Playing with Feeling: Exploring Vibrotactile Feedback and Aesthetic Experiences for Developing Haptic Wearables for Blind and Low Vision Music Learning

Leon Lu
leon.lu@carleton.ca
Carleton University
Ottawa, Ontario, Canada

Jin Kang
jin.kang@carleton.ca
Carleton University
Ottawa, Ontario, Canada

Chase Crispin
chase.crispin@gmail.com
Lincoln Public Schools
Lincoln, Nebraska, United States of America

Audrey Girouard
audrey.girouard@carleton.ca
Carleton University
Ottawa, Ontario, Canada

ABSTRACT

Musical haptic wearables (MHWs) that convey information through vibrotactile feedback holds the potential to support the music learning of a blind or low vision (BLV) music learner. Yet, it is unclear how these technologies can give functional support to a BLV person. We also investigated material preferences in such technologies to understand the role of non-functional aesthetic experiences in shaping their music learning. We conducted 5 co-design workshops with 10 BLV participants. Participants explored eleven materials common in a music learning environment and engaged in bodystorming with a prototype that communicated six vibrotactile patterns. Through thematic analysis, we found that MHWs with vibrotactile alerts and variations in vibration are suited to communicate instructional information, aid music reading and support technical guidance and practice. We categorized the participants' material experiences into sensorial, interpretive, and affective levels. Based on our findings, we discuss considerations when designing vibrotactile interactions to support music learning for BLV people and highlight material experiences that should be emphasized to make the music learning experience wholesome for BLV music learners.

CCS CONCEPTS

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

KEYWORDS

Blind and Low Vision Music Learning, Assistive Technologies, Vibrotactile Feedback, Musical haptic wearables, Material Experiences, Material Aesthetics, User Experience Design

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1 INTRODUCTION

Musical haptic wearables (MHWs) have opened another door for people of all abilities to experience music through touch. Conceptualizing music as multimodal, MHWs can communicate musical information by utilizing tactile sensations (e.g., pressure), with the vibrotactile feedback being one common input [46, 81, 82, 84, 85]. These body-worn devices can empower people who are blind or have low vision (BLV) to participate in music without taking their hands off from their instruments [36, 52, 81]. Despite their potential for people with disabilities, limited research has explored the application of MHWs for BLV people, specifically in music learning.

People who are BLV face several barriers when learning music and we explored how MHW can address important music challenges, including limited access to non-verbal cues and gestures (e.g., a conductor's facial expressions) [1, 38], and the experience of cognitive load from learning by ear or by reading braille music [1, 5, 60]. We sought out to contextualize the application of MHWs to BLV music learning and asked, "How do BLV musicians and learners envision using MHWs with vibrotactile feedback to support music learning?" (**Research Question 1**). By asking the question, we can identify specific use cases of how MHWs can functionally support BLV music learners.

We also investigated BLV people's material preferences for the envisioned MHWs. Prior work has focused on devising functional requirements of MHWs [69, 72, 73]. This effort is understandable given the origin of assistive technologies rooted in rehabilitation engineering to "fix" a person's problem [14]. Yet, people seek beyond functionality and usability from assistive technologies. They need devices catered for aesthetics where devices represent their self-concept [74] and evoke a range of good emotions and thoughts [18]. Assistive technologies without the consideration of aesthetics can result in user abandonment of the devices, regardless of how good a technology is in giving functional support [24]. Thus, we explored the materiality of MHWs, which is one critical aesthetic qualities [34], and asked, "What are the material perceptions and preferences of BLV musicians in the design of MHWs?" (**Research Question 2**).

We developed a proof-of-concept MHW prototype that communicated six vibrotactile patterns and conducted five co-design workshops with ten BLV music teachers and students. The workshops consisted of participants' active interaction with eleven music-related materials, consisting of fabrics to wood, and bodystorming with the prototype. Participants discussed the suitability, durability, and applicability of materials in relation to the prototype and ideated multiple scenarios in which the prototype can support BLV students' music learning. We found two themes in response to two research questions.

Paper Contributions: First, we present findings that explore the applications of vibrotactile feedback to aid music-related activities such as non-verbal communication and music reading. Second, we present findings that explore the material experiences of BLV musicians and offer a reflection on how material experiences can inform user experiences. Third, we provide design considerations for designers and developers to make MHWs, so that they can create a wholesome user experience for BLV music learners, taking into account aesthetics and functionality.

2 RELATED LITERATURE

In this section, we will identify the challenges of BLV music learning, outline the developments in technology that combine vibrotactile feedback and music, and describe how we can inform user experience design through material experiences.

2.1 Understanding Challenges of BLV Music Learning

Learning music as a BLV person is a complex and challenging endeavour. Conventional pedagogical practices of music learning are inaccessible [1, 5] as they predominantly rely on vision to access information and communicate with others. One significant barrier to music learning is the cumbersome and limited access to musical scores. Most BLV musicians and learners will memorize music either by ear or by reading braille music [1, 5, 49]. Both methods require significant mental effort and have major shortcomings. Learning by ear is not always accurate as the subtleties within the music may not always be identified through listening alone [5]. This also limits the conceptual understanding of music [23]. Learning music by reading braille music requires access to braille music scores and knowledge of the braille music code [1, 5, 60]. The braille music code can be time-consuming to learn, and acquiring braille music on embossed paper can be expensive and resource intensive [49, 58]. Furthermore, reading braille music is laborious and slow as it requires BLV musicians to take their hands off their instrument and commit the music notes to memory before learning to play it.

Another obstacle to music learning is the absence of non-verbal cues and gestures [1, 5]. Pointing, nodding, and facial expressions are common non-verbal cues that sighted music teachers, conductors, and musicians use to communicate with one another during performances and practice. Furthermore, certain technical aspects of music learning, such as body posture and wrist action, are often conveyed through gestures [5]. BLV musicians and learners are not privy to this information. A further hurdle to music learning is the difficulty in understanding the performative aspects of music playing. Performing music for a sighted audience requires an understanding of social norms such as how to stand on stage, when to bow, and what to wear. Baker and Green describe this as the "*stage craft*" of playing music for an audience. BLV musicians may not be adept at music performance and uncertainty about how they are being perceived can affect their confidence [5].

Prior studies found that BLV musicians and learners would greatly benefit from the development of music learning tools [47, 49, 58]. However, currently available assistive technologies only address a small fraction of the challenges of BLV music learning. Commercially available tools are predominantly geared towards improving access to already existing music composition and music reading software [91, 92, 94]. For example, MuseScore [51] is a popular music notation software that comes with screen reader support for JAWS [93], NVDA [54] and VoiceOver [3]. However, these existing solutions are far from ideal because they rely heavily on graphical user interfaces that make screen reader interactions significantly difficult to navigate and complicated to use [61].

More recently, Payne et al. [59] developed a text-based music notation software called SoundCells. It is specifically designed for BLV musicians and composers. SoundCells is easy to navigate and use while outputting audio, print and braille. Additionally, multi-line braille displays like the Canute 360 [16] have enabled BLV musicians and learners to read braille music and lyrics simultaneously by connecting the positional information of the lyrics with the musical notes. Despite these recent developments, the current state of assistive technologies for BLV musicians and learners is inadequate and requires further research and development.

2.2 Substituting Vision Through Vibration

Studies found that BLV musicians and learners leverage alternative sensory modalities such as touch and hearing to substitute vision [1]. For example, BLV musicians in an orchestra would ask fellow sighted musicians to tap on their shoulder to let them know when to play and when to pause [49]. Similarly, BLV musicians in a rock band would ask fellow sighted band members to speak out loud or play a unique rhythm to indicate transitions in a song [1]. However, these strategies are far from perfect as they require additional assistance and support from sighted music teachers, conductors and fellow musicians, which may not always be feasible. Furthermore, aural cues may interfere with music performance and possibly distract musicians from playing their instruments.

Augmenting the sense of touch through vibrotactile feedback is a promising direction for the development of assistive technologies for BLV people. Recently, vibrotactile feedback has been used to convey navigational cues [31], enhance interpersonal communication through shared awareness of breath [2], synchronize running [26] and play video games like Guitar Hero[1] [96].

A large body of work has explored the relationship between music and vibrotactile feedback [4, 7–9, 19–21, 56, 83, 85, 86]. Studies

[1]Guitar Hero is a music rhythm game that uses a guitar-shaped game controller to simulate guitar playing. The game's objective is to hit the notes in time with the music to score points.

also found that musical information (such as pitch, tempo, timbre, dynamics and rhythm) can be perceived through vibrotactile sensation [69, 72, 73].

West et al. [90] created the body:suit:score, a bodysuit embedded with an array of vibrating motors to convey a musical score. Commercially available wearable devices such as the Soundbrenner [76] promise to teach rhythm and tempo by feeling vibrations. Furthermore, researchers have applied vibrotactile feedback to support breath guidance for vocal training [44], body posture [88] and to learn fingering techniques [95].

Recently, there has been a growing trend toward using vibrotactile feedback to design assistive technologies for BLV musicians and learners. Tanaka and Parkinson [77] designed the Haptic Wave, a physical device that vibrates to convey musical information from digital audio workstations. Turchet et al. [83] designed haptic wearable devices to support synchronization between BLV musicians, and Baker et al. [4] explored how a conductor's gesture can be wirelessly communicated to BLV musicians. However, the question of how BLV musicians and learners prefer to use vibrotactile feedback has received limited attention.

2.3 Exploring User Experience Design through Material Experiences

MHWs have the potential to significantly improve BLV music learning. However, the adoption and real world usefulness of such technologies may also be influenced by how these technologies feel [11, 18] and how they are perceived by others [67]. Influential design researcher Don Norman argued that "pleasant things work better" [79] and quantified user experiences into three levels of processing: The *Visceral* level which is the initial, automatic response to the appearance of an object, the *Behavioural* level that relates to the usability and function of an object, and the *Reflective* level which relates to the meaning attached to an object and how it fits into a person's self-image [53]. While an object's functional requirements shape a user's evaluation of the object at the behavioural level, it is the object's non-functional aspects, including materiality, that significantly shapes a user's evaluation of the object at the visceral and reflective levels.

Given this, there has been a growing trend to explore user experiences through material experiences [89]. Prior research has also explored how material experiences have influenced behaviour of BLV people. In the field of fashion and textile, Burton et al. [11] found that touch was the most important sense when making purchasing decisions and tactile features on clothes were more appealing. Later on, Cho et al. [13] found that textiles can hold both practical values (such as comfort and fit) and symbolic values (such as self esteem and social acceptance).

In the field of HCI and accessibility, a number of researchers have explored the use of textures, hardness and shape of materials to improve accessibility. Tactile materials in the form of tactile graphics have been utilized to depict visual information [6, 43] and share ideas [68]. Tactile materials have also been utilized to teach mathematics [30], computer science [35] and natural sciences [32, 75] and to increase engagement in learning [29, 39, 63, 65]. However, limited research has explored the intersection of material experiences and the design of assistive technology for BLV people. An exception is the work of Giles and van der Linden [18], who studied the relationship between materiality of eTextiles, gestures and emotions. They found that the shape and texture of different eTextiles generated many gestures and thought associations. For example: An eTextile that took the shape of a pom pom was deemed to be a child-like object that was cradled and gently squeezed while a crocheted circle was spun around and compared to braille because of its lumpy texture.

One method of articulating the aesthetic experiences of materials is the materials experience framework proposed by Giaccardi and Karana [17]. The framework acknowledges the experience people have *with* and *through* materials [71]. Furthermore, it considers the properties of materials, a person's prior experiences and expectations with materials and the social and cultural values attached to materials [37]. The framework conceptualized people's experience with materials into four experiential levels: *Sensorial* (based on a person's first encounter with a material linked to how they touch, see, smell, hear and taste), *Interpretive* (based on how a person interprets and ascribes meaning to materials based on prior experiences and expectations), *Affective* (based on emotions that arise from inner thoughts, beliefs and attitudes when interacting with a material) and *Performative* (the actions that a person may perform based on the other experiential levels).

In sum, we see the current knowledge gap on the limited application of MHWs and exploration of two design dimensions, functionality and materiality. We sought out to address the gap by exploring 1) the application of MHWs to address important music learning challenges faced by BLV individuals (vs. the application of MHWs for sighted individuals), and 2) how two design dimensions of MHWs as a whole can support BLV music learning, which have previously been studied independently.

3 METHODOLOGY

Our study consisted of two parts: a pilot study and a series of co-design workshops. The research team consisted of three sighted researchers (first, second, and fourth author) and one blind researcher (third author). The first author, who is sighted and experienced with music learning, accessibility research and physical computing, facilitated initial ideation and defined study goals. The second and fourth authors, who are both sighted and experienced with HCI research and accessibility supported data collection and data analysis. The third author is a music teacher, musician, performer who plays the piano, clarinet and saxophone and is also blind, brought their expertise in music learning to structure and refine the workshop design through the pilot study. Later, the third author supported data analysis and uncovered insights from the findings of the study. All workshops took place in collaboration with BLV music teachers and learners from The Filomen M. D'Agostino Greenberg (FMDG) Music School[2]. A total of five in-person co-design workshops that took place in groups of two (a mix of BLV music teachers and learners).

3.1 Part 1: Pre-planning Process

This process composed of two phases. During the first phase, the first and third author held several online meetings to discuss the

[2]A music school for the blind based in New York City

goals of the workshop, develop discussion prompts, identify material swatches, and outline the procedures. While the study was intended to generate ideas, we developed prompts to guide the discussion. We touched on topics such as non-verbal communication, music reading, and technical guidance. In selecting swatches, we reflected on materials commonly touched and felt in a music learning environment. We also explored material textures that were unique and may be of interest to BLV musicians and learners. In the end, we narrowed down to eleven material swatches (Figure 1). The first and third author also discussed the design, vibration patterns and form of the prototype. Based on these discussions, we designed and developed a wearable haptic device that can be attached to any part of the body and be controlled remotely (Figure 2). Finally, we created a script that outlined our procedure and highlighted the goals of the workshop.

Figure 1: Swatch of materials (clockwise from top left): Rough dish scrubbers, Silicon, Soft sponges, Vinyl (Faux Leather), Felt, Soft fluffy felt, Metal ring, Wood block, Rubber mat, Textured plastic and Cork board.

3.1.1 Pilot Testing. In the second phase, the first author acted as a facilitator and the third author acted as a participant of a pilot workshop. This pilot workshop lasted for two hours and was conducted in person. Based on this pilot workshop, we found that the procedure logistics needed to be more explicit and refined to make it more accessible. For instance, we learnt that material swatches need to be arranged in a specific order to prevent over stimulation and participants might like to be given information about each material when they touched it. Also, the mock workshop confirmed that the design of the prototype would enable participants to explore different use cases and attach the prototype to different parts of the body. Lastly, we improved upon the discussion prompts to address our RQs. For instance, we expanded on questions about materials beyond taste and preference to include considerations such as durability, comfort and suitability.

3.2 Part 2: Co-design Workshop

3.2.1 Participant Recruitment & Information. In partnership with The FMDG Music School, we recruited 10 BLV musicians and learners through a call for participation that was approved by our institution's research ethics board and shared with The FMDG Music School community. In the end, we had ten participants (Table 1); nine participants identified their gender as male, and one identified as female. Participants were between 25 and 72 years old (M = 40.4, SD = 18.36). Four participants indicated they were completely blind, four indicated they have low vision and two participants mentioned that they were deafblind.

Participants used a variety of assistive technologies both for music-related activities and for non-music-related activities like navigation, reading and communication. Software that made music reading more accessible such as Sibelius, Lime Aloud, Sonar, and Good Feel were specifically mentioned.

We refer to each participant with a letter P, followed by a random number.

- P1 is a multi-instrumentalist who has made a career as a composer, arranger, producer and performer. They have studied music and have regularly performed music in concerts across Asia, Europe and North America.
- P2 has a degree in music education and has performed in many solo and ensemble concerts. They have taught braille music, music appreciation and piano.
- P3 is a braille music reader and transcriber, they play predominantly classical music and sings in the music school's vocal ensemble.
- P4 has been reading in Braille from a very early age, they play predominantly classical music, participate in an adult choir, and have over ten years of musical experience.
- P5 has multiple degrees in music performance. They are a performing jazz saxophonist and have been teaching music for over seven years.
- P6 has received extensive ear training and describe their ability to pick up notes, cues and chord progressions, as near perfect. They have more than 12 years of musical experience.
- P7 is a multi instrumentalist who began playing the piano from a very early age. They currently play in a band with other blind musicians. They have over 10 years of musical experience.
- P8 is a classically trained pianist who now only plays music as a hobby. They play music casually and also participate in drum circles.
- P9 has a degree in music education and another degree in choir directing. They are a multi-instrumentalist who has also taught braille music.
- P10 is a beginner music learner who started to take piano music lessons for 6 months at the time of the study.

3.2.2 Procedure. The first author facilitated five two-hour-long in-person workshops over two days at The FMDG Music School. Participants were paired into groups of two based on their availability and asked to come with their musical instruments for the workshop. Our workshops remained consistent throughout and did not undergo any changes. Before the start of each workshop, participants were informed about the goal of the study and asked to

Table 1: Study participant information

Participant	Age	Gender	Vision Ability	Status	Instruments Played	Co-design
P1	68	Man	Blind	Teacher	Trumpet, Piano, Keyboard and Voice	Session 1
P2	72	Man	Blind	Teacher	Voice and Piano	
P3	28	Man	Deafblind	Student	Voice and Piano	Session 2
P4	25	Man	Deafblind	Student	Voice and Piano	
P5	32	Man	Low Vision	Teacher	Saxophone and Clarinet	Session 3
P6	26	Man	Blind	Student	Piano	
P7	27	Man	Low Vision	Student	Piano, Drums, Guitar and Bass	Session 4
P8	26	Man	Blind	Student	Piano	
P9	54	Woman	Low Vision	Teacher	Cello, Piano, Accordion and Recorder	Session 5
P10	46	Man	Low Vision	Student	Piano	

share their experiences with music learning as a BLV person. Each workshop was divided into three subsections. Taking inspiration from Turchet et al. [83], for the first two workshop activities, participants engaged in sensory bodystorming and ideated by physically feeling and placing the prototype and materials on their bodies [87].

3.2.3 Section 1 - Exploring Vibrotactile Feedback: We encouraged participants to generate ideas and explore the application of vibrotactile feedback by engaging with sensorial stimuli and experiencing embodied vibrotactile feedback. We started this section by introducing the prototype to the participants and encouraging them to touch and feel it. The prototype consisted of multiple vibration motors encased in 3d printed coin sized casing attached to Velcro band and a Bluetooth-enabled microcontroller encased in a stationary box sized case (Figure 2). Next, we instructed participants to attach two vibration motors to their left and right wrist using the attached Velcro bands. The first author informed the participants that they will feel a vibration sensation similar to the vibration felt from a smart phone notification. Then, the first author demonstrated the following series of preset vibration patterns over Bluetooth (Figure 3):

(1) Vibrotactile Alert: Both Vibration motors were turned on and then turned off together.
(2) Repeated Vibrotactile Alerts in Fixed Intervals: Both Vibration motors were turned on and then turned off repeatedly at 60 beats per minute. Then increased to 80 beats per minute and 100 beats per minute.
(3) Variating Intensity (Increase): Vibration motors on both wrists increased in intensity gradually from very low to high intensity.
(4) Variating Intensity (Decrease): Vibration motors on both wrists decreased in intensity gradually from very high to low intensity.
(5) Variating Intensity (Increase and Decrease): Vibration motors on both wrists increased in intensity gradually from very low to high intensity and then gradually back to very low intensity repeatedly.
(6) Variating Speed and Pattern: Vibration motor on left wrist turned on and then off for one long beat, followed by vibration motor on the right wrist turns on and off twice for two short beats.

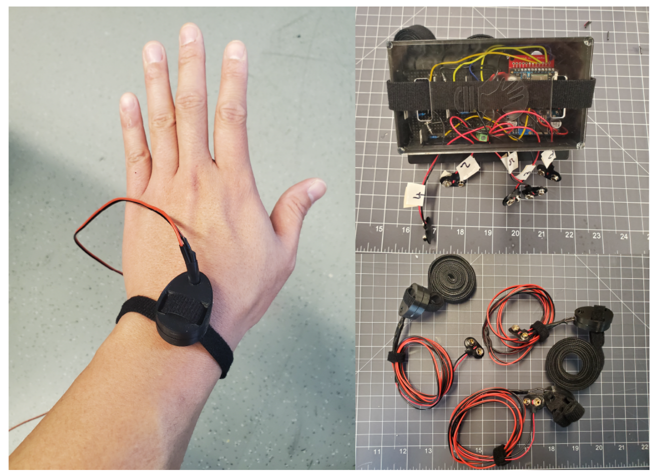

Figure 2: From top left, clockwise: Hand with vibration motors attached using velcro, microcontroller in 3d printed case with connectors, vibration motors in 3d printed casing with velcro, wires and connectors

After feeling the vibration on their body, we prompted participants to come up with ideas on how vibrotactile feedback could be used to support music learning. While the discussion was open-ended, we provided discussion prompts to guide the conversation. These discussion prompts touched on topics such as non-verbal communication, music reading, and technical guidance. We prompted questions such as:

- Non-verbal Communication: How could vibrotactile feedback communicate non-verbal cues and gestures between students, teachers, conductors and other musicians? What type of information can and cannot be conveyed through vibration?
- Music Reading: Can vibrotactile feedback can be used to read music, memorize new music, and enhancing music performance? If so, what would this device do?
- Technical Guidance: How could vibrotactile feedback support music teachers convey instruction? Do you see it being used in a classroom and in private classes? How so?

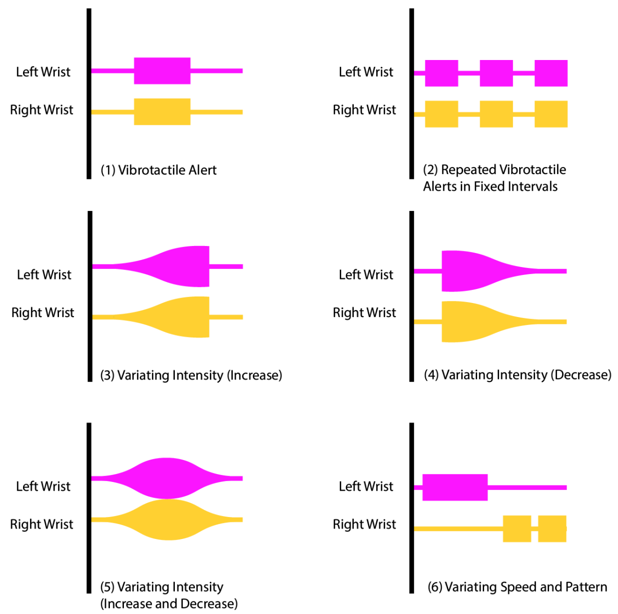

Figure 3: Visualization of 6 vibration pattern demonstrations

After generating ideas, participants engaged in sensory bodystorming to enact their concepts. They determined the placement of vibration motors and the vibration pattern to convey information, while also situating themselves with their instruments. As an example, one pair of participants suggested using vibrotactile feedback to signal when to start and stop playing music. Next, they decided that a vibration on the left wrist would indicate the start of playing, while a vibration on the right wrist would indicate a stop. The participants then sat with their instruments and the first author prompted participants to start and stop playing using the vibrations.

For the purpose of this study, we defined *Vibrotactile Alerts* as a strong, short vibrations that would be akin to being tapped on the shoulder and we defined *Variations in Vibration* as all vibration patterns that produced variations in vibration intensity, speed and duration of vibration.

3.2.4 Section 2 - Exploring Materials: We gave each participant 11 material samples (Figure 4) to touch and explore. The swatches were intended to act as material probes [33] to facilitate exploration and reflection. We encouraged participants to freely touch the materials in front of them and were asked a series of open-ended questions to uncover preferences, perceptions and thought associations with certain types of materials. This session was semi-structured, and the first author asked participants several prompting questions. He prompted this exploration through thought starters related to durability, comfort and suitability of materials, such as:

(1) Durability: Which of these materials would you say are more durable and which would be less durable?, Is durability important for music playing/learning? if so, why? Which of these materials could you wear for a long time of your body?
(2) Comfort: Which of these materials would you say are more comfortable and which would be less comfortable? How would you define comfort in context of music playing?
(3) Suitability: Which materials would you say are suitable for the design of tools for music learning? Which materials would you combine for the design of tools for music learning, why these materials? Other than durability and comfort, are there other aspects of materials that are important to you when playing and learning music?

Figure 4: Participants touching material swatches

3.2.5 Section 3 - Ideating through Making: In this last section, we prompted participants to ideate and create imagined tools for music learning based on the ideas that had been discussed so far. Participants were provided with materials such as clay, paper tape, Velcro bands, bendable pipe cleaners, Lego blocks of varied shapes and sizes, stackable plastic rings, sticky thumb tacks, rubber bands and popsicle sticks. Participants were informed that they may choose to use as many materials as they would like to conceptualize and design these imagined tools for music learning. At the end of the making exercise, participants were asked to describe what they had made to each other and to the first author.

The first author video-recorded the co-design sessions using a personal camera and also took photos. We transcribed the video recordings of each co-design session using the Trint transcription software [80]. The first and second authors then manually reviewed all transcribed files and corrected them for errors.

3.3 Data Analysis Approach

The first and second authors conducted an inductive thematic analysis using MAXQDA [45], and we followed the exact six steps outlined by Braun and Clark [10, 12], except our approach used a code book to ensure the consistent application of codes across transcripts. While we used categories from the materials experience framework[17] to organize the results at a high level, we developed the smaller codes linked to the data and these codes did not come from the materials experience framework (e.g., Breathability). Our approach aligns with the inductive approach described by Braun and Clarke. Our thematic analysis is descriptive and used for data reduction and our analytical focus was to describe participants' experiences and ideas.

To begin with, the first and second author familiarized themselves with the data by independently reading through two randomly chosen transcripts multiple times. Next, we read transcripts line-by-line and assigned initial semantic codes along the transcripts. Afterwards, we compared our assigned codes line-by-line, refined codes based on (dis)agreement, and created a code book that had a code name and its definition. Most codes were semantic codes (i.e., the explicit content said by participants) and as each transcript was revisited and we formed themes, we assigned latent codes to capture implicit assumption not expressed by participants.

We repeated the systematic coding process; we read the next two transcripts (of a random order) multiple times, assigned codes line-by-line using a code book, and created new codes. We then discussed on our (dis)agreement, further refined the code book, and repeated the process for the last transcript. Third, we grouped the codes into potential themes and categories based on similarities. Fourth and fifth, we reviewed and refined themes, going back and forth between the codes, potential themes, and participant quotes representative of themes. Lastly, we report the results, offering connection of the themes to prior work and responding to the **RQs**.

When presenting participant quotes, we omit inessential parts for the ease of reading (e.g., filler words). The annotation [...] indicates that the part of text that was not relevant to the analysis and was removed/omitted.

4 FINDINGS

In this section, we present ideas on how to apply vibrotactile feedback for music learning activities, including providing instructional information, supporting music reading, and facilitating technical guidance and practise. Additionally, we report participants' preferences and perceptions of materials using the Material Experience Framework.

4.1 Simple and Complex Mapping

During the sensory bodystorming part of this study, participants experienced wearing and feeling vibration on their body while engaged in music learning activities. This enabled them to develop an understanding of the potential applications and limitations of vibrotactile feedback for music learning. Participants began this exploration by utilizing vibrotactile feedback as an alert to know when to start or when to stop and also as a simple repeating on and off buzzing to detect changes in tempo while on their instrument. Participants also imagined using this feedback to "feel the music" and understand technical aspects of music playing that were conveyed visually. Their responses were grouped into three categories: instructional information, music reading, and technical guidance and practise.

4.1.1 *Instructional Information:*

Participants were quick to point out that vibration can be utilized to convey instructional information between teacher and student, conductor and musician and in between musicians while playing music. Six participants reported that they were able to detect *vibrotactile alerts* (which was akin to being tapped on the shoulder) while playing their instrument, and that this could be utilized to indicate when to start and when to stop playing. P8 described *vibrotactile alerts* being especially useful in scenarios of improvisation between musicians, they said, "I remember when I used to play in a jazz band. You would have people improvising and doing stuff like that. We don't get visual cues, so they would just yell at us and say it is your turn. But maybe you could program this to vibrate and tell someone, it's their turn". Furthermore, P9 described the application of *vibrotactile alerts* between conductors and performers. They said, "Sometimes our conductor would have a Fermata [3]. We don't see it, [so vibrotactile alerts could help]".

Additionally, participants discussed the potential application of *vibrotactile alerts* for teachers in classroom settings to discreetly communicate with music students. P2 said, "I was thinking about how you could let somebody know that they are flat or sharp without saying anything to anybody". Furthermore, P5 imagined a system that would enable teachers to communicate with sighted and BLV students at the same time. They said that sighted students could see and hear the teacher's instruction while the BLV student could hear and feel the information. Participants also discussed the application of *vibrotactile alerts* for memorization. P5 said, "It's almost like you could give the cue ahead of time, the vibration could just sort of be a signal, like a landmark that this is coming up". P8 added, "If a person can have like a remote to play three or four bars of music again and again. Then pause and memorize it [without having to take their hands off their instrument]. That would make it easier".

We also found how *variations in vibration* could be used to signify musical information. Participants noted a relationship between changes in vibration intensity, speed and pattern, and how these can convey musical concepts such as dynamics [4] and articulation [5]. P6 was quick to point this out when asked about vibration, they said, "Definitely dynamics! If I was playing a phrase that needed to be quieter or I needed to transition to a different dynamic, [*variations in vibration*] intensity would convey that". After experiencing how vibration felt on their shoulder while playing the saxophone (Figure 5), P5 reflected that *variations in vibration* speed and intensity can be used to convey articulation while teaching music and said, "Sometimes a student does not get it by hearing it, sometimes you have to tap their shoulder [lightly] and say, this is [how] a short note [feels] opposed to tap their shoulder [with more intensity] and say, this is [how] a full length note [feels like]". P8 added, "the [*variations in vibration*] feedback really adds a whole new dimension to communicating in the middle of playing music because it involves less talking between individuals".

However, we also found limitations of *variations in vibration*. Participants found perceiving tempo change [6] challenging. In this scenario, we asked participants to try and alter their playing tempo to the changing tempo of the repeated vibration pattern. P2 missed the change in tempo and said, "I was totally disconnected. Once I got playing the music, the vibration was just there". Interestingly, P1 successfully followed the tempo change on their piano. Yet they spoke, "I had to concentrate so much on the arm, not so much about

[3] Tell us to hold a music note for an unspecified amount of time
[4] Dynamics refers to the variation in loudness of a sound or musical phrase.
[5] Articulation refers to how a note is played, it involves length, intensity and emphasis given to a note or a group of notes.
[6] Tempo refers to speed of music, usually described in beats per minute

Figure 5: P5 holding their saxophone while wearing vibration motors on their right shoulder, left bicep and left wrist

the playing". Vibration seemed to increase participants' cognitive load because they needed to pay close attention to the *variations in vibration* and play their instrument at the same time. P7 implied another scenario in which vibrotactile feedback can increase a BLV student's cognitive load: "you're going to get lost [with the feedback] as you can't keep up with a Beethoven score or anything like that." The underpinning logic is complex music scores contain a lot of information that needs to be encoded through vibrotactile feedback and musicians will become overwhelmed upon receiving a multitude of vibration patterns. However, participants also contradicted one another as two participants were optimistic that any system would get easier over time, as evident in P6's excerpt, "I think if you were to do it [use the prototype] enough, it would become natural." P8 also added, "I want to emphasize that not every tool is immediately usable especially when it comes to a discipline like music. It is okay if you need a week or a month to learn how to use it, especially in regards to our ideas about vibration".

4.1.2 Music Reading: For the second category, participants explored potential applications of vibrotactile feedback for music reading. P4 described the challenge of music reading and said, "It's important for me to memorize the whole piece before a concert because fortunately or unfortunately I don't have the luxury of reading music while playing for an audience". Other participants further articulated this challenge by stating that reading braille music [7] is slow and cumbersome process as it requires taking one's hands off the instrument, memorizing the notes, and then practising how to play them.

In response, four participants discussed creating a code based on vibrotactile feedback to enable BLV musicians to keep their hands on their instruments while reading music. P8 said, "The first thing that came to mind was Morse code. Making some sort of notation based on vibration". P5 proposed a system that combined braille music and *variations in vibration* to read music. They said, "Right now, if you are reading braille, it's hard to read and play music simultaneously. Braille music has all the information. It has the melody, the rhythm, and the annotations about the dynamics and tempo. But what if braille music could just have the melody and the rhythm could come from the vibrations". They suggest that by reducing the cognitive strain on memory, BLV musicians may be able to read music quicker and more effectively. P8 had another idea of making a tactile musical staff [8] with movable vibration motors to convey musical notes by their position and convey other musical information through *variations in vibration*. They added, "A display system would be a lot faster than reading braille. I think the information would be communicated a lot faster to blind people than actually reading and interpreting every symbol, especially when braille music is so inconsistent".

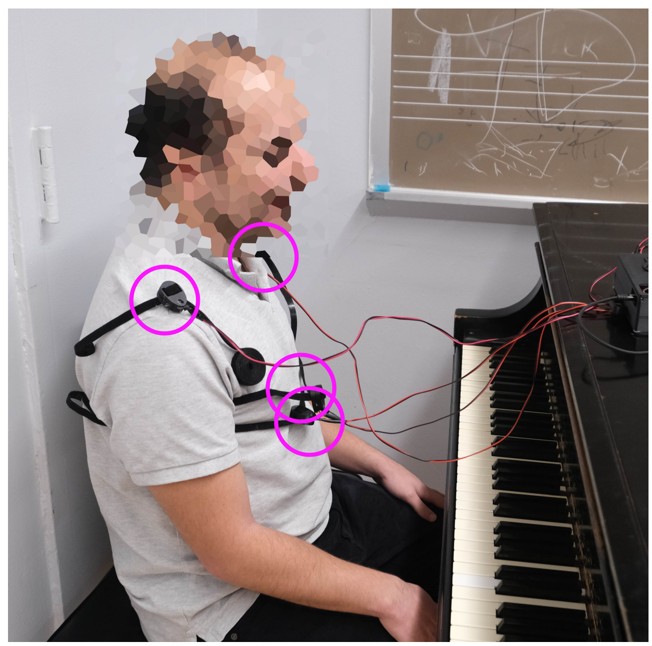

Figure 6: P7 playing out how vibration motors can be used to convey musical notes

Three participants had the idea of mapping musical notes to individual vibration motors on the body with every unique *vibrotactile alert* signifying a particular music note. P8 and their co-design

[7] Braille music is a coded system that allows BLV musicians to read and create music using a combination of braille dots

[8] A musical staff is a set of five horizontal lines and four spaces where musical notes are written to indicate their pitch and duration.

partner P7 acted out the idea; P7 wore four vibration motors; One on their left shoulder to represent the C note, One on their right shoulder for E, and two motors on their upper and lower chest to represent a G and B flat note (Figure 6). The pair played out this scenario and were able to identify individual musical notes. Later, P7 raised the idea of placing seven vibration motors on the body to correspond with the seven notes in an octave [9], with the length of *vibrotactile alert* indicating duration and timing of the musical note.

Related to position of vibration motors on the body, we noticed that participants chose to wear vibration motors on various parts of their body, including wrists, ankles, shoulders and chest. However these observations would not indicate participant's preference; most participants did not seem to reflect on their initial and later placement of the prototype, understandably considering that they were wearing it for the first time and they had experiences with different instruments. We assume a BLV musician's placement preference might be related to their own personal preference and their instrument. For instance, P7, who placed four motors on their shoulders and torso, said, "I wouldn't want anything on my arm while playing piano". Instead we found that participants valued flexibility of being able to wear the vibration motors anywhere on their body. P2 said, "The beauty of this [the prototype] is that you can put it anywhere. So we could just leave it open. It doesn't have to go on the arm or the leg. It could do all kinds of nice possibilities". Three other participants added that placement of vibration motors would depend on personal preference as well as on what instrument they were playing.

Lastly, we found some reluctance about the practicality of MHWs for music reading. From their exploration (Figure 6), P7 and P8 imagined that such a system could become quite complex and were hesitant of the real world applications of such an idea. P3 and P4 echoed similar concerns and said that this system might be useful for simple music like folk songs but not applicable for more complicated pieces. Additionally, participants reported the cognitive challenge of being able to feel and decipher musical information while also continuing to play music. P2 said, "This is where I could see it getting tricky. I don't know if you'd be able to understand it while you are playing. Eventually, you will be get lost in it as you can't keep up with a Beethoven score". P3 added that *vibrotactile alerts* can communicate macro level information such as tempos and time signature, but not micro level information such as the pitch of an individual note and individual rhythms; the participant described micro level information needs to be received on time (i.e., at the immediate time when a student needs to play a note). They said, "A BLV musician would need a lot of skill to discriminate [a pitch] from vibration patterns..." That is, even if a BLV student receives 12 different notes through different patterns, they will find it difficult to decipher between different patterns, ultimately slowing down their learning of new music.

4.1.3 Technical Guidance and Practise: Participants talked about diverse music practise scenarios that can leverage *vibrotactile alerts*. P7 described the application of the feedback to a five-finger exercise [10]. From their view, *vibrotactile alerts* can work with a mobile phone where a student can practise preprogrammed lessons, with each lesson programmed to teach what finger to move by vibrating a corresponding motor. P10 imagined a pair of socks with embedded vibration motors that could convey musical instruction and said, "Well, we have 5 fingers on each hand and 5 toes on each foot. Each toe can be related to each finger".

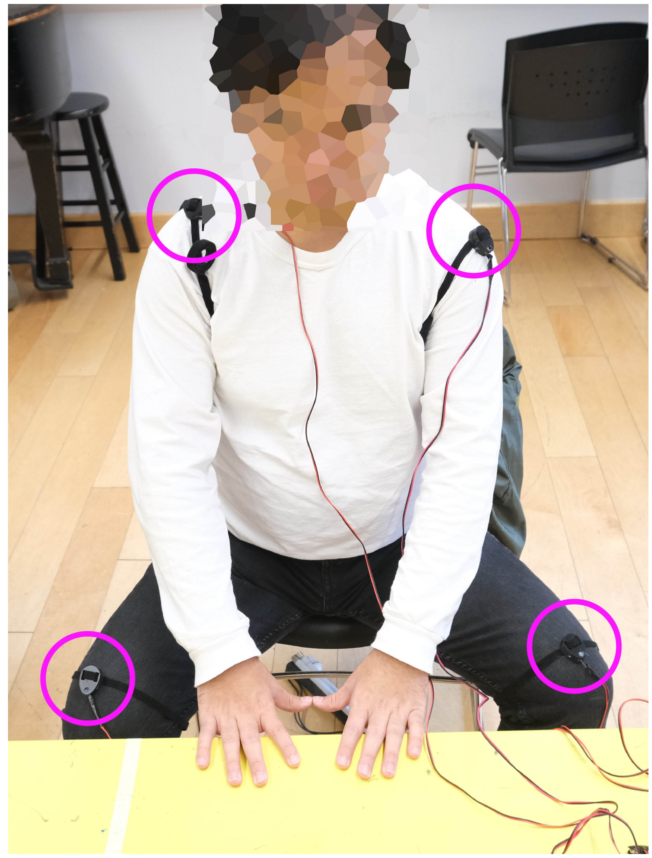

Figure 7: P8 demonstrating how vibration motors can be used to learn complex rhythm patterns

Three other participants explored the potential use of *vibrotactile alerts* to learn coordination between different body parts. P5 pictured learning complex rhythm patterns like Polyrhythm [11] by repeatedly feeling the vibrotactile feedback in the rhythm pattern. P8, who played in a drum circle (Figure 7), noted that thoughtfully placed *vibrotactile alerts* could be used to convey not only rhythm patterns but also information about how to play the rhythm patterns, they said, "There are different things like sometimes you slapped the drum, sometimes you muted the drum and sometimes you do a palm strike. Basically, you could notate all of that with a few of these (vibration motors)". Furthermore, they added that such a system could also enable remote learning.

[9]An octave of music notes in western music is represented by 7 English alphabets along with sharps and flats

[10]A musical composition designed to help a player exercise all five fingers of the hand

[11]A simultaneous use of two or more rhythm patterns with different time signatures or beats

4.2 Meaning from Materials

We observed that participants described materials through a variety of lenses, from properties of materials to emotional responses based on preference and personal experiences. Some findings were common to both sighted and BLV people, while other findings were unique only to BLV musicians and learners. Furthermore, our conversation oscillated between discussing properties of materials and imagined future technology that may be embodied with these materials. We made sense of these findings by employing the Material Experience Framework and categorized our findings into sensorial, interpretive and affective experiential levels [17].

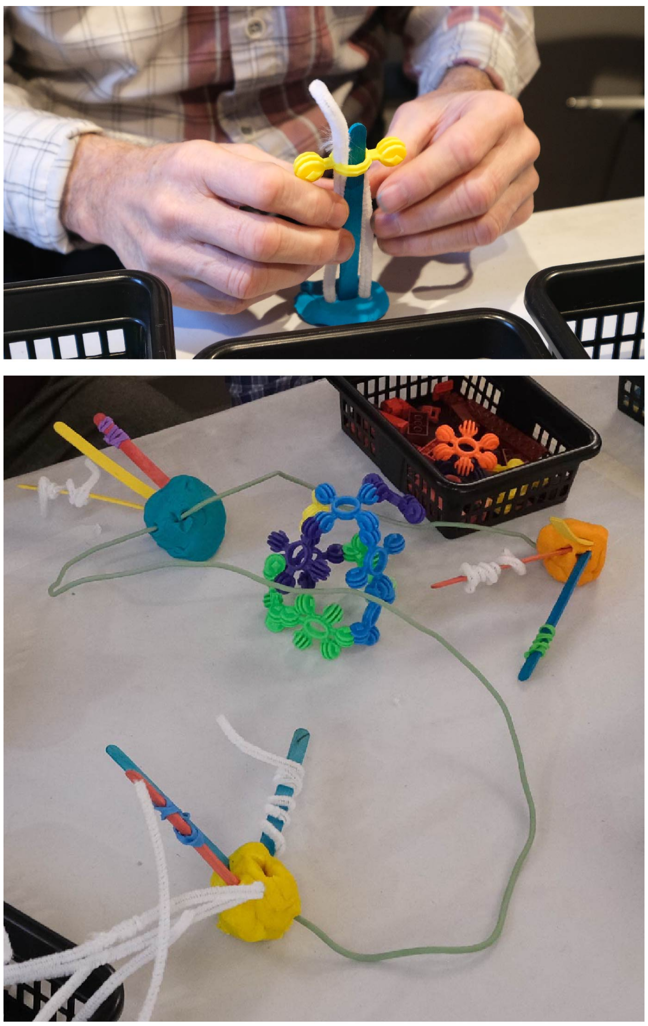

Figure 8: On top: P2 making tactile analog controls, on bottom: P5 communicating nonverbally using textures

4.2.1 Sensorial Meanings from Materials: By touching material swatches, participants explored material properties that were important to them:

- *Breathability:* Multiple participants described this as important for wearable technologies. P2 expressed similar ideas and said, "Right away, I'm thinking if it's too warm, I don't want to wear it. When it gets humid, my hands get moist and it becomes hard to read [braille]". P5 described real leather to be comfortable as it would retain less heat and be more airy.
- *Malleability:* P5 described real leather to be comfortable because it could conform to different shapes. P10 described the metal watch they had on and said, "This has to be removed, if you're playing many instruments, it's on your body, you want flexibility because you would be moving".
- *Distinguishability:* P1 said, "the shape of hard materials is easy to identify and easy to feel". P2 created a model of tactile controls using a plastic ring that can be rotated around a popsicle stick (Figure 8 - on top) and said, "I love analog controls, I want to ensure that this device would have analog controls. Don't give me this swipe on a screen, I want to touch it. Analog controls give you feedback in the controls itself". P5 imagined a system where students and teachers can communicate with each other nonverbally using textures (Figure 8 - on bottom). They said, "I inserted the popsicle sticks into each play-doh ball and each stick has a different texture on it. So it's almost like a different button that can activate different cues, this is all based on touch."
- *Sound Dampening:* P5 said, "Something that doesn't create excess noise is important [as it would distract them from listening to the music]".
- *Durability:* P6 said, "If it is anything that you are going to be interacting with on your body, it will take damage. Music [playing] can be very rigorous. [Plastic as a durable material] is probably more practical, [especially] if you are going to be using it for a long time". P5, P7 and P9 also found plastic a durable choice of materials while P3 considered wood and metals durable.
- Participants also described *Irritation* and *Dirtiness* as material characteristics that they would like to avoid. P9 described rough and abrasive materials to be a source of irritation and discomfort while P5 found soft materials such as plushy felt to also cause irritation on the skin, if used extensively. Also, P2 remarked that materials such as silicon are prone to collecting dust which can lead to a perception of the material being dirty.

4.2.2 Interpretive Meanings from Materials: Participants also made connections between material properties and perceived values based on prior experiences and memories:

- *Associations with Musical Instruments:* Participants associated material properties with their experience playing musical instruments. P1 said, "I play the trumpet that is made out of metal. I once played a trumpet made out of plastic and it was pretty uncomfortable, not only the material but the sound was not good".
- *Weight with Quality:* P6, who also played the trumpet said, "A heavier trumpet definitely sounds better. A weight difference makes it feel expensive and the heavier materials sound good to me".
- *Form for Functionality:* Participants discussed using material properties [such as shape] to convey musical information. P8

imagined a system that can be physically manipulated and said, "Pipe cleaners are very versatile. You can fold them into different shapes. Imagine a conductor telling the trumpets to play by shaping this [into a particular shape]".
- *Mobility and Transportation:* Participants also described what they would like to see in future assistive technologies. P8 said, "it should be something small enough that you can carry with you easily" while P2 added that things made out of metal are always hard to carry through airport security.
- *Affordability:* P6 and P8 agreed that objects made out of plastic are practical because they would probably be cheap to make and more easily replaceable.

4.2.3 Emotional Meanings from Materials: Lastly, participants reflected on how certain materials can evoke particular emotions and how this could influence music learning:

- *Encouraging Curiosity:* P5 was curious about materials that were unfamiliar to them. They said, "Most instruments are made out of wood [or metals]. I play the saxophone, which is made out of bronze. I am familiar with it and used to it, so something that is new to me is a lot more interesting. It's almost like I'm curious about it. I know if I use them to teach, it will spark some interest".
- *Enjoyment of Textures:* We observed that participants enjoyed touching particular textures even though they may not be durable or even comfortable for music learning. P8 said, "I am very much a texture based learner, so I really like this one [soft plushy felt]". P4, P6, P7 and P9 also expressed enjoyment while touching the soft plushy felt texture. While, P3 and P8 found enjoyment from rubbing their fingers on corrugated plastic sheets. P10 found particularly pleasing to touch a mouse pad with a knitted surface on one side and a textured rubber surface on the other.
- *Comfort of Familiarity:* P3 and P4 discussed spending a significant amount of time playing and practising on the piano. P4 said, "I don't really think about comfort too much, I just want to concentrate on getting the right notes. I play the piano and I am used to it. I've been playing for several years and it is comfortable for me". Here P4 attributed their sense of comfort to their familiarity with the piano.

5 DISCUSSION

In this section, we discuss our findings and connect them to prior literature. We propose to 1) make non-verbal cues accessible, 2) aid music memorization, 3) support technical guidance and practice and 4) inform user experience design through material experiences.

5.1 Making non-verbal Cues Accessible and Discreet Through Vibrotactile Alerts

While playing and performing music is a complex and mentally demanding activity, musical communication, such as non-verbal cues and gestures, remain straightforward and simple. We found that *vibrotactile alerts* (Section 4.1.1) are suited to communicate simple, timely information to both musicians and learners. Our findings and others [83] suggest that *vibrotactile alerts* can be used to communicate when to start and when to stop playing. This is especially handy for musicians in bands and ensembles who are improvising and responding to cues from other musicians and conductors. It is important to note that *vibrotactile alerts* are only effective when musicians, teachers, and learners agree on their meaning and timing beforehand. This collective agreement is not uncommon with wearable assistive technologies that leverage touch [46, 83]. A *vibrotactile alert* can be used to signal a blind band member that it will be their turn to start playing from the next bar of music. This collective meaning would have to be predetermined between band members before their performance.

From a material design perspective, our findings and others [41, 64, 70] found that sensorial (functional) meaning from materials such as *breathability*, *comfort* (through malleability) and *durability* play an important role in the adoption of wearable assistive technologies. In addition, we found that materials that had *sound dampening* properties would be preferred. This aspect becomes particularly relevant when designing MHWs, as vibration motors produce sound while buzzing. Therefore, selecting materials that can effectively reduce sound while still being able to convey vibration is an important design consideration.

Additionally, the *location* and *interaction type* of this MHW will depend on the context of use. Our findings and others [78] found that people cared about discreetness of technology when it came to public settings, such as performing music in front of an audience or receiving instruction in a mixed visual ability classroom. We can infer that BLV music performers would want this assistive technology to be hidden and discreet in public settings but would be less concerned about the location of the device during rehearsals and music practice. Relatedly, designing MHWs by taking into account the social situations of BLV music learners so that the student feels accepted in their immediate environment is designing for social accessibility [74]. Discreet MHWs have the potential to nurture self-confidence and encourage long-term use [15]. At the time of writing this paper, we found limited research that designed MHWs for BLV music-related communication apart from Turchet et al. [83] and Baker et al. [4]. This is a promising area of research that requires further exploration. Additionally, we are yet to fully understand the impact of material choices on the learnability and intelligibility of MHWs, particularly during prolonged usage. However, our study provides some insights into this matter. Given the nature of communication in non-verbal cue contexts, which is often straightforward and simple, we speculate that the muffling of vibration intensity may not have a substantial effect on the functionality of the system. Additionally, considering that non-verbal cues are typically delivered in advance of the corresponding action, we hypothesize that even minor latency between the transmission and reception of information would have negligible impact on the functionality of the MHW.

5.2 Aiding Music Memorization Through Variations in Vibration

While there is yet to be a perfect solution to replace braille music or make sight reading accessible, developing MHWs with *variations in vibration* can reduce cognitive load, given the songs being practised are simple. We found that *variations in vibration* (Section 4.1.1) can effectively communicate contextual musical information (such as dynamics and articulation) when felt in time with music being heard. As P5 put it, "sometimes a student does not get it [only] by hearing it". Our participants imagined a MHW that could be used to support music memorization by *feeling* musical information rather than having to memorize it. This would empower musicians to play and follow along with the music as their hands would be free to play their instrument.

Exploring the tactile aspect of this MHW, we found that similar to the design of MHWs for non-verbal communication, sensorial (functional) meaning from materials such as *breathability*, *comfort* (through malleability), *durability* and *sound dampening* continue to play an important role in adoption of ATs. In addition, we emphasize the significance of emotional (non-functional) meaning from materials. Factors such as *curiosity* and *enjoyment* through different textures play an important role in enhancing the experience of music practice. These considerations are particularly important as music practice often requires repeated focused efforts, which can be sustained through personal motivation and discipline.

Also, we highlight two noteworthy findings related to cognitive load. First, P5 had the idea of distributing music reading across braille music and *variations in vibration* (Section 4.1.2) and this idea is yet to be put into practice but the literature on distributed cognition [27], which theorizes that cognitive load can be reduced by distributing it across individuals, objects and the environment would suggest that this is definitely possible [97]. Second, we emphasize the importance of utilizing simple *variations in vibrations* based on our participants' experiences. They reported a high cognitive load from simultaneously feeling vibrations and playing music on their instrument.

Additionally, we underscore the importance of flexibility in the *location* of the MHW. Our participants demonstrated varied preferences in terms of the location of vibration motors, taking into account their personal preferences and the specific instruments they played. It is important to allow for customization and adaptability in the placement of the MHW to accommodate individual needs and instrument requirements. This was best articulated by P2 who said, "The beauty of this [prototype] is that you can put it anywhere. So we could just leave it open. It doesn't have to go on the arm or the leg, it could do all kinds of nice possibilities". Moreover, we envision that incorporating customizable placement options for the MHW would facilitate its versatility for BLV individuals in playing various instruments. For instance, a BLV multi-instrumentalist who plays the piano could attach the system to their shoulder to read piano music, while opting to attach it to their ankle when reading and playing music on the violin. This adaptable approach allows for the seamless adaptation of the MHW to different instruments without needing to learn a new system. Thus, enhancing its usability and effectiveness across a range of musical contexts.

Our findings and others [59, 60] also point to the benefits of multimodal music reading by combining braille music with other modalities (such as synthesized audio, text description and vibration). Prior work in MHWs has explored the application of *vibrotactile alerts* and *variations in vibration* to convey musical information [20, 90]. To the best of our knowledge, MHWs have not yet been developed to aid BLV musicians with music reading and memorization. An open question is whether future MHWs can replace braille music and make sight reading accessible to BLV musicians. Further research is needed to better understand how BLV musicians would interact and utilize MHWs for music memorization, what the learning challenges of using MHWs are and what the long-term benefits and limitations might be.

5.3 Supporting Technical Guidance and Practise Through Vibrotactile Alerts

While the role of the music teacher cannot be substituted by technology, strategically placed *vibrotactile alerts* can provide technical guidance and act as a practice aid. We found that strategically placed *vibrotactile alerts* can convey technical information (such as fingering patterns) when felt in time with music being heard, this is especially useful for music beginners who are just starting out. Our participants and others [28, 88] found that *vibrotactile alerts* placed close to the body parts involved in producing sound could help music learners train their body to play complex rhythm patterns and develop muscle memory. Participants also imagined that such a system can support remote learning as music teachers and their students would not need to be present in the same physical location.

From the perspective of music teachers, strategically placed *vibrotactile alerts* can aid teachers who are either not comfortable guiding their students through touch [1] or cannot provide individual attention to BLV music learners in diverse music classrooms [5]. Furthermore, our research, along with the study by Phutane et al. [65], found that texture *distinguishability* can convey conceptual information effectively. We envision that by combining static tactile information with temporal *vibrotactile alerts*, music teachers can enhance their ability to convey both technical and conceptual instructions more effectively. This is a promising area of research that requires further exploration. Open questions remain about determining which type of musical information are most effectively conveyed through static tactile media and which are better suited for temporal *vibrotactile alerts*. Other open questions include: what are the long-term impacts of using MHWs for technical guidance and practise? Would BLV musicians become dependent on this system for support? Or would this act as a "training wheel" that can be phased out over time?

5.4 Designing for Materiality in Musical Haptic Wearables

From the twelve material perceptions and preferences, we identified at the sensorial and interpretative levels, we noted that Sound Dampening (Section 4.2.1) and Associations with Musical Instruments (Section 4.2.2) are most directly relevant to the design of MHWs. The former is important for all musicians because they rely on an acute sense of hearing during music-related activities. The latter is meaningful for BLV musicians, as their prior experiences with materials embodied in musical instruments may influence their perception of the quality of MHWs designed to assist with music learning.

While our participants did not explicitly state this spillover effect of evaluating the quality of a device based on prior experiences, the literature on how BLV users apply the mental model that they have for existing technologies in interacting with new technologies suggests the effect is highly probable [42, 50]. For instance, a BLV musician who considers a heavier trumpet to be more premium may also associate other objects (such as MHWs) that are heavy to be made off superior quality. If so, this spillover effect highlights the need for accessibility researchers and designers to better investigate the material associations and preferences of BLV people to inform the design of assistive technologies. This is further explored in emotional design [53] as a *behavioural level* and in the material experience framework [17] as a *performative level*. Both bodies of research discuss how perception, ascribed meaning and emotions affect how people make decisions and perform tasks. To date, many MHWs have not got past the prototyping phase and have thus been made of typical prototyping materials (e.g., Velcro straps, regular fabrics, 3d printed casing) [44, 46] and more work is needed to understand what other material experiences can frame user experience design of assistive technologies.

Our notable finding is that material properties can evoke positive emotions in BLV participants, and we outline two implications of feeling good from interacting with materials. First, positive emotions can increase a BLV musician's intention to use musical wearable haptics by increasing their perception of perceived usefulness and ease of use of the devices [40]. Furthermore, one's intention to use is positively related to the actual use of the device [25]. Second, positive emotions are positively linked to learning motivation and academic achievement [48, 62] and the quality of relationships with a teacher [22, 49]. While prior work on educational psychology has investigated positive emotions evoked from learning materials and classrooms, our findings and others [11, 18] suggest positive emotions can be evoked from materials. As a BLV person may develop an immediate perception to an object based on touch, it is critical for wearable devices to be made of the right materials to be able to evoke immediate positive emotions, with the goal of eliciting positive learning outcomes and long-term device usage. An open question is whether positive emotions from materials translate into positive learning outcomes in music learning. Furthermore, future work should explore the potential influence materials can have on 1) the self-identity of BLV people and 2) on the perception of others watching BLV musicians.

6 LIMITATIONS AND FUTURE WORK

Our study is not without caveats. We conducted workshops with a small population of experienced BLV musicians and learners who had musical experiences within mostly "western classical" music. Also, our participants' creativity and ideation are limited by the six preset patterns in our prototype and thus our findings represent narrow possibilities of how wearable haptic technologies can functionally support BLV musicians. We did not translate our findings into a tangible prototype to validate the effectiveness of wearable musical haptics in the application areas identified in the study or whether the device can be used in more than one application areas (e.g., can the device communicate vibrotactile feedback to communicate stop and start playing *and* information about polyrhythm?). Future work can create a tangible prototype that reflects our findings and conduct a longitudinal evaluation study to understand the actual impact of the prototype on a BLV musician.

Second, we identified the possibilities of MHWs that can potentially address a BLV person's music learning challenges, but we do not know the implications of the findings for a sighted or BLV teacher. Future work can examine questions such as "How can a prototype that reflect our findings be incorporated into a teacher's lesson plan?" or "How would a prototype be perceived and accepted by a teacher?" A BLV student learns music by being embedded in a large social environment that consists of a teacher and other students. For instance, we found the musical wearable haptics can be used to support a BLV student to remotely practise with a teacher. The successful implementation of assistive technologies partly depends on a teacher's acceptance of the technologies and our findings can only be interpreted in an isolated manner.

Third, we identified materials that make BLV participants feel good, but we do not know if feeling-good materials can be equated with materials that accurately represent a BLV musician's private and public self-concept [53]. Bulky and "uncool" assistive technologies make people with disabilities feel embarrassed for wearing something that does not represent who they are to themselves and others, which consequently result in abandonment of the technologies [55, 57, 74]. Hence, future work can investigate materials that feel good on touch and accurately represent a BLV musician's self-concept.

Lastly, we acknowledge external threats related to participants' representativeness: other researchers should be cautious in generalizing the results to participants of different demographics and we encourage them to replicate our study with different population groups and with participants having varied musical experiences. There is a misconception that qualitative research cannot be generalized, however, one must make a distinction between statistical generalizability and transferability [66]. The former applies to quantitative research and views generalizability is possible with the employment of experimental research techniques (e.g., random sampling) and the latter applies to qualitative research and emphasize a reader can extrapolate the findings as long as they judge the findings are applicable to new situations. To accurately generalize our findings to different groups of BLV musicians, we encourage researchers to evaluate the similarities of our participants' demographics to their population of interests.

7 CONCLUSION

Learning to play a musical instrument as a blind or low vision (BLV) person remains a complex and challenging endeavour. The development of musical haptic wearables (MHWs) that augment touch through vibrotactile feedback is a promising area of exploration. In this study, we examined both the practical applications of vibrotactile feedback to aid music learning, as well as the user experience of future technology through non-functional aesthetic experiences of BLV musicians. Through conducting five co-design workshops with ten BLV music teachers and learners and employing bodystorming and material exploration sessions, we found opportunities for utilizing vibrotactile feedback for instructional information, music reading and technical guidance and found material experiences that hold practical and emotional values to BLV participants. We invite accessibility researchers and designers to consider both functionality and materiality in developing MHWs for BLV music learning.

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