. also found that learning music by hearing audio recordings alone provided a limited and incomplete understanding of the music [26]. They reported that BLV musicians could miss parts of the music, such as Dynamics and Articulation (Table 1). Goldstein added that students who had never learnt Braille music code struggled to comprehend complex rhythmic concepts and timing [15]. Furthermore, Baker and Green pointed to the importance of Braille music for music literacy, as Braille music enables a shared language between sighted and BLV musicians to communicate and collaborate [6].

Prior studies also found that some BLV musicians accessed new music through a combination of Braille music and audio recordings. Making their choice based on the complexity of the music, learning and performance goals, time available to learn, access to music scores and personal preference [1, 6, 26, 29]. Baker and Green summarized that learning by hearing audio recordings was typically for speed, while Braille music notation was for accuracy [6]. From the literature so far, we assert that music reading and memorization remains a particularly challenging and time-consuming task for BLV musicians. Further research involving the BLV music community is required to design assistive technologies to address this challenge.

2.2 Multimodal Assistive Technologies for Learning

Recent MATs have improved the way BLV people learn and access information. Prior research has employed modalities such as touch and gesture to navigate and understand digital art boards [53], read schematics of electronic circuits [36] and create interactive maps [2]. Furthermore, prior studies used a combination of tactile interactions combined with sound outputs to teach drawing on a touchscreen [51], provide contextual information about the topography of continents [13] and to teach computational concepts [28].

However, due to the temporal nature of music, learning and accessing musical information is distinctly different from the examples described thus far. Most commercially available aids focus on screen-reader-friendly software solutions to transcribe music notation into Braille music code [47–49]. More recently, Payne et al. created a browser-based platform that makes music notation screen-reader-friendly while outputting music in audio, print and Braille music notation [33]. Another promising development in the design of Braille displays takes the form of the Active Braille 2021 [19], which integrates sound with the Braille display, enabling people to read Braille music code while also listening to the music simultaneously. In the field of music and HCI, researchers have explored vibrotactile feedback to provide timely reminders for technical guidance while learning a musical instrument [12, 20, 41, 50], convey musical information during performances [43] and convey musical expression to an audience [42].

Furthermore, prior studies have highlighted the promise of multimodal interactions (including vibrotactile feedback) and customizable solutions to improve BLV music reading and memorization [26, 34]. Zheng et al. [54] designed 3D-printed tactile buttons and switches with force-feedback to mock tactile interactions with a system enabling BLV people to actively participate in the design and making process. According to Lu et al., variations in vibration intensity could convey musical information such as tempo, rhythm, dynamics, and articulation [27]. Tanaka and Parkinson created the Haptic Wave, a physical device that conveys the amplitude

Terminology	Description
Arpeggiate	To play the notes of a chord consecutively, rather than simultaneously.
Articulation	The way a note or series of notes are played and connected, influencing the expression and character of the music.
Chord	A group of notes played together simultaneously.
Dynamics	The loudness or softness of notes or phrases and how quickly the volume changes. Intended to convey mood and meaning to a piece of music.
Learning By Ear	The method of accessing and memorizing music solely through listening.
Musical-Information	All the musical elements in a score, including pitch, tempo, rhythm, articulation, dynamics, and other instructions.
Perfect Pitch	The ability to recognize and identify a note by hearing it without any reference tone.
Pitch	The perceived highness or lowness of a sound, determined by the frequency of sound waves.
Rhythm	The pattern of sounds and pauses in music, including the timing and rest of notes.
Tempo	The speed at which a piece of music is played.

Table 1: Musical Terminology and Descriptions [16]

of sound from a digital audio workstation through the intensity of vibration [38]. Turchet et al. designed a haptic wearable device that assists BLV musicians in synchronizing with one another during performances [39].

2.3 Cognitive Load, Working Memory and Multiple Resource Theory

Learning to use a new type of assistive technology requires a measure of cognitive effort to familiarize interactions and functionality prior to use. Cognitive Load Theory (CLT) [37] provides a framework to understand a person's mental resources to perform tasks in conjunction with external factors like interaction and modality. According to CLT, the amount of information a person can hold in their working memory is limited, and this working memory is necessary to understand a system and perform tasks within it [4, 11, 22]. For instance, a person trying to memorize a speech on a new digital interface must first dedicate mental resources to understand how to use and interact with the interface and then dedicate mental resources to memorize the speech.

Furthermore, CLT classifies the cognitive load of memorization as an *intrinsic complexity* and the cognitive load of learning a new interface as an *extraneous complexity* [30, 37]. According to Oviatt's research, we should design interfaces that decrease *extraneous complexity*, making systems more intuitive and easier to use [30]. Additionally, it is important to point out that the design of new interfaces must also account for how people currently perform tasks and interact with systems in a particular context. Paas et al. explain that over time, people form "schemas" or mental models that allow them to engage with complex systems without reliance on working memory [31] and as such, we must build on existing mental models when designing new technologies.

When framing the task of music reading and memorization as outlined in Section (4.1), we assert that a high amount of *extraneous complexity* is involved in accessing new music, thus reducing the working memory capacity to perform the task of reading and memorization. The Multiple Resource Theory (MRT) developed by Wickens and colleagues offers valuable insights into potential solutions for this challenge [44, 45]. MRT states that tasks can be performed more efficiently when attention and workload are distributed across different visual, audio and tactile modalities. Additionally, Baddeley posits that working memory consists of multiple independent processors [4]. i.e., visual information and auditory information are processed independently in different memory centres. In sum, multimodal interactions have the potential to reduce the cognitive load of completing complex tasks. Subsequently, music and HCI researchers such as Kuchebuch et al. combined auditory, visual and tactile systems to teach motor functions during music training [23]. Furthermore, Chin et al. applied visual, audio and haptic feedback to develop a computer-aided flute tutoring system [12]. Both studies indicated that multimodal interactions improved learning efficiency when compared to unisensory input methods for learning. Our research builds on this prior work to explore multimodal music reading and memorization for BLV learners.

3 METHODOLOGY

Our study consisted of two phases: an initial ideation workshop (Phase One) followed by a co-design workshop (Phase Two). The research team comprised two sighted researchers (first and third author) and one blind researcher (second author). The first author, with experience in accessibility research and design of assistive technologies, worked with the second author, a music educator, a Braille music reader and a musician (piano, voice, clarinet and saxophone) to identify the goals and methodology of this study. Later, the third author supported data analysis and synthesis of findings.

In collaboration with BLV musicians and learners from The FMDG Music School[1], we invited people with experience with Braille music and/or Learning by Ear (Table 1) to participate in this study through workshops conducted individually, in pairs and in small groups. A total of nine people participated in this study.

3.1 Initial Project Planning

Through a series of virtual meetings, the first and second authors outlined the study's objectives, designed the workshop procedure, and created prompts to generate ideas and facilitate open-ended discussions. We focused on common music reading and memorization strategies, cognitive load and challenges of music memorization and the potential advantages and limitations of multimodal haptic wearables for BLV music reading and memorization. We also explored the usefulness of tactile interactions and the suitability of particular vibration patterns and intensities to convey particular musical information.

3.2 Participant Recruitment and Information

Our institution's research ethics board approved the protocol and call for participation, and we shared it with The FMDG Music School community. We recruited nine BLV musicians and learners; four participants identified their gender as female, and five participants identified their gender as male. Participants were between 18 and 72 years old (M = 29.0, SD = 19.9). Seven participants indicated they were completely blind, one indicated they had low vision, and one participant mentioned that they were deafblind.

We refer to each participant with the letter P, followed by a number:

- P1 has a degree in music education and choir directing. They teach piano and mostly learn new music using Braille music but can also Learn by Ear when they cannot access Braille music scores.
- P2 is a Braille music specialist who works as a Braille music translator. They play the piano and sing. They primarily rely on Braille music to access new music.
- P3 is a multi-instrumentalist who plays piano, guitar and percussion. They mainly access new music through hard copy or digital Braille music.
- P4 is a music learner who takes piano, violin and voice lessons. They can read Braille music and also Learn by Ear.
- P5 is a multi-instrumentalist who primarily plays and teaches piano but is also familiar with other wind and string instruments. They primarily memorize new music through Braille music but can also Learn by Ear.
- P6 is a music learner who has taken piano lessons for over 10 years and also takes voice lessons. They describe themselves as a slow Braille music reader and do not enjoy reading Braille music. Instead, they prefer to Learn by Ear.
- P7 is a professional musician and recording artist with music and music therapy degrees. They play the piano, trumpet, and sing. They find Braille music very difficult and much prefer Learning Music by Ear.
- P8 is an amateur musician who has taken piano lessons for over ten years. They also play percussion instruments and participate in choirs. They are comfortable with Braille music.
- P9 is a professional musician and a music educator. Their primary instruments are the saxophone and the clarinet. They primarily access music using large print or sheet music but can also memorize music by hearing recordings.

3.3 Procedure

The first author facilitated three sessions of the initial ideation workshop (Phase One); one in-person and two online, followed by five sessions of the in-person co-design workshop (Phase Two) over a period of four days at The FMDG Music School. The design and activities of Phase One and Phase Two were predetermined beforehand during the initial project planning phase (Section 3.1). However, discussion prompts and questions during Phase Two were also informed by insights from Phase One. Phase One was designed to act as a space for open-ended ideation, while Phase Two explored specific modalities for the transfer of musical information (such as audio and vibration) and modalities for interaction (such as tactile interactions). BLV students and teachers participated individually, in pairs and in small groups based on their availability, with the exception of P7, who did not participate in Phase Two due to their unavailability (Table 2). Each phase of the study lasted for approximately one hour. Before the start of the research, we informed participants about the study's goal and asked them to share their experiences with music memorization, Braille music and Learning Music by Ear.

3.3.1 Phase One - Brainwriting and Brainstorming: The initial ideation workshop took the form of Brainwriting [14] and Brainstorming [10]. We tasked participants with generating ideas and conceptualizing how different modalities, such as audio (pitch of notes), vibration, and touch (reading Braille music), can make music reading and memorization more accessible and less cognitively demanding. We encouraged participants to think beyond current technological limitations, allowing for creative and imaginative ideas. To facilitate this ideation workshop, we asked participants questions such as:

- Describe how you read and memorize new music. What are some of the challenges when trying to read and memorize music?
- Imagine you have a piece of music that you would like to learn. Describe the steps you would take to access and memorize the music.

[1] A music school for blind and low vision people in New York City

	Participant Groups	Activity	Location
Phase One	P1, P2, P3, P4 and P5	Brainstorming	In-person
	P6, and P7	Brainstorming	Online
	P8 and P9	Brainwriting	Online
Phase Two*	P9	Co-design workshop	In-person
	P3, P6 and P8	Co-design workshop	In-person
	P2	Co-design workshop	In-person
	P1 and P4	Co-design workshop	In-person
	P5	Co-design workshop	In-person

Table 2: Summary of Participant Groups and Activities. *P7 was not available.

- Imagine a technology that utilizes sound (audio and spoken word) to make music reading and memorization easier and more accessible. What innovations might emerge from this approach?
- Envision a technology employing vibration to aid music reading and memorization. What potential benefits and limitations might arise from the use of vibrotactile feedback?
- Picture a technology that can integrate touch, particularly for Braille music reading, to improve music reading and memorization. What innovations might emerge from this approach?
- Now, envision combining the various modalities discussed along with any other ideas that might have come up to conceptualize technology that could make music reading and memorization more accessible and easier to do. What would such a technology look like?

The intention behind these questions was to foster open-ended discussions, leading to follow up inquiry into the design specifications of the imagined technologies. This approach prompted exploration into various aspects, including interaction methods with the system, technology placement on the body and the instrument, and advantages and limitations.

Initially designed as a Brainwriting exercise, we intended for participants to contribute ideas on a shared virtual Word document, facilitating reading and reflection by others. However, due to accessibility challenges and participant discomfort with virtual document navigation in two sessions, we transformed the workshop into a Brainstorming activity. Participants verbally shared their thoughts in response to prompts, with others offering their insights and ideas. Phase one of this study concluded with one virtual Brainwriting workshop and two Brainstorming workshops (one in-person and one online). We made audio recordings of all virtual and in-person workshops that were later analyzed.

3.3.2 Phase Two - Sensory Bodystorming and Wizard of Oz: Informed by prior literature on the use of haptics in BLV music contexts [27, 39], use of tactile materials for mock interactions [35, 46, 54] and through the lived experiences and expertise of the first and second author, our co-design workshop combined Sensory Bodystorming with a Wizard of Oz exercise. We developed a wearable haptic prototype controlled by the first author to play, pause, stop and repeat the sound of a sample audio track in sync with vibrations. We used vibrations to 1) convey the Tempo of the piece through timely intermittent vibrations, 2) represent changes in Dynamics through changes in vibration intensity, and 3) communicate timely reminders in the music through predefined vibration patterns (Figure 1). Additionally, the vibrations and sound of the sample audio track could be independently toggled on and off or slowed down and sped up. We asked participants to attach the vibration motors (encased in a 3d printed case) to their forearm. Using the prototype, we demonstrated how participants can access musical information through a combination of audio and vibration as well as leave themselves temporal markers in the music through predefined vibration patterns. We initially demonstrated the interactions and then allowed participants time to explore and suggest how they would like to simulate the interaction.

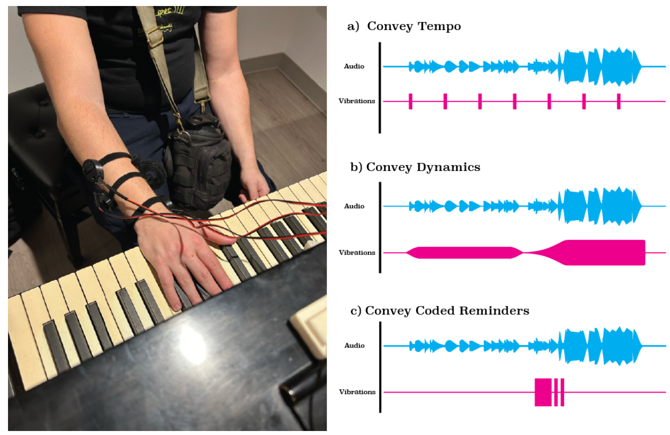

Figure 1: (Clockwise, from left) Image showing a participant's hand on a piano with vibration motors attached to their forearm as they feel the different types of vibrations in sync with the sample audio track. Graph a) a visualization of the audio sample in sync with vibrations to convey tempo; Graph b) a visualization of the audio sample in sync with vibrations to convey changes in Dynamics (loudness and softness of music); and Graph c) a visualization of the audio sample in sync with coded reminders through vibrations.

After completing the demonstration, we asked participants to imagine a new piece of fairly challenging music for them and ideate on how they may want to use an imagined multimodal wearable system to read (using Braille music notation) and access (by listening and feeling the musical notes) the music score. We also fabricated and modified a series of 3D-printed tactile buttons and switches from the Mechamagnets [54] project to mock up tactile interactions with this system. The Mechamagnet buttons and switches were fitted with magnets that provided force feedback when pressed or turned and attached to velcro, enabling participants to move and orient individual buttons and switches as they see fit and attach them to different points on their body through the fabric (Figure 2).

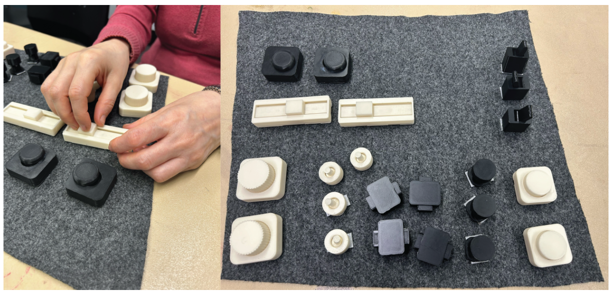

Figure 2: Image on left: Participant interacting with 3D-printed Mechamagnet sliders stuck onto fabric using velcro. Image on right: 3d-printed Mechamagnets [54] switches, sliders, toggles, rotary encoders and joysticks with embedded magnets that provide force feedback positioned onto fabric using velcro

3.4 Data Analysis

The first and second authors conducted an inductive thematic analysis following the six steps outlined by Braun and Clark [8, 9]. Our thematic analysis is descriptive and used for data reduction. The analytical focus was to describe the experiences and ideas of our participants.

To begin with, the first and second authors acquainted themselves with the data by individually reviewing randomly chosen transcripts from both the first and second phases of the study. Next, we read the transcripts line-by-line and assigned initial semantic codes (i.e., the explicit statements people made) along the transcript. Afterwards, we compared assigned codes, refined codes based on agreements and disagreements, and created a codebook with code names and definitions. We revisited the transcriptions to assign latent codes (i.e., the implicit meanings based on what people said) and added those codes to our codebook.

The first author repeated the systematic coding process. They thoroughly reviewed the remaining transcripts multiple times, meticulously applying line-by-line coding with the assistance of the codebook, while also generating fresh codes as needed. The first author then shared these new codes with the second author, and through agreements and disagreements, they devised additional codes and corresponding definitions. Next, the first author grouped the codes into potential themes based on similarities and relevance to the **RQs**. Subsequently, informed by the theoretical framework of CLT, the first author and third author reviewed and refined the themes, going back and forth between the codes and the potential themes and pinpointing quotes that represent the themes. Lastly, we report the results, offering connections between the themes and prior work and responding to the **RQs**.

When presenting participant quotes, we omit inessential parts for the ease of reading (e.g., filler words). We indicate parts of the text that were not relevant to the analysis and omitted with the annotation [. . .].

4 FINDINGS

In this section, we first describe the challenges and strategies for BLV music reading and memorization. Next, we report multimodal technological ideas to meet the requirements of BLV music learners. Lastly, we describe design considerations for future technologies.

4.1 Challenges and Strategies of Music Reading and Memorization

In response to **RQ1**, we asked participants to describe the challenges and strategies of music reading and memorization. In this section, we classify their responses into four categories: *Intrinsic complexities of Braille Music*, *Intrinsic complexities of Learning by Ear*, *Extraneous complexities of Access* and *Strategies for Music Reading and Memorization*. The first two categories relate to the innate complexity of Braille music code and audio recordings for music reading and memorization, the third category pertains to the challenge of accessing musical information through Braille music and audio recordings, and the fourth category relates to the approaches utilized by music learners.

4.1.1 Intrinsic Complexities of Braille Music: We found that seven of the nine participants primarily relied on Braille music to read music. However, participants quickly pointed out the challenges and limitations of Braille music. P8 said, "I've noticed that the older I get and the more stressed my life gets, my short-term memory suffers. When I'm reading Braille music, I will read the same line dozens of times just to be able to play the line once all the way through... it's such a time waster". P6, who prefers memorizing new music using audio recordings alone, added, "I hate Braille music. I wish that I could learn everything by ear. But I understand that's not feasible because I need these skills if I'm going to do anything with music in life. To put this into perspective, I love reading Braille... the thing I hate most about Braille music is that the code for literary Braille is not the same code for music Braille (For example, the code for the letter D in literary Braille is the same as the code for music note C in Braille music). Every single letter is off by one letter. Sometimes, my brain doesn't switch between reading lyrics and reading music. This makes no sense".

Three participants described the challenge of understanding complex rhythm patterns and time signatures using Braille music. P8 added, "I feel like it takes me really long to understand rhythm. I haven't studied music long enough to internalize the rhythms on a page. In my mind, there is always a five-minute period where I am reading a bar of music, and I'm counting the notes without knowing what it sounds like. It is frustrating for me". P3 further explained the challenge of complex rhythms and said, "You're counting the notes, but it can be overwhelming, especially if there are a bunch of dotted notes followed by a bunch of other notes. You're trying to analyze it (before hearing it), and it takes a while".

Additionally, participants reported that Braille music notation includes instructions for the repetition of certain sections and instructions on how to play specific sections. However, as pointed out by P5, the details about the sections remain incomplete. They said, "So there's nothing in the Braille music notation that says this is the exposition or this is a recap. There's nothing that says that. It just gives you a measure number. It says go back to measure 45 or whatever, and that's it". Furthermore, BLV musicians read Braille music linearly in a single line. All information about how to play a particular note, including the time signature and the expression, is given before the note itself. So, at times, a large number of Braille dots are taken up by information about the note. P7 described this challenge and said, "Well, you understand that when we read a score in music, it's not the same as a sighted person seeing a score. You can't see it all at once. You can't glance at a whole measure. For us, it's like one symbol at a time. It could be a tie symbol, an octave mark, a sharp sign, an accidental sign, or that type of note. By the time you've gotten 4 or 5 symbols, you're only reading one note, and then you don't even know whether it's a quote you don't even know. You also have to figure out the rhythm. It just takes a long time".

P2 and P3 also added that Braille music code had changed over time, making reading Braille music even more complex. P3 said, "With Braille music, you really have to pay attention to every single thing that you are reading. I mainly find that because Braille music has changed throughout, some codes and symbols have changed over the years. Knowing the different signs depends on knowing when the score came out".

4.1.2 Intrinsic Complexities of Learning by Ear: Participants also pointed to the challenges of learning music by ear, especially for learners who cannot identify the pitch of notes by hearing alone. P7 said, "If someone has a good ear, then they could use sound to receive the pitch of notes... But if you can't do that, it's very difficult". P9 added that trying to listen to and play complex music simultaneously can be overwhelming. They said, "It's almost like a sensory overload. Music is oral for the most part. It can be too much if you're getting too much information at once; it can slow down or hinder the learning process". Furthermore, P7 added that listening to the notes and then playing them in two steps makes learning by ear as complex as reading Braille music for people who do not have Perfect Pitch (Table 1). They said, "You will have to hear the notes, and then you play after it. It would be like learning Braille music. That's the same thing. You would have to learn it by ear, and then you play it. Or you read it in Braille and you play it. But how can we play and read it at the same time?". P3 (while demonstrating on piano) said, "If you have complex chords like this (plays a series of notes together), a person can't decipher it by hearing alone".

4.1.3 Extraneous Complexities of Access: Participants reported difficulties related to accessing musical information. Four participants described the tedious nature of accessing Braille music. P7 said, "When a blind person first reads a score, they cannot play and read at the same time. That's not possible. I only read one line at a time". Later, they added, "When learning piano music, I have to basically look at (the music for) each hand and then put them together in my mind. That is not easy, especially since some music can take up a whole page, which is unbelievable... I mean, it just takes a long time". P6 agreed with P7 and said, "I don't often use Braille music. Reading a piano score (with Braille music) would slow down my learning a lot". P9, who has low vision, said, "What's challenging for me is that I can't process information through my eyes as fast as someone with 20/20 vision. There is always a slight delay, whether I'm reading music or learning it in real-time. I have to do it slowly in order to get it where I want it to sound like".

We also found that Braille displays have not made Braille music easier to access. Braille displays are typically single line, allowing only one line of information to be read at a time. P7 explained, "I've read music on a Braille display before. It's awful. Especially for vocal music because one line is for words, and one line is for the notation itself. But you can only read Braille one line at a time on a Braille display". P4 noted that, unlike traditional music notation on paper, Braille music does not permit musicians to leave notes or markers in the score. They said, "If I have to change the fingering, for example, I have to make sure it's on the audio recording of the music. Because you can't leave notes in a Braille score, you cannot even erase Braille".

Additionally, P2 and P9 added that Braille music notation is not always available and can, at times, be inaccurate. P2 said, "From time to time in Braille music, there might be some ambiguity; when the transcriber prepares the Braille score, they're trying to map (Braille music code) onto what's in the print score. And sometimes, I see an error in the music, and I'm not sure what it should be. If it's a misprint on the note or maybe something that looks like an articulation sign".

4.1.4 Strategies for Music Reading and Memorization: Through lived experiences, participants developed personal strategies to simplify music reading and memorization. We found that participants preferred reading and memorizing music using a combination of different modalities (i.e. audio recordings and Braille music notation). P2 explained, "I think listening is good for finding the structural elements of a piece, the larger details, the macro world of the piece. But then I have to read the music to be able to zoom in to measures". P5 added, "I have to hear the music to understand the overall concept of the piece first". P2 also added that they would first need to listen to the piece of music before determining if they wanted to memorize it and learn to play it. They said, "I have to first hear the music to figure out how technically difficult it will be for me before I see all the ins and outs of the notation". P9 summarized, "We don't have the luxury of time as teachers or professionals. We have to learn things very fast in a short amount of time, and we have a limited time to practise. So we look for shortcuts, if I can learn something two ways and do two different ways at once, it's going to work for me personally. I guess you could say that I'm a multimodal learner".

Participants also described the importance of internalizing the music. P1 said that they would sing to familiarize themselves with the music. Additionally, participants discussed the importance of repeatedly listening and slowing the tempo of the music. P9 said, "I think the most important thing for me is to hear it slowly. Being able to hear it at a very slow tempo is critical to picking up all the bits of information. If I hear it at tempo or too fast, then it doesn't mean anything because it's just going to go out of the brain". Later, they added, "When I listen to the sound, I will isolate different elements of the music such as pitch and rhythm; I will replay and repeat what I am listening to memorize it". P8 described the process of memorizing small parts of music before putting it together. They said, "When I had to learn music, I would basically build it up like Lego blocks in my head of everything that I have to read. It's just me sitting at the piano, reading (and listening) to it slowly, bit by bit".

Additionally, participants pointed out the importance of music teachers in music reading and memorization. P6 said, "I record my lessons with my teacher, and she guides me through it. She plays a phrase, and I play it back for the recording. Later, I take that recording and practise it more in-depth". Similarly, P8 reported, "I like having someone to work with and teach me how to play the notes on the piano or maybe have a score to follow."

In summary, BLV music learners face complex challenges when reading and memorizing new music. *Intrinsic Complexities of Braille Music* include the significant cognitive load involved in reading Braille music, difficulty interpreting rhythm and time signatures, incomplete musical instructions and non-standardized coding. *Intrinsic Complexities of Learning by Ear* include struggling to interpret details in the music, especially if someone does not have a good ear or does not have a Perfect Pitch (Table 1). *Extraneous Complexities of Access* include the slowness of accessing Braille music as you need your hands to read music and play the instrument, the unavailability and inaccuracy of Braille music notation and the limited utility of Braille displays. Additionally, we found very little evidence of technological applications to address these challenges. However, P9 did mention that they used many different systems to assist them with reading and memorization. They said, "I think it would either be a metronome and a tablet to read the music or headphones to listen to the music while reading it, but there is no system which would sync this all together so you can just focus on one thing."

4.2 Matching Modalities to Requirements

In the previous section, we found that music reading and memorization is a complex, time-consuming task that requires significant *working memory*. In Phase Two of our study (Section 3.3.2), we explore vibrotactile feedback, synced audio and imagined interactions. In response to **RQ2**, our participants present ideas that incorporate different modalities to support music reading and memorization.

4.2.1 Improving Readability of Braille Music Notation: To reduce the cognitive demands of Braille music, P5 imagined a system that would allow them to show and hide parts of the Braille. They said, "I would love to be able to segment the music. For example, if I have a piece of choral music, I can look at just the words, or I can look at just the music, or I can look at the music without annotations, only the raw notes". P9 further described this idea and said, "I would like to break up the music into sizable chunks that I can isolate and loop over. It could be the arrangement of notes or the succession of notes. It's just about breaking it down into smaller chunks, so it's easy to practice". P8 proposed a system that would audibly play Braille music while it is read. They said, "Translating Braille music into sound directly is not something I ever thought about before. I think that would be especially helpful to me, but I recognize it's probably more like a beginner tool".

4.2.2 Utilizing Vibrations to Convey Rhythms and Timing: P9 said, "If I'm listening to a metronome and learning a piece by ear, it can get confusing. If the audio of the metronome can be replaced by vibrations, then I can feel the beats and hear the music. I can engage in learning through different ways". P3 suggested that complex rhythm patterns requiring asynchronous left- and right-hand patterns could be conveyed through vibrations on the piano. They said, "If you had a metronome mode, you could have the left (vibration on the left hand) going to play the left-hand rhythm while the right (vibration on the right hand) just count out the metronome". Later on, P3 mentioned that vibration can be utilized to perceive musical timing. They said, "if you have like a simple passage where it's a constant stream of either 32nd or eight notes or something like that, and you have the vibrations mimic that, that would be better than the Braille music". However, P7 and P8 remained skeptical of using vibration to convey rhythm and timing. P7 said, "I'm honestly not sure how something like that would work because if it were just vibrations, then you might be able to get rhythm across, but I don't know how you could get each note across like this".

4.2.3 Using Vibrations as Timely Landmarks: According to four participants, vibrations could serve as timely reminders while listening to or playing music. P6 said, "Vibrations could be used to know a cue. Okay! Difficult measure number 64 is coming. Yeah. Remember that". P2 addressed the temporal element of the landmarks. They added, "I think maybe you would feel a vibration a couple of bars before there's a notable change in some parameter. It doesn't have to be vibrating the entire time for tempo. It could be just a warning that there will be a change in general dynamics or a time signature. Yeah, I guess that's a big thing, especially in music that changes all the time". P8 added that leaving vibration-based signposts in the music might be particularly useful; they said, "While hearing and reading the music, you could leave notes for yourself through vibrations. The intensity or the pattern could mean something. It would obviously differ from person to person but you could have some defaults like a short vibration means this is where the fingering gets tricky".

4.2.4 Providing Technical Guidance with Multiple Vibrations: According to P8, vibration can be utilized to indicate which finger should be used for playing. They said, "If you could customize it for a single person, like if they're playing a very complex Mozart or Bach piece, vibration motors could be attached to your body, and you could simulate multiple fingers, or you could have up to 5 or 6 of these like all over the body to do different melody lines". According to P2, using multiple vibration motors to accurately represent fingering patterns is possible.

4.2.5 Augmenting Audio to Improve Comprehension: P3 suggested breaking complex chords into individual notes to aid understanding. They said, "If you have very complex chords, say a person can't read it or decipher it by hearing alone. Maybe the system can arpeggiate (play notes individually and sequentially) the notes of that chord". They then demonstrate this idea by playing a chord (group of notes together) on the piano and then play the individual notes sequentially to describe their idea. Additionally, P5 described a play-along feature to help left- and right-hand coordination. They said, "While I'm learning the right hand, the system could play the (audio) of the left hand so I can hear what it sounds like together". Additionally, four participants suggested that the ability to modify the music's time signature to be slower or faster would assist them in understanding the notes when listening to it alone.

4.2.6 Integrating Multiple Modalities for Flexibility and Control: We also found that participants were keen to integrate Braille music, audio and vibrations together. P6 said, "The notes could be with Braille. The vibration could be used for rhythm. And the sound could be for things that you wouldn't notice in a score like dynamics". P9 added, "I would focus on (hearing) the pitch first. Next, I'll (feel) the rhythm in sync with the pitch". While P2 and P3 described vibrations for changes in dynamics and tempo. P8 mentioned that timely vibrations could be utilized to amplify subtle sounds. They said, "I find it hard to focus on certain timbres (texture of musical notes) in ensemble performances, so I would suggest the ability to sync up a vibrating tool with certain instruments in a track in order to better facilitate memorization of rhythm. I feel this would be particularly useful for the more subtle instruments in an ensemble (like the altos in an acapella group or the near-silent hiss of a shaker)". Seven participants expressed a desire to dynamically switch between different modalities for accessing musical information.

Additionally, P2 pointed out that any new system can feel complex, and having the ability to toggle between modalities and turn things on and off is important. They said, "It's a novel thing that hasn't been around before. It takes kind of getting used to the stimuli. For some people, it might be a bit of a sensory overload. That's why it's good to have options available like turning things on and off". P9 further articulated this idea and said, "I would want the ability to control all those things. I think that's what we do. Without all this technology, we musicians know how to divide and conquer. I'll feel the rhythm first, then hear the pitch, and then put it together. Then, I will play it upside down and play it backwards, slow and fast. I would mark out the strong beats so I get vibration feedback, and I might read the pitches visually, and I might hear the rhythm".

4.3 Future Design Considerations

The open-ended discussion prompts in Phase One (Section 3.3.1) and the Sensory Bodystorming and Wizard of Oz exercise in Phase Two (Section 3.3.2) led to discourse between participants about the utility of technologies and other conceptual ideas that remain unexplored. In response to **RQ2**, we report the advantages, drawbacks, and potential factors to consider for future technologies.

4.3.1 Make It Simple and Tactile: During Phase Two (Section 3.3.2), P4 and P9 described the importance of making technology that is easy to understand and simple to use. P9 said, "This makes me think that whatever the system is, simplicity is really important. There is enough complexity with the instrument and learning the music. The interaction would be very simple and straightforward". P4 echoed a similar thought and said, "Technology is developing, but it still needs extra work just to make it more useful". Later, P9 added, "I think I'm gravitating to tactile buttons. They are kind of binary in a way. To an extent, they are inherently accessible because the system gives you feedback about what you did". In response, P8 also articulated the potential of tactile interactions and said, "This reminds me of old cassette tape recorders. The buttons provided very good tactile feedback". P6 imagined a tactile control system that they mocked up and said, "I have a power switch that goes on and off; I have a play, pause, backward, forward switch; I have a slider for vibration intensity; I have a dial to make it faster or slower" (Figure 3). However, P4 also pointed out that tactile controls may not always be accessible. They said, "Some controls may be harder for people who have issues with their hands. Instead, the voice could potentially make it more accessible".

Figure 3: Image on left: P6 places the Mechamagnet switches on their lap to depict position and suitability of interaction. The image on the right: P6 creates a layout of tactile buttons and switches and wears it on their forearm.

4.3.2 Enable Hands-free, Body-centric Interactions: During Phase Two (Section 3.3.2), four participants also discussed considerations for hands-free technologies on and around the body. P1 said, "I need my hands to be free. I mean, if the vibrations are on my hands, I don't know if it's going to help me in my reading. I put my hands down on the piano, and they are constantly moving". P8 described a device that could sit on their lap like a Braille display. They said, "I'd rather just put my hands down on my lap where it's very close to the piano keys. It's just like easy access because we want this to be sustainable over a long period of time. And if I'm sitting at the piano trying to learn a piece for two hours, being able to just reach down and feel the music in my lap (works for me). It's not too cumbersome and won't get in the way of things".

P6 added that the wearable device would need to be durable and comfortable. They added, "If it's like somewhere on your body, it has to be made of a pretty durable material. If you're a pianist and you wear it on your head, you have to be careful that it doesn't accidentally hit the keys or if it's on your foot that you don't hit it on the pedals or something. And that goes for like a lot of other instruments as well".

P9 added that making the device modular might make it more useful for different instruments. They said, "I am almost thinking like it was an Apple Tag. You can wear it anywhere. The general design is enough that there are no limitations of where you put it on your body". P6 echoed a similar idea and added, "I like the idea of velcro. It's kind of a more adaptable wristband for a watch. Depending on what instrument you're playing and what you need, it could be on your arm, it could be on your thigh or could be on your ankle".

4.3.3 Voice Commands Can Save Time or Can be Confusing: Participants had differing opinions regarding the utility of voice-enabled interactions. During Phase Two (Section 3.3.2), P2 and P9 reported that voice-enabled interactions may save time as they are inherently hands-free. P9 said, "I don't use a screen reader but like dictating information on a smartphone. It saves me a lot of time, and it's hands-free." P2 added, "Voice commands would be convenient. It would be nice to have voice commands. Like play measures one through six. Or stop as it's playing". However, P3 and P8 were not convinced. P3 noted, "I really don't care for it when it comes to music. It might kind of get in the way if it mistakenly starts playing something or fast forwards, rewinds or whatnot". P8 added that voice commands may also not work in crowded areas with loud external sounds.

4.3.4 Imitating Musical Interactions Can Create Intuitive Interfaces: When asked about how they wanted to interact with the system, participants reported mimicking musical interactions such as tapping, breathing, and stomping. P3 described tapping as an interaction. They said, "Tap once means stop, tap once again to start. Kind of like the gestures on the iPhone. You can tap to interact". While P1 imagined a system that used breathing. They said, "I would do with the breathing. Like I would blow into the system to tell it I need help". P6 and P8 reported stomping their feet to interact with the system. P6 said, "I think that depends on what instrument you'd be playing. If it's vocals, then you could stomp your foot to pause and play and tap your foot a little to the left to go backward and tap a little to the right to go forward". P6 suggested that users could also interact with the system through subtle gestures such as flexing muscles. They said, "Maybe it could be in some super-sensitive area where you could just tense your muscles, and it's visible. That could mean something without being too disruptive to what you're doing".

4.3.5 Importance of Accuracy and Trustworthiness: Five participants described the importance of accuracy and trustworthiness when it came to technology. P3 said, "It's not always going to be correct. You're always going to want to confirm by reading (the Braille again)". P5 added, "I could see it making mistakes with this. We'd have to live with it to understand what it really is doing". P4 said, "I realize sometimes AI can be wrong; I was thinking, what if it displays the wrong fingerings? I would rather not deal with anything inaccurately, and I would rather know the truth. I don't like to know what comes up wrong". P1 added, "What if you get used to it, and then it's not working one day? Then you get frustrated".

4.3.6 Potential Benefits and Limitations: P8 noted that technological support can make them feel more confident when reading and memorizing new music. They said, "I think a big aspect of studying music for me was my lack of confidence and my unfamiliarity with a lot of the process. I know that professional musicians spend so much time on their craft that they can overcome these barriers. However, for someone like me, one of the biggest problems was picking up the bass guitar because I was afraid of getting notes wrong. And I think these tools would do a lot to build up my confidence for that sort of endeavour". P8 and P9 also added that technological support can help them learn faster. P8 said, "We can use this technology to see if you're learning it correctly. I believe this can also expedite the learning process". P2 said that technological support may also increase their capacity to learn in an academic setting. They said, "When I was in college, my professors understood that things had to be memorized completely. There was no sight reading. So my brain could only hold so much, and I could only learn so much in a short period. I wouldn't have to maybe perform as many things or prepare the same amount for each semester (as other sighted students). But this can increase one's capacity for learning". Additionally, P1 and P2 also reflected that integrating vibrations may also help people who are hard of hearing to read and feel the music.

However, P6 added that any form of technological support cannot fully substitute Braille music. They said, "I feel like a device like this. Absolutely should not be a substitute or at least a complete substitute for Braille music. As much as I despise Braille music. However much I've always struggled with it, and as much as I dislike it. I don't know what I'd do without it. I don't think a device could fully replace it". P2 added, "I think whatever technology we're talking about won't necessarily replace the utility of Braille music. I think there's just so much more information in the full score. In terms of learning, it might make the interpretation of the Braille score easier. It might make it so that one could learn the piece more quickly than before". Additionally, P8 added that technological support cannot replace the music teacher's role either. They said, "I sense that (technology) could accommodate a bunch of different needs, but also, in doing so, create a very complicated and difficult user interface. So you would need someone to facilitate that. So probably a teacher would have to set that up or something". P6 added that technologies can also be distracting to other musicians. Especially if the vibration motors are also producing sound. Three participants highlighted the importance of affordability. P8 added, "The first thing that comes to mind is cost. Braille displays are just so gosh darn expensive".Two participants noted that technological support may not always be accepted in professional settings. P8 said, "If somebody is a professional musician, they might look at it and be like, why do you need this?".

4.3.7 Potential Scenarios of Use: Four participants added that technological support might be useful for amateur and early music learners. P1 added, "Someone who is new to Braille music and just started learning. Maybe the device would be useful for them". P2 added, "I think early learners might be excited to use tools like this. They might see it as something that's kind of becomes normalized for them going forward". However, P2 also added that since technological support could make music memorization quicker, this might be especially useful for auditions and performances. They said, "I'm thinking probably it would be a good system for people who have to learn a lot of music to perform in ensembles or if you have a long solo piece that has to be learned quickly. Like as part of audition prep in college". Relatedly, P8 said, "If the main goal is to memorize the music. I am not relying on it during performances. It will serve its purpose when you learn and practise the music. But ultimately, in performance, if the music has been internalized, then it's not really needed because it's just another obstacle to making the music".

P9, who advocated for flexible interactions, suggested that technological support might be especially useful for people with developing disabilities. They said, "I think this kind of system could be good for musicians who don't have a permanent disability yet, but a developing disability, like losing their hearing, losing their sight or losing their motor skills".

4.3.8 Other Speculative Design Concepts: From the initial ideation workshop (Section 3.3.1), we encouraged participants to imagine a technology that could make music reading and music memorization simpler and more accessible. We encouraged participants to be creative and think beyond what is plausible with current technologies.

P5 described a hands-free, voice-activated AI bot that can help them learn new music. They said, "I imagine an AI bot teaching me a piece of music. It actually plays a small segment of the music. It plays four bars, and then I say to it, play just the right hand, four bars, and it does that. And then I say play it slower. And then I try to play it, and I say, how did I do? Or maybe I don't say anything. It just speaks back because the AI is now talking, and it says, you need to hold this note longer". Additionally, P8 described a computer vision mobile application that can take photos of Braille music and convert it into MIDI files in real-time.

P8 and P9 imagined a Braille display that could be integrated onto existing musical instruments. P9 said, "I can totally imagine a two-line 80-cell Braille display sitting on a piano". In response, P8 added, "Maybe we can find a way to get the Braille display compatible with the piano with AI or something; you could easily start dictating music in real-time from the piano demo to the Braille display".

P6 had the idea of a modified keyboard that vibrates. They said, "A vibrating keyboard might tap the rhythm or vibrate the keys that you need to play, like feeling the vibration on the corresponding keys. You would learn to play the notes by feeling the keys". However, later, they critiqued their idea and said, "The only flaw I could see in that is if your finger wasn't touching one of the notes that was vibrating. Then it would be impossible to tell". P8 also imagined utilizing vibrations to communicate information. They said, "I occasionally use my Apple Watch, particularly for fitness stuff. One way they bypass the fact I can't hear the watch in a swimming pool is that they will give you vibrations to tell you the exact time. That's definitely something that could be explored more. The haptic capabilities of a smartwatch". While P7 described a wearable haptic suit with multiple vibration motors on the body to convey musical information such as pitch and timing. They said, "You could develop a system where an octave (of music) takes the form of vibration motors from the bottom to the top of your back. You could actually have little things you feel on your back. It could be very difficult to do, but nothing's impossible."

5 DISCUSSION

To help guide future accessibility researchers, we recap our findings and draw connections with related literature. In this section, we discuss 1) the potential multimodal Braille music displays and 2) how hands-free vibrotactile interactions can help teachers communicate with learners during lessons.

5.1 Potential of Multimodal Braille Displays for Music Reading and Memorization

Despite the obvious benefits of Braille music notation for music reading, many BLV musicians, particularly hobbyists and amateurs, often choose to avoid it altogether [1, 6, 26]. We found that reading Braille music has *intrinsic complexities* related to deciphering information from the code. Such as interpreting complex rhythm and timing and understanding musical instruction (including when to repeat particular sections or how to express particular aspects of the music). Additionally, we also found *extraneous complexities* in accessing musical information through Braille music. BLV musicians must first read a section of the music with their hands, then commit it to memory and finally attempt to play it on their instrument, making the process slow and cumbersome.

Our findings and others [27] pointed to the potential of vibrotactile interactions to aid music reading and memorization. We found that specifically timed vibrations can be useful in conveying rhythm and timing and act as temporal landmarks in the music to signify a predetermined instruction. Additionally, our findings and others [4, 33, 34, 44, 45] reported the benefits of accessing information through multiple modalities for tasks like reading and memorization. P9 described this sentiment and said, "We don't have the luxury of time as teachers or professionals. We have to learn things very fast in a short amount of time. So, we look for shortcuts. If I can learn something two ways and do it two different ways at once, it's going to work for me personally. I guess you could say that I'm a multimodal learner".

While advancements in Braille display technologies have incorporated sound with Braille music reading [19], incorporating vibrations to convey temporal information such as rhythm and timing could vastly improve the utility of Braille displays for reading and memorizing music. This is a promising area of research that warrants further exploration and development. We recommend further design and development into multimodal Braille displays, including in-the-wild testing and evaluation of these technologies through longitudinal diary studies. This approach will give BLV learners time to familiarize themselves with new modalities and account for the *extraneous complexities* of learning a new interface. Furthermore, this will provide insight into patterns of use and preferences between modalities during reading and memorization.

5.2 Hands-Free Vibrotactile Interactions with Teachers Can Improve Music Lessons

While reading and memorizing music is essential, the goal of all musicians is to play and perform music. Our findings and others [26, 29] found that music teachers play a critical role in supporting BLV learners in this endeavour. Amongst their many responsibilities, music teachers help learners understand complex musical concepts, provide technical guidance for body movement (such as correct fingering patterns and posture) and help learners internalize and feel the music they are performing [1, 15, 29]. Our findings, along with others [3, 5, 27, 39], indicated that real-time vibrotactile feedback can help convey important aspects of musical information to BLV learners, including rhythm, timing, articulation and dynamics. In particular, we found that feeling vibrations that sync with the rhythm and tempo of music can enhance a learner's ability to internalize and feel the music. We also found that the changing intensity of vibrations can convey dynamics and articulation in the music or highlight aspects of the music that are not clearly audible.

Our findings also highlighted vital design considerations for developing technologies that facilitate real-time communication between music teachers and learners. 1) participants noted the importance of hands-free interactions, enabling both the music teacher and the learner to play their instruments while simultaneously sending or feeling vibrotactile signals. This design consideration is especially helpful during piano lessons, where it is standard practice for the teacher to play one hand of the music while the learner plays the other hand in unison [7], 2) our participants underscored the value of straightforward tactile interactions as P9 reflected on the accessible nature of tactile controls and the existing challenges of memorizing and performing music and 3) we found that intuitive interactions with this system should emulate familiar musical interactions such as stomping, breathing or tapping to send vibration signals.

This remains a promising area of research that requires further exploration. Open questions remain about how wearable vibration-based devices can integrate into current music teaching practices and how other musical scenarios can become more accessible from such interventions. To address these questions, we recommend co-design as a method of involving BLV students and teachers in the design process to make semi-functional prototypes that can be felt, heard and interacted with. This will also provide further insight into how teachers and learners may use such systems in music-learning settings.

6 LIMITATIONS AND FUTURE WORK

The overarching purpose of our research was to explore the nuanced challenges of music reading and memorization and to investigate how multimodal interactions can facilitate improvements in music reading and memorization for BLV musicians. However, the insights and findings do come with caveats. The research took the form of workshops with a small population of BLV musicians and learners with experience in music reading within mostly Western classical music. The complexities of accessing music might differ for BLV musicians in other music genres and contexts. This may lead to alternative research questions or uniquely different findings. For example, Indian Classical music is based on the concept of 'Ragas', which heavily relies on improvisation and less so on memorization [24].

Our population was disproportionately skewed towards blind musicians who preferred Braille music as their primary means of reading and accessing music, which meant that the insights and findings also reflected a larger focus on Braille music than learning music by ear. Also, this study focused on specific modalities of interactions (such as vibration and audio), as most of our participants and the second author were blind; thus, we did not consider alternative modalities such as high contrast visuals or magnification of text on screens which might be particularly useful for low-vision musicians and learners. Furthermore, since this was an exploratory study that combined audio and vibration, we did not explore auditory enhancements (including audio enhancements of music or spoken description). Future work should examine questions such as "How can technological interventions improve Learning music by Ear?" or "How do low-vision musicians read and memorize music (including screen-based interactions), and how can technology support them?".

Furthermore, the design ideas from Phase Two (Section 3.3.2) resulted from the contexts and examples we demonstrated to participants. We designed the Wizard of Oz exercise to explore how vibration can enhance music reading and memorization when used in sync with music. However, other technological modalities would require further exploration. Also, we conducted the co-design workshops over a short period of time, which reflected the ideas and insights of participants at that particular moment. We believe that future work can examine how BLV musicians may develop personal preferences and habits when using multimodal interactions for music reading and memorization. Future work can examine questions such as "What patterns of behaviour may emerge from using multimodal Braille displays over a long period of time?".

7 CONCLUSION

Reading and memorizing music remains a complex and cumbersome challenge for blind or low-vision (BLV) musicians and learners. The field of multimodal assistive technologies (MATs) has shown significant promise in accessing visual information. Through an ideation workshop and a co-design workshop with nine BLV musicians and learners, we classified the complex challenges of music reading and memorization into *intrinsic* and *extraneous complexities* based on Cognitive Load Theory (CLT). We also introduced specific design ideas that tackle the challenges of music reading and memorization by pairing modalities with distinct needs. Lastly, we provide design considerations for future researchers to make MATs that holistically improve music reading and memorization for BLV musicians and learners.

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