Project TapTap: A Longitudinal Study Exploring Non-Verbal Communication through Vibration Signals Between Teachers and Blind or Low Vision Music Learners

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Figure 1: Image on Left: Image of a person wearing the TapTap prototype on their right leg while also holding the prototype pair. Image in Middle: Image of a person playing the piano while wearing the TapTap prototype. Image on Right: Image of student and teacher playing the violin, both wearing TapTap prototypes.

ABSTRACT

While wearable haptics hold promise for making non-verbal cues like gestures and facial expressions accessible to blind or low-vision musicians, our understanding of how vibration signals can be interpreted and applied in real-world learning environments remains limited. We invited five music teachers and their seven students to participate in a ten-week longitudinal study involving observations, weekly catch-ups, group discussions, and interviews. We explored how wearable haptics could facilitate communication between sighted teachers and BLV students during one-on-one music lessons. We found that students and teachers derived particular meanings from vibration signals, including time-coded meaning, mutually agreed and intuitive meaning, and haptic metaphors. Additionally, wearable haptics significantly improved the experience of learning music for both sighted teachers and BLV students. We conclude by highlighting key design implications and outlining future research directions to create wearable haptics that significantly improve the music learning experience of BLV people.

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

While non-verbal communication, such as gestures and facial expressions, remains fundamental to conventional music teaching, it is largely inaccessible to blind and low-vision (BLV) musicians [1, 6, 27, 33], especially during practice sessions and performances. BLV musicians rely on sensory substitution techniques such as listening to breathing patterns and rustling of clothes [27] and interpreting musical gestures from other musicians [1] to make sense of non-verbal communication. However, these strategies are not always practical as BLV musicians must focus on both the music performance and the additional auditory cues [6, 33]. During music lessons, teachers play a vital role in providing accommodations and personal adaptations to meet the needs of their students [1, 27, 33]. They often utilize the modality of touch to provide technical guidance [36] and to convey conceptual instructions within the music [27].

Wearable haptics holds promise for conveying non-verbal communication through pre-agreed meanings and codes [2, 19, 22]. In music learning settings, studies have explored wearable haptics for making music more accessible to BLV musicians [3, 5, 28, 29, 50]. Prior studies have explored haptic wearables to support synchronization [49] and conveyed the amplitude of recorded sound files through modulation of vibration intensities [47]. Relatedly, Lu et al. found that the timing and intensity of vibration signals can convey particular aspects of music, including rhythm, tempo, dynamics, and articulation, to BLV music learners [29]. However, we do not fully understand how BLV students and their teachers want to use vibration signals to convey real-time guidance and instruction, especially over a long period of time.

To address this gap, we conducted a ten-week-long study asking student-teacher pairs to experiment with wearable haptics during weekly music lessons. To guide our approach, we pose two research questions:

- **RQ 1:** What meaning can students and teachers derive from timely vibration signals during music lessons?
- **RQ 2:** How can wearable haptics improve real-time communication during music practice and performance?

Our study comprised observations, short weekly catch-up interviews, two town hall meetings, and an individual final interview. We invited five music teachers and their seven students from The Anonymous Music School[1] to explore how vibration signals can be used to convey musical instructions during music lessons. We intentionally provided participants with time to become familiar with the wearable haptic system, allowing them to explore, experiment, and reflect on how vibration signals can be utilized for communication. This longitudinal approach allowed us to identify behaviour patterns and provided us time to respond and adapt the wearable haptic system based on participants' feedback. We found that specific vibration signals can convey distinct types of musical information including time-based information (such as rhythm and tempo) and performative information (such as articulation and dynamics). Additionally, we found that wearable haptics can enhance the learning experience for both teachers and students in the music classroom.

[1]A music school for blind and low vision individuals in an anonymized city, country.

Paper Contributions: First, we describe how students and teachers derived meaning from vibration signals, including time-coded meaning, mutually agreed and intuitive meaning, positive and negative perceptions, and the development of haptic metaphors. Second, we report on the impact of wearable haptics on the overall music-learning experience, including keeping musicians in flow, easing the communication demands on teachers, and providing students with a clearer understanding of the music. Third, we provide specific design considerations for assistive technology designers and researchers to make wearable haptics for communication, focusing on the needs of BLV musicians and learners.

2 RELATED LITERATURE

In this section, we describe the challenge of non-verbal communication in music-learning settings and explore the potential role of wearable haptics in communicating and conveying information. To provide context, we articulate definitions for commonly used music theory terms in the appendix.

2.1 Challenges of Non-verbal Communication

Missing non-verbal cues such as eye contact, facial expressions, head movements, body posture, and gestures can significantly hinder social interactions and interpersonal communication between sighted and BLV people [7, 13, 20, 45]. This can lead to confusing situations [37, 44], difficulty following instructions [33] and not knowing others' feelings in particular scenarios [54]. In addition, Morrison et al. found that BLV folks expressed a desire for technologies that could help them understand non-verbal cues to better manage social interactions, such as knowing if someone is engaged in conversation or understanding when someone extends their hand for an offering [32].

In a musical setting, sighted musicians rely on real-time non-verbal cues from teachers, conductors and peers to guide their performance during practice and live shows. In contrast, BLV musicians do not have access to this information, which can significantly affect their music learning practice [1, 6, 27, 33]. Baker and Green added that a teacher's smile or frown can communicate approval or disapproval during performances. However, this information was not available to BLV learners [6]. Lu et al. observed that in choir and ensemble settings, BLV musicians had difficulty following the non-verbal cues and gestures given by their sighted conductors and fellow musicians, which hindered their ability to coordinate, collaborate and improvise in the moment [27].

Prior studies highlighted the role that music teachers, music conductors, and peers play in the music learning experience of BLV musicians [1, 27, 33]. Experienced music teachers devised alternative strategies to access visual information by replacing it with verbal communication, tactile interactions, or musical gestures [1, 27, 33, 39]. Abramo and Pierce found that teachers would either voice their instructions during performances or encourage their students to listen for changes in rhythm as a non-verbal cue to know when there is a transition in the music [1]. Lu et al. added that BLV musicians in choirs and ensembles looked for auditory clues, such as listening to a conductor's breath or listening to the rustling of clothes, to indicate an upcoming change in music [27].

Touch plays a significant role in helping teachers communicate with their students [26, 36]. Some music teachers reported lightly and strongly tapping on their students' shoulders to communicate the duration of notes [29]. Additionally, teachers used tactile modelling and hands-on guidance by placing their hands over their students' hands while playing an instrument, offering technical guidance and support [1, 18, 36]. However, these strategies are not always practical, as some teachers and peers may be unfamiliar with BLV music learning practices and may be uncomfortable using the sense of touch to communicate and instruct [18, 33]. Furthermore, tactile instruction raises the question about the interpretation of touch as appropriate or invasive, depending on existing relationships, cultural norms, and social context [14]. More recently, Lu et al. [29] suggested that augmenting the sense of touch with wearable haptic systems can make music learning more accessible to BLV people. We see a need for additional research to fully explore the potential of this field.

Non-verbal communication also plays an important role in facilitating musical instruction and learning. Traditional pedagogical practices, such as the Dalcroze Eurhythmics method, heavily rely on body movement to represent and internalize musical information [23]. Baker and Green found that sighted musicians often described musical concepts through visual metaphors like a "bright or dark tone" [6]. However, a lack of access to non-verbal musical instruction can hinder the learning process for BLV musicians. Moss found that BLV music learners struggled to understand and respond to their sighted teachers' physical gestures, body movements, postures, and facial expressions, which were crucial for conveying technical instructions and musical cues [33]. Relatedly, Reed et al. examined the role of abstract metaphors for instruction in musical settings [40]. They categorized metaphors into auditory, kinetic and visual metaphors and argued that the flexibility and ambiguity of metaphors can foster the creation of shared meaning between teachers and learners, resulting in more effective and intuitive communication. For example, the idea of "Spinning Air", which by itself does not have a specific meaning or context, can help students understand the concept of maintaining a steady airflow during singing. In this study, we expand on the idea of abstract metaphors for music learning through wearable haptics, exploring how intuitive and predetermined meanings can be applied to abstract vibration signals as haptic metaphors for communication and instruction.

2.2 Wearable Haptics For Communication

Leveraging haptics as an information modality creates numerous opportunities for designing systems and assistive technologies for BLV people. Recently, vibrotactile feedback has been used to convey navigational cues [22], enhance interpersonal communication through shared awareness of breath [2], synchronize running [19] and play video games like Guitar Hero[2] [56]. McDaniel et al. investigated the use of tactile rhythm patterns from a haptic belt to convey non-verbal social cues, such as the location and distance of nearby individuals, enabling BLV users to accurately identify people in their surroundings [30]. Yasmin and Panchanathan explored the creation of a haptic language through the design of the Haptic Mirror Project [55].

In music settings, studies have explored haptics as musical instruments [9, 48, 51], for conveying musical instruction [17, 21, 24, 25, 36], as a technical learning aid [10, 53], for communication [50] and for synchronization [3, 5, 15, 16]. Commercially available wearable devices such as the Soundbrenner Pulse [46] promise to teach rhythm and tempo by feeling vibrations. Studies also found that musical information (such as pitch, tempo, timbre, dynamics and rhythm) can be perceived through vibrotactile sensation [41–43].

Lu et al. and others [27, 29, 38, 50] have explored the potential of haptic systems to convey simple, discreet information in real-time to BLV musicians and learners. Tanaka and Parkinson [47] made sound files on digital audio workstations more accessible by conveying the amplitude of recorded sound files through modulation of vibration intensities. Turchet et al. [49] designed haptic wearable devices to support synchronization between BLV musicians, and Baker et al. [5] explored how a conductor's gesture can be wirelessly communicated to BLV musicians. Relatedly, BLV musicians reported that timely vibrations could be used to convey fingering patterns for a piano or be used to access new music through a combination of audio and vibration [29]. BLV musicians subsequently emphasized the effectiveness of vibration as a medium for information transfer, noting that it would not disrupt their ability to listen to the music being played and performed as well as being discreet in performance settings [27].

Bandukda et al. highlighted the importance of context-dependent information needs, describing the correlation between the social context a BLV person is in and the detail of information they require based on where they are and who they are with [7]. Relatedly, Lu et al. identified that the timing and intensity of vibrations could be utilized to communicate different aspects of musical information to BLV music learners. They found that timely vibrotactile alerts in the form of haptic codes or patterns could be used to convey predetermined information and instruction, while changes in vibration intensity could be used to convey musical information such as dynamics and articulation [29].

To summarize, simple vibration signals have real potential for delivering real-time information to BLV people, especially during music practice and performances. Yet, more research is necessary to better understand the range of meanings these signals can convey.

3 METHODOLOGY

To explore how BLV music learners and their sighted teachers could derive meaning from vibration signals, we conducted a ten-week-long study involving in-person observations, short weekly virtual catch-ups, two virtual focus group discussions and in-person final interviews. In partnership with The Anonymous Music School, we invited seven BLV music learners and five sighted teachers to participate in this study. We intentionally designed this study to provide participants with time to familiarize themselves with a functional wearable haptic system and allow them to explore, experiment, and reflect on how vibration signals can be used for communication in a real-world setting. The research team consisted

[2]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.

of four sighted researchers (first, third, fourth, and fifth authors) and one blind researcher (second author).

3.1 Initial Ideation and Project Planning

The first author, with experience in accessibility research and design of assistive technologies, worked with the second author, a music educator, a musician (piano, voice, clarinet and saxophone) and a performer, to identify the goals and methodology of this study. Through a series of virtual meetings, we agreed that students and teachers needed time to familiarize themselves with the TapTap prototype and time to explore, experiment and reflect on using the system. For the design of the wearable system, we recognized that musicians needed unrestricted movement of their upper body, including their arms, wrists, fingers and neck, to play their instruments, making these body parts unavailable for interacting with the system. Additionally, we wanted both teachers and students to have a clear perception of when a message was sent or received while ensuring the sensation was not startling. Taking these considerations into account and drawing from the lived experiences of the second author, we envisioned a wearable haptic system designed to fit around the ankle and foot. The system could be activated by a deliberate heel-tapping motion, combining intentionality with a degree of dexterity.

3.2 Design of the TapTap Prototype

The TapTap prototypes are a pair of haptic wearable devices that enable people to send and receive real-time haptic signals by tapping their heels together (Figure 2A). The prototype consists of two parts. The main module contains a micro:bit microcontroller [4], a custom printed circuit board (PCB), a 9v battery and a stomp switch, and the auxiliary module contains a strap attached to two vibration motors embedded in an acrylic casing. We opted for mini coin-style 3-volt rated vibration motors featuring a precious metal brush and commutator system, offering efficient and reliable performance within a compact form factor (Figure 2D). Through initial tests with the vibration motors at varying voltages, we found that a 6v power supply provided sufficient power for the vibration signals to be perceptible when positioned above the ankle. Before the start of the ten-week study, we conducted mock interactions in which the second author used the TapTap prototypes while performing music, further verifying that musicians could perceive the vibration signals even while concentrating on playing their instruments.

During music lessons, students and teachers could send and receive vibration signals by tapping their heels together. The signals matched the press duration of the stomp switch and were transmitted instantly without any perceivable latency. This enabled students and teachers to communicate rhythm and timing-related information while playing music. Additionally, we imagined that during individual music lessons, teachers typically would send vibration signals to their students to convey instructions. However, informed by the Interdependence framework [8], we designed the system to be bi-directional, allowing students to have agency in selecting which vibration-based codes or signals were most effective for them. This choice also encouraged both students and teachers to consider other potential contexts for using the system beyond the music classroom.

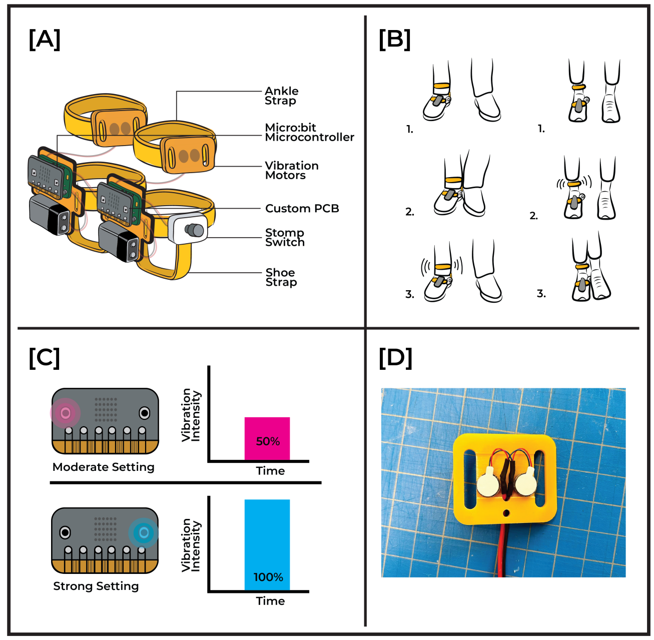

Figure 2: [A]: Illustration of the TapTap prototype, displaying all its components. [B]: Illustration of the bi-directional communication in three main scenarios. In scenario 1, both users are at rest with some distance between their feet; in scenario 2, the left user presses the stomp switch with their foot, triggering a vibrotactile sensation to the right user; in scenario 3, the right user can also press their button, sending a vibration back to the left user. [C]: Illustration showing how to set vibration intensity using two onboard buttons on the microbit microcontroller. [D]: Mini coin style vibration motors encased in acrylic housing

Based on insights from Lu et al. [29], the initial system design featured simple vibrotactile alerts with a constant amplitude that was easy to perceive, operating in a simple on-and-off state without any fade in or fade out. Later, in response to the participant's feedback in week six, we added the functionality of setting the vibration intensity to two separate settings, moderate and strong, as shown in (Figure 2C). Using the built-in buttons on the micro:bit microcontroller, participants were able to set a moderate (50 percent intensity) or strong (100 percent intensity) setting. The participants could then send and receive signals using the stomp switch pedals. The system would continue to send and receive the defined vibration setting until changed. However, since we could only alter software remotely, we were unable to offer alternative tactile interactions that would enable more nuanced and gradual control of the vibration signals.

3.3 Participant Recruitment and Information

Our institution's research ethics board approved the protocol and call for participation, and we shared it with The Anonymous Music School community. We recruited twelve participants, which comprised five music teachers and seven of their BLV music students.

Seven participants identified their gender as female, and five participants identified their gender as male. Participants were between 11 years old and 69 years old (M = 27.5, SD = 13.6). All music teachers were sighted; six students indicated that they were blind, and one mentioned that they were deafblind.

Below, we refer to each teacher with the letter T followed by a number and each student with the S followed by a number. Additionally, we provide more detail about each music teacher and student, describing their music experience and working relationship with one another. All lessons between teachers and students were individual, with some teachers having two students who participated in the study.

- Piano Lessons with T1: T1 is a professional pianist with extensive music experience performing both as a soloist and in chamber ensembles worldwide. She holds degrees in music and performance arts, a postgraduate diploma in piano performance and has over five years of experience teaching piano to BLV students. S1 is an accomplished pianist who has been learning piano for over 10 years. He has performed as a soloist and in ensembles. S2 is an early piano learner who is also learning other musical instruments, including percussion. T1 has been providing individual piano lessons to S1 and S2 for over two years.
- Piano Lessons with T2: T2 is the director of music studies at The Anonymous Music School, where she leads both the youth and adult vocal ensembles and has decades of experience teaching piano to BLV learners. S3 is an accomplished guitar player and performer who recently started piano lessons. T2 and S3 have been working together for under a year.
- Voice Lessons with T3: T3 is a classical soprano and voice teacher who sings and performs in operas and choirs. S4 is a skilled singer who has performed with several choirs, including a gospel choir. She also plays the piano and is part of a laptop orchestra. T3 has been providing individual voice lessons to S4 for over three years.
- Violin Lessons with T4: T4 is a graduate of The Yale School of Music and The Juilliard School. She is a professional violinist who has performed as a soloist for over twenty orchestras. S5 is a talented violinist, pianist and percussionist who has been learning music for over 10 years. S6 is an amateur violinist who also sings, plays the piano and is part of a laptop orchestra. T4 has been providing violin lessons to S5 for over three years and has been working with S6 for over a year.
- Music Composition Lessons with T5: T5 is an award-winning music composer and guitarist and is also completing his PhD in music composition. S7 is a talented pianist who has been taking composition lessons for under a year with T5.

3.4 Procedure and Timeline

Before the start of the study, the first author introduced the TapTap prototypes to the students and teachers in person and described how the system can be worn and used during music lessons. They also specified that students and teachers had complete freedom to use the TapTap prototypes as frequently or as sparingly during the music lesson as they best saw fit. The longitudinal data collection took place in multiple phases over a period of ten weeks (Figure 3):

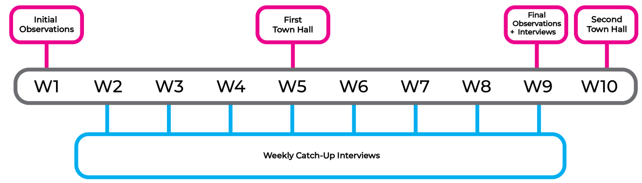

Figure 3: Illustration showing breakdown of data collection from week 1 to week 10

(1) *Initial Observation:* In week one, the first author observed one-hour music lessons, noting how the TapTap prototypes were used without disrupting the class. He also collected audio recordings and photographs.
(2) *Weekly Catch-Up Interviews:* From weeks two to nine, students and teachers were encouraged to use the TapTap prototypes during lessons as they wished (Figure 4). After each lesson, the first author conducted a 15-minute phone interview to discuss usage, benefits, drawbacks, and design ideas. All interviews were audio recorded.
(3) *First Town Hall Meeting:* In week five, students and teachers attended a virtual town hall meeting to share their experiences with the TapTap prototypes and discuss how the system could fit into their practice. They also provided feedback on potential improvements and their perceptions of sending and receiving haptic signals during lessons. This focus group encouraged idea exchange between student-teacher pairs for further testing in the study's following weeks. The session was audio recorded.
(4) *Final Observations and Interviews:* In week nine, the first author observed lessons to assess how TapTap use had evolved, taking notes without disrupting the class. Afterward, he interviewed students and teachers about their experiences, limitations, and design ideas. Audio recordings and photographs were taken.
(5) *Second Town Hall Meeting:* In week ten, students and teachers joined a final virtual town hall to reflect on how wearable haptics impacted their music learning experience. They also discussed future applications and design improvements. The session was audio recorded.

We note that not all participants were available for every phase of data collection, either due to scheduling conflicts or because of missing music lessons in certain weeks. Participation and absences for each phase of the study is included in the appendix). In response to feedback from the first town hall (week 5), we added the ability to modulate vibration intensity with two settings: moderate and strong. Audio recordings of the observations, weekly catch-ups, two town hall meetings and final interviews were made and transcribed for data analysis.

3.5 Data Analysis

The first, third and fourth authors conducted an inductive thematic analysis following the six steps outlined by Braun and Clark [11, 12].

Figure 4: These images demonstrate the TapTap prototype being worn during music lessons with a teacher and a student. Image on left: the TapTap being used in a violin lesson. Image on right: the TapTap in use during a piano lesson.

Our thematic analysis is descriptive and used for data reduction. The analytical focus was to describe the experiences and ideas of our participants. To enhance the trustworthiness and rigour of this analysis [35], we engaged deeply with the data, systematically coded it to identify meaningful patterns, provided clear and transparent descriptions of our analytical process, and critically reflected on our roles as researchers to acknowledge and address potential biases and assumptions. Detailed steps are summarized below.

To begin with, the first, third and fourth authors acquainted themselves with the data by individually reviewing the transcripts from the first and second town hall meetings. We selected these two specific data sets because they encapsulate key ideas and discussions from participants during the mid and final phases of the study. Next, we individually read the transcripts line-by-line and assigned initial semantic codes (Included in the appendix). Afterwards, we compared the 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. Next, we repeated the systematic coding process, equally dividing the remaining data sets between the three authors. We thoroughly reviewed the remaining transcripts multiple times and meticulously applied line-by-line coding with the assistance of the codebook while also generating fresh codes as needed. Also, we met weekly to discuss and share fresh codes and through agreements and disagreements, we devised additional codes and corresponding definitions.

Next, the first author and the third author grouped the codes into potential themes based on similarities and relevance to the **RQs**. Subsequently, the first and third authors reviewed and refined the themes, going back and forth between the codes and the potential themes and pinpointing quotes that represent the themes.

Later, in response to the **RQs**, we report these themes in (Section 4). Additionally, to draw insights from the weekly catch-ups (From week two to week nine), we selected important codes from our codebook that were relevant to our **RQs**. Then, we created simple graphs showing a ratio (from 0 to 1) of how many participants mentioned each code compared to the total number of interviews per week. The Y-axis represents this ratio, and the X-axis shows the timeline from week two to week nine. Additionally, the data for these graphs were checked individually by the first and third authors to account for errors.

4 FINDINGS

In this section, we first describe how participants attributed meaning to vibration signals. Next, we report on the impact of wearable haptics on communication during music lessons. Lastly, we report on future design considerations for wearable haptics.

4.1 Making Meaning of Vibrations

4.1.1 Time Coded Musical Information: We discovered that vibration signals were especially effective in conveying time-sensitive information during music learning. Elements such as rhythm, tempo, and musical cues were communicated effectively and in real-time using the system. To provide an overview of the different types of time coded musical information discussed each week, we visualized weekly mentions in (Figure 5).

Five participants, including three students and two teachers, specifically highlighted the usefulness of vibration signals to communicate rhythm patterns. T4 said, "S5 was learning a really rhythmic piece recently for an audition, and her rhythm was not good. Before the device, a lot of times I would have to keep doing this [demonstrating tapping their thigh] and say don't rush or don't stop or something like that. But with the device, I just needed to tap, and she would know that she was rushing". T1 added, "I was surprised that it worked so well for the rhythm. Like, I thought it would be confusing, but it seemed like it was working really well in real-time". T1 further explained, "I was trying to describe the rhythm I wanted, like the Waltz. I tried one long buzz, followed by two shorter buzzes to try to imitate that". T4 also added, "I've been using it to tap the rhythm while demonstrating it on the violin at the same time. I will ask them not to rush using the device; it's been helpful for S5 and S6". Later, during the final town hall, they added, "I've actually been really missing the device when I'm teaching sighted students. They're not feeling the rhythm; they're always rushing". Both S5 and S6 agreed that time-sensitive vibration signals were effective in helping them understand rhythm. S5 said, "I was kind of surprised in a good way, like how much information that the device was able to add to my interactions with T4, I find it especially useful for demonstrating how long to hold the notes while I'm playing". S6 added, "I find it really useful for rhythm. I have a tendency to rush; those really help me make sure I don't speed up".

Three other participants also used vibration signals to communicate tempo. T2 explained, "There is a piece where the timing of the beats changes in different sections. We started using the system to maintain tempo. S3 has a difficult time with subdividing beats. I was trying to reinforce the changes in subdivisions [by using vibration signals]".

We also found that timed vibration cues could help musicians know when to begin singing and performing when playing with others. S4 said, "I had been struggling with cutoffs all week. There's a long instrumental section in the middle of the song, and I wasn't sure how long it was. T3 gave me a count of four when I had to start singing along to the recording. It was incredibly useful". At the same time, we also found that musical instruction through pre-agreed codes needed to be sent ahead of time. T1 explained, "I'm trying to give the signal a little earlier. So he has time to catch up on what he needs to do. That's actually been going pretty well".

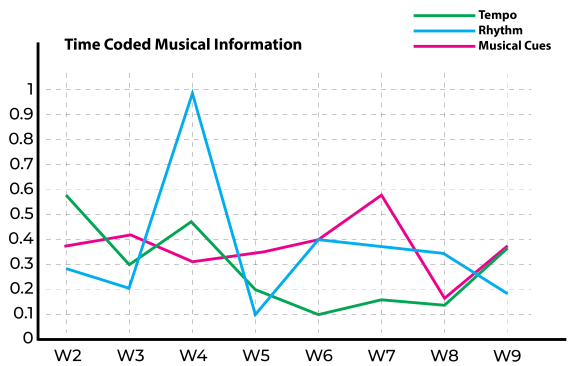

Figure 5: The three colour-coded line graph illustrates the weekly ratio of participants who discussed Time Coded Musical Information out of all participants interviewed each week. It highlights the most frequently mentioned aspects of musical information, including tempo, rhythm, and musical cues, from week 2 to week 9.

4.1.2 Discussed Versus Intuitive Meaning: Participants explored two distinct strategies to make meaning from vibration signals. Five participants, including 4 students and 1 teacher, reported that vibration signals only made sense if students and teachers discussed what it meant beforehand. S1 said, "We need to verbally establish meaning beforehand, discussion is key. As long as you have clear communication established, it works really well". During the first town hall, S5 added, "Having prior understanding and agreement on what meaning we are making is important. It's kind of like setting ground rules".

T1, who taught piano to S1 and S2, described how they created coded messages. They said, "I think one tap of the vibration signal would be the number one code, as that's the easiest one to do. So maybe we want to relate the number one code to the most important instruction that I need to give. For S1, that might be more legato in his right hand". Later, they added that the meaning of vibrations could also change. They said, "We use it for different things each time rather than only one thing or one idea. In each session, we use it for something different, which is different from what I initially imagined". Additionally, they mentioned that vibration signals needed to be given ahead of time, "We learnt that it makes sense to send a signal a little bit in advance so the student can anticipate what I want them to do".

Conversely, some participants described an intuitive use of vibration signals, interpreting their meaning based on the context of the music being practiced. T4, who taught violin to S5 and S6, never explicitly discussed the meaning of specific vibration signals yet effectively used the system to communicate during music lessons. They said, "I actually don't have to really explain. [As you observed] I didn't have to talk with S5 or S6 prior to using the device. They just kind of get it and understand what I'm trying to convey". In response, S5 said, "It's a bit intuitive. There are places in the music where I tend to rush or drag or have tempo fluctuations that are not warranted. So I know what T4 means when they activate the device. I'm paying more attention to the pulse". Later in week two, S5 added, "I was struck by how natural it was. We were doing the same thing from previous weeks and it was pretty seamless. We are using it so I know what to pay attention to, and you don't need to talk too much". T4 added, "I think rhythm-wise, they get it. But for dynamics and articulation, things that are more interpretations, then I need to come in and communicate with them first".

4.1.3 Modulating Vibration Intensity: In the first five weeks of the study, participants sent coded messages by adjusting the duration and timing of vibration signals. However, they also showed a keen interest in exploring vibration intensity modulation. In week two, S5 said, "Could we make the intensity of vibration variable? Not all crescendos are linear. I think the dream would be to have a smooth gradient for things like dynamics so that I could feel the curve of things, not just the timing of when to play". In week four, T1 added, "Maybe something that could be gentler. I think that would help if you were trying to communicate a softer sound. If you only have a loud shock, it's counter-intuitive".

After introducing vibration intensity modulation, we found that variations in vibration intensity were particularly suited to communicate loudness and softness in music. In week six, T2 said, "I think the varying vibration intensities can help us communicate dynamics better. S3 is sort of playing everything at one level. This could remind him to check on that". S2 added, "We used the system to remind me of loud (Crescendo) and soft (Diminuendo) parts. The strong vibration meant to go louder, and the soft vibration meant to go softer". Reflecting on the suitability of variations in vibration intensity for dynamics, T1 said, "I was trying to get S1 to play quieter, so the system allowed us to focus on the lower dynamics, so he wouldn't be as loud". Later in week nine, they added, "Speeding up is no problem, you get a [strong] impulse, and you go. Slowing down is more difficult [with a weak impulse]. If you get poked, you want to go faster but the idea that you'd want someone to settle down, we still don't have a vibration signal that does that". As shown in (Figure 6), students and teachers increasingly favoured using vibration modulation to communicate musical information during music lessons.

4.1.4 Negative Connotations and Positive Affirmations: We also found that the perception of the vibration signals influenced their utility. Three teachers were initially reluctant to employ vibration signals as a correction mechanism. T1 compared the use of vibration signals to electric dog collars used for pet training, which they found uncomfortable. T5 added, "I'm really not into the idea of using that device to bring someone to my attention. It becomes a punitive sensation". However, S1, S4 and S5 didn't particularly perceive vibrations to be positive or negative. S4 said, "I prefer to be buzzed when I do something wrong. I know that might sound weird, but that helps me understand what I need to work on. If I'm doing it right, I don't want to be distracted by the buzzing".

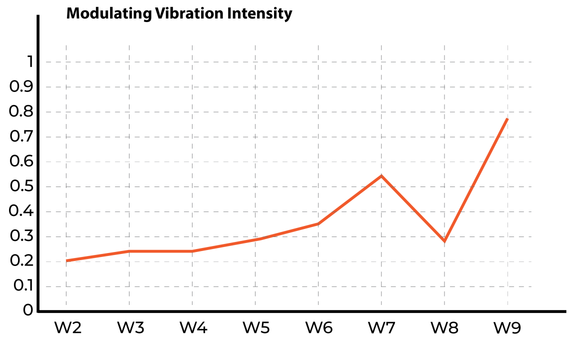

Figure 6: The line graph shows the weekly ratio of participants who discussed the topic of Discussion and Use of Intensity Modulation Across Time out of all participants interviewed each week, from week 2 to week 9.

T3 explored the positive meaning of vibration signals, calling them "Buzzes of Affirmations". T3 said, "I really try hard not to use negative language in my lessons. I like the idea of changing the meaning of the vibration. Instead of using the device when the student does something wrong, what if we used it when they do something right. Like a buzz to send a warm hug when they've played something really well". In reply, S4 added, "I am a bit of a perfectionist, and I hate it when I can't do something on the first or second try. I think T3 would use it to give me a gentle nudge, reminding me it's okay to mess up". T1 and T3 reported that moderate vibration intensities could be perceived as positive. T1 said, "My sense of the vibration intensity was that the [moderate] one was nicer to use; it's less disruptive and less jarring." T3 added, "The moderate vibration is more positive. It can't be mistaken for anything else. I think it is more mellow".

S4 and S5 also described the sensation of receiving a vibration as a form of physical contact. S5 said, "I think the device can be startling. If I'm working with an unfamiliar person, it's important to establish some guidelines about how to use the device and what activation means". Later, they added, "Something I hadn't considered before was that tapping with the device could be construed as the equivalent to physical touch. Boundaries are really necessary when using it, just like when touching another person."

4.1.5 Building Haptic Metaphors: Teachers used a combination of varying vibration lengths and intensities to effectively explain abstract musical concepts. T3, a voice teacher, highlighted the difficulty of teaching steady airflow to S4. They said, "I tend to relate the idea of having a constant flow of breath to sighted students with the idea of powering a light bulb. Too much air or too much electricity and the bulb would burst, too little air or too little energy, and the light won't turn on. I am looking for a steady stream of electricity. But this is a hard analogy for BLV students to understand". In response, T3 used long constant vibration signals to remind S4 and said, "What I wanted her to do was correlate the consistent buzzing sensation with a consistent stream of air from the beginning to the end of the phrase. It actually made a lot of sense to S4. That was a nice breakthrough for her". S4 added, "T3 held down the vibration to remind me to keep my mouth open and maintain an open breath while singing. She reinforced these techniques during warm-ups. It reminded me to keep my mouth open, my jaw and shoulders relaxed". Later, during the final interview, S4 added, "When I'm singing, I'm breathing out, and that's what the vibration feels like. It's less about the individual notes and more about the long breath. I can let the notes flow freely. I felt like everything T3 had been trying to explain to me for the past five years suddenly made sense. I honestly don't know how or why, but it just did".

We also found that students and teachers were at times confused about what type of vibration signal could be used for a particular conceptual idea. S1 explained, "There is a section with a dynamic called *Serré* which in French translates "to squeeze". It is a unique ornament which leaves the interpretation to the player. We were not sure how we would want to emphasize squeezing in a vibration signal".

4.1.6 Nudging for Attention and Focus: We also found that teachers employed vibration signals to refocus or draw the attention of students instead of conveying a specific instruction. T1 said, "Maybe it could be used to push them along. It wouldn't mean anything specific. It would mean that they need to pay a little bit more attention to what they are doing. Something more general rather than an instruction". This was particularly useful for S1, who is hard of hearing. T1 said, "I think it definitely reminds him to do something. I noticed that he changed something, it's not exactly what we discussed, but he definitely noticed that I was giving him an instruction". T4 added, "I like to alert my students when a note is out of tune. I don't need to say much. Sometimes students forget, and this is a good way to remind them".

Reflecting on this, T2 added that these nudges also gave their students the sense that their teacher was closely paying attention to what they were playing. They said, "One of the rules while learning music is 'Always play as if a master was listening'. The fact that somebody is signalling means they are paying attention to you. If I'm quiet, my student doesn't know if I'm still there, but if I'm buzzing them, they know I'm listening, and they have to be on their game". From a student's perspective, S4 and S5 appreciated the timely reminders they received while playing their instruments. S4 said, "T3 is constantly buzzing me, and it's sort of like a reminder of all the things I'm supposed to be doing that I might forget, like relax my shoulders, relax my jaw, keep my mouth open. I find it really helpful".

We also found that students and teachers preferred using simple vibration signals to send and receive musical instruction. T1 said, "I feel like a short or long or single or double [vibration] is all I really need. Very simple things are all I really want to use". However during the final interview, they added, "One problem I noticed was that because we used the same vibration code for different things every week, you start to get mixed up, if you associate one code with one thing too often, it gets hard to add something else".

4.1.7 Duality of Information: Participants reported that a majority of instructions can be simplified into binary commands such as loud or soft, fast or slow, and up or down. We found that these binary instructions can be mapped to two distinctive vibration signals, such as longer and shorter, weaker and stronger, or one and many.

As T1 explained, "If you want to go faster, the vibration should be stronger, and if you want to be slower, the vibration should be softer. That seemed to fit. It's very binary". Later, they added, "A lot of times during music lessons, we are working in gradients. A little more of this or a little less of that. It's all relative". In response, S2 added, "If I was slowing down, T1 would give me a hard tap to go faster, or if I was going too fast, T1 would give me a soft tap to go slower".

Participants also found that the distinction between vibration intensities could only be made in relation to one other. As T1 explained, "If I do two settings [stronger and softer], back to back, then it would be obvious, but if I were to only use one, like in the middle of the piece, it might not be immediately obvious which one it was. Like in comparison, in context it would make sense, but maybe not in isolation by itself".

4.2 Impact on Music Learning Experience

4.2.1 Clearer Understanding and Staying in Flow: We found that using wearable haptics could make communication clearer and more direct. S5 explained, "I think the system offers a new layer of resolution for things that my teacher is already doing. Musicians sometimes breathe to cue at the start of a bar of music. I think I was using the input of the device together with T4's breathing or even the tapping of her heel or thigh. I'm hearing when she's breathing and when she's tapping and I'm adding it up to understand what she wants. Conveying more bandwidth of information that I can perceive". T1 added, "For S1, who is also hard of hearing, this makes a big difference. I know that he actually doesn't hear some of the things I say. I have to wait for him to stop and then explain later". In response, S1 added, "I could really feel the vibration patterns while I'm playing the music so I wouldn't need to stop or be interrupted just to speak".

Participants also reported that the ability to receive information while continuing to play their instrument enabled them to concentrate and remain in flow. T1 said, "A lot of times, I will tell my students not to stop. I'll ask them to keep playing. Because if you keep stopping every time you make a mistake, you lose the flow of the music". S5 added, "Usually it is me playing and T4 yelling, but I couldn't really hear her [over the sound of the violin], so I wasn't sure what she was saying, and we'd have to do it again anyway. But with the device, she doesn't have to yell, and it's natural for me to understand and follow directions". Participants also found that they could be more efficient during the limited time they had during music lessons. T3 said, "S4 doesn't have to wait for me to say good or wait to hear something. She's breathing, and she's going into the next frame. She knows that if she doesn't get the buzz, then she can work a little bit differently at this phrase. For sighted students, I would have just nodded, smiled, or given a thumbs-up. This replicates that".

We also found that teachers could introduce more spontaneity into lessons. T1 explained, "We had some specific parts where S1 had to go loud or soft. But then when he started, I randomly added stuff [instructions through vibrations]. It was spontaneous based on how I felt he was doing". Later, she added, "He didn't pause, and he didn't get it quite immediately, but he knew he had to do something different". T3 also mentioned that they constantly adjusted how much instruction they provided based on how well their student understood the tempo changes. S5 summarized, "It allows for a lot more versatility in what we could communicate; a lot more work could be done while I'm playing".

Students also said that the modality of touch is better suited than sound because it can't be confused with music. S5 said, "Drums are really noisy. So having a communication method that doesn't require noise is extremely helpful. Just like how a conductor would wave their hands around and you get the information. This serves as a substitute for [sight]".

4.2.2 Easing Communication Demands on Teachers: Three teachers noted that the TapTap system significantly reduced their communication workload while teaching. T1 noted while teaching piano to S1, "I could save my breath, and I don't have to use as much energy. S1 is hard of hearing, so I really need to talk very loudly sometimes, and it does get tiring". Later, they added, "I didn't have to speak, and I didn't feel like I was interrupting S1". During town hall one, T2 said, "It was something S4 and T3 discussed, It's very useful for teachers because they don't have to repeat themselves again and again like a broken record". Relatedly, T4 also pointed out that they can provide more information with less effort. They said, "It really requires me to talk less. I just use the device when there needs to be an accent here or there. I don't have to yell or shout, and they don't have to stop because they couldn't understand what I said".

However, we also found that this system was not particularly useful for scenarios where speaking to each other was required. S7 said, "I take a composition class with T5. We just play and talk. There's not much use for this device". Similarly, T1 noted that wearable haptics cannot replace discussion. They said, "I think if you already know the piece, then it makes sense because then we can polish the performance. But if you're just learning a piece, I don't think there's any reason to use it".

4.2.3 Understanding Intricacy in Music: Participants also reported that vibration signals were useful for understanding intricate details within the music. T1 summarized and said, "I think it helps students to play more accurately. It doesn't help them learn the notes, but it helps them with the shape of things".

Three participants, including one teacher and two students, specifically found it useful to communicate Dynamics (loudness or softness). S1 said, "I'm working on a piece that can suddenly go from very loud and passionate to all of a sudden, very soft. So I think the vibrations made me realize that I need to pay more attention and be aware of the different dynamics". T1 also noticed this in S1's playing and said, "I thought it worked really well for the dynamics. It was really nice because he really did have a lot more contrast in the dynamics. I think he just needed to be aware that he was not doing enough".

Two students also described using the system to fine-tune tempo and timing in music. S5 explained, "So instead of holding the buzz for a long time, it would just be a short buzz. It told me I could wait a tiny bit more on this rest". S3 described understanding a complex timing pattern and said, "I tend to slow down and speed up during different parts. On every offbeat, I have to sync with the vibration, it's helping me count and understand". Participants also found that the tapping sensation can depict accents in the music and indicate what note to play strongly and what note to play lightly.

4.2.4 Feeling the Music: All participants agreed that they preferred feeling the music through vibrations over hearing instructions. S5 compared using the TapTap to the sense of touch. T4 explained, "I can communicate how I want them to feel the music. Music is not just about saying it, you really have to feel it to play it. For example, I could say don't rush or don't go too slow, but if you really feel the rhythm, it makes more sense". T1 added that feeling the music also helped S1 remember dynamics. She said, "You could tell that he was trying really hard. The difference in dynamic was more dramatic as compared to if I just told him. I feel like he was trying to play soft and he was trying really hard. It was actually more effective. Maybe he just needed this impulse". Later T1 added, "I feel like with all of my students, I need to repeat myself 10 million times. I don't know if the device will change this, but maybe the device will help people remember better".

During the first town hall, T1 asked the students about their preference between feeling vibrations and hearing instructions, in response, S5 said, "Personally, I like the the vibrations. I'm not a huge fan of people touching me. So the vibrations are appreciated". T3 also added, "S4 doesn't particularly like to be touched. So this was a better way of approaching it because I didn't have to touch her. And that makes her more comfortable".

Later T2 added that tapping a BLV student to explain things could be perceived as invasive. They said, "I've heard this story from so many people that they hated it when the teacher would come over and tap them on the shoulder to keep the beat". S3 echoed the same feeling and added, "Someone once accidentally tapped my shoulder a little too hard, and I lost my guitar pick. It was not a pleasant experience." S5 also noted, "The nice thing about sending vibration signals as opposed to reaching over to touch someone is that it's a lot more convenient. Like when someone's sitting, and I'm standing, if she needs to touch me for something, sometimes she needs to walk over, and the timing of the note is lost; this is instantaneous".

4.2.5 Building on Preexisting Relationships: As part of the design of this study, students and teachers were given the freedom to choose how they would use the TapTap system during their music lessons. Over time, we found that the open-ended design encouraged ownership and agency. This sentiment was best summarized by S5, who said, "I think the standout feature of this device is that it is so open-ended as far as you can use it". During the final interview, T1 added, "I think if the system was limited to one thing, it wouldn't be as interesting. Depending on the student and the piece you're working on, different things wouldn't be as applicable".

Students and teachers also adapted the system to suit their interpersonal communication styles and preexisting relationships. T4, who teaches violin to S5 and S6, said, "Tapping could mean a random note is off, or something needs to be longer or have more of an accent. S5 just gets it. We don't need to talk much about what to do. However, S6 is more of a beginner, so we need to discuss and define the meaning of the tapping beforehand". In response, S5 added, "T4 and I didn't really have any issues as far as communicating what the signals meant. We've known each other for a long time". S4, who takes voice lessons with T3 said, "It depends on the teaching style and personality of the teacher. T3 is really cool, she's nice and playful, and we mess around all the time with the TapTap. It puts me at ease during lessons. I think trusting the person who will cue you is very important". T2 also reflected, "Since we were working with the device together, we had to figure something out together. This maybe brought us closer a little bit because S3 opened up and offered his opinions more forthrightly".

4.2.6 From Startling to Normal: Students initially found the sensation of feeling a vibration startling. T1 observed this and said, "S1 is not really able to keep playing; he has to stop and then continue; the vibrations throw him off". S5 also said, "I think the first few times I used it, it was a bit startling, but now it's quite normal, especially since the volume doesn't interfere when I'm playing". However, over time, the sensation of feeling vibrations became more normal. As S1 reported in week five, "After using it for the past month or so, I'm more or less used to it by now... it definitely feels more normal than it has the first time around". During the final town hall, T1 added, "Initially, we had to pause and think about it before we could actually use it correctly. But once we got used to it, it made things a little more seamless. So it was less of an interruption, and we could integrate it without stopping the process".

Participants also noted that experimenting with a haptic wearable during lessons made the experience more novel and interesting. We observed that S4 and T3 used haptic wearables as a form of play, buzzing each other and laughing out loud at the same time. S4 said, "The first time we used this, we just kept buzzing each other endlessly. At first, I got startled, but then we just had some fun with it". Later, T1 reflected that even though the novelty of haptic wearables faded over time, it was still useful for lessons. They said, "I think the students liked it more than I expected. Initially, I thought it was a new and shiny thing, but that didn't wear off, and the students really found use with it".

4.2.7 Sending Complex Signals: We also observed that teachers explored new ways of using haptic wearables over time. T4 said, "I was initially conservative [about using the system], only using it for rhythm, but over time, we explored tapping to indicate a lot of different things. From dynamics, accents, and intonation. Over time, the progress is evident". Later, we observed that teachers had become so comfortable with the system that they could send haptic signals while simultaneously playing their instruments. T4 described the use of multimodal instructions and said, "I have another student who has ADHD[3]. I know words are like background music to him. So giving instructions through different ways could really help him remember quickly, students really need to feel it".

4.3 Design Considerations for Wearable Haptics for Communication

4.3.1 Body-centric Considerations: When designing wearable haptics for communication in music learning environments, participants identified several factors to consider. Five participants pointed to the importance of freedom of movement while wearing the system. S5 said, "I think there are limited spaces on the body you can put this thing, especially for instrumentalists who need freedom of movement". T2, T4 and S4 explored attaching the device to their

[3]Attention-deficit/hyperactivity disorder (ADHD) is a developmental disorder marked by persistent symptoms of inattention and/or hyperactivity and impulsivity that interfere with functioning or development [34].

wrist, elbows, forearms and ankles (Figure 7). T2 said, "I definitely think the the positioning on the foot is awkward. The fact that you have to use your ankles to tap is awkward. For violinists, it lets them off balance, and for piano, they're using the pedal [on the piano], they can't find the thing". S4 added, "I wore mine on my right forearm with the vibration device on the back of my wrist and hand. The button was positioned so that I could press it with my palm or push it aside when I needed my hands free. For rhythm. It helped a lot because when I was singing".

Figure 7: Image on Left: Designed placement of the TapTap in a music lesson scenario, with both T1 and S1 wearing the device on their right feet. The image on Right: S4 experimented with wearing the TapTap on their right arm for improved comfort.

Three participants, including a teacher and two students, recommended customizable haptic wearables that can be positioned on different body locations. S7 said, "I think you can make a model that goes on different parts of the body. You can customize it based on the instruments you play". T1 added, "There is a lot of variability based on the instrument and the person. Could there be a flexible design where the users can choose where to put it, like with adjustable straps? Maybe it is on your wrist or your knee or ankle. For me, as a pianist, I would probably want it on my left knee. I wouldn't want it on my arms or elbows, but for violinists or cellists who are standing, it would be impossible to put it on your knee". Furthermore, S6 added, "I realize depending on the type of clothes, you may or may not even feel the vibration".

Participants also proposed integration with existing technologies, such as smartwatches or smartphones. T2 imagined a menu of pre-programmed vibration signals that they could send from an iPad or a smartphone to their students in real-time. S1 added, "I agree that a watch or an iPhone app would be easier and more convenient. It would make it easier to manage with your body". Participants also suggested using haptics on existing devices rather than developing new wearable systems. During the final town hall, T3 said, "I think there could be an app on the phone using the phone's vibration. Most students already have Apple products and could benefit from that is some way. There are already vibration elements in the phone, and there are already things you can wear."

We also found that participants wanted to integrate wearable haptics with braille displays. S7 said, "I can imagine an app called the TapTap controller on my braille display. I could press the enter key and send a signal".

Participants also noted that the strength of the vibrations could be influenced by the location of the vibration motors on their bodies. S4 said, "The vibration signals would definitely be stronger if I didn't have boots on". While T2 and T3 related the sensitivity of particular body parts to how startling the vibration signal might feel. Additionally, S3 added, "I tried it on my arm. It's a lot more comfortable for me. When it was on my leg, I would instantly lift up my foot a little early from the piano sustain pedal [in response to feeling the vibration signal]".

We also discovered that the system needed to function effectively in both sitting and standing positions. S5 said, "I was in a duo performance where we were both standing. I don't think we would have been able to balance and click our heels together while playing". T4 added, "It's a little harder for me to tap the device while I'm standing and playing the violin. I have to balance myself on one foot to tap the device". Later S4 also added, "I was like thinking about the feasibility of using the device when playing or in my lesson. It's actually not that easy. Your feet are involved in playing. You need your feet to balance and move around and also pedal".

4.3.2 Designing for Dexterity: Over the course of the study, students and teachers sought to send more intricate signals through the system. However, the existing stomp pedal, though durable, demanded a substantial amount of pressure and physical effort to activate. T4 decided to hold the device in their hand during a lesson and said, "I controlled the device with my hands as it is faster for me to do with the hands. But there are pros and cons to this because I had it in my hand, I can't demonstrate anything with my violin at the same time". In response, S5 noticed, "The cues and the instruction were much more precise, and the cues were for shorter intervals. It occurs to me that the placement of the system on the body and the type of appendage used to send the signals really affects what you can do with it". Participants also discussed alternative forms of input that would enable more intricacy and dexterity. T1 said, "If the design was more like a button or a laser pointer, I might be more inclined to use it with my thumbs". Relatedly, T3 also added, "It's not so suitable to wear on my ankle. It has to be a manual device. Operated by my hands".

Five participants were excited by the idea of being able to send more complex signals by modulating vibration intensity. T4 said, "It would be cool if I had a stick or something where I can really control the intensity of the signal I'm sending". T1 imagined a joystick that could be pressed forward or back to control not only the intensity of the vibration signal but also the shape of the signal. While T1 and T4 imagined a pedal on the floor next to their foot. T4 said, "I think something like a pedal might be good, it's not ideal in the hands as I can't demonstrate with the violin while also giving instructions through the device. Also lifting your leg every time to tap onto your other feet can get quite tiring".

4.3.3 Making Accessible User Experiences: All participants, especially the students described the wearability of the TapTap system to be particularly challenging. S1 said, "My least favourite part is just getting it set up. I never know when it is attached correctly".

T1 and other teachers expressed challenges with putting the device on due to its multiple Velcro straps, which took up valuable time during music lessons. Later in week seven, S1 did add that they were getting comfortable wearing the system; however, they still did not enjoy the process of putting it on.

Relatedly, we also found that making accessible user interfaces necessitated delivering status updates to inform users of the system's operation. S1 said, "There should also be some way for the blind person to know when their battery might be becoming low, especially if the device is supposed to be adapted for blind people. Maybe a set number of vibrations will let the person know that the battery is getting low". Later, they also added, "I think it would be nice, especially for us as blind people, if it somehow told us that the system had been set up correctly. Unfortunately, I never know if the system is put on correctly. I always feel the vibration, but it seems like every week we put it on differently because we may have missed a velcro strap or maybe we don't know if it was correctly attached to my ankle or foot".

4.3.4 Unidirectional Versus Bidirectional Communication. When discussing the need for one-way versus two-way communication using the TapTap prototypes, we noted two distinct perspectives between students and teachers based on the context of use. During music lessons, teachers believed that while students were focused on performing or practicing a piece, they would likely not have the time or need to send vibration signals back to their teacher. T4 said, "I think the students are busy trying to process the information I'm giving them, I don't think they have the time [to communicate back]". T1 added, "We can build it, but there doesn't seem to be a need for it to be reciprocal". Later they added, "I think it depends on what the purpose is. For me, with S1 and S2, it's mostly me giving the signals. I'm not really receiving a signal unless we are testing it".

However, some students were encouraged by having the ability to also communicate back to their teachers through vibration signals, especially to clarify codes and build a shared vocabulary. S1 said, "I would like it both ways. We are only human and we all make mistakes. It is very possible for teachers to also get the signals wrong at times. So I think students could also use it to clarify an error or as for a repeat". Later they added that the two-way communication also helped them understand that their device was running out of battery as they were not receiving vibration signals but could still send them. Additionally, we also found that two-way communication encouraged social interactions that expanded on pre-existing relationships between teachers and students. For example, during the initial observation, S4 and T3 turned the system into a running joke—intentionally buzzing one another, playfully apologizing for mistakes, and then repeating them—highlighting their already lighthearted, playful dynamic.

5 DISCUSSION

To guide future accessibility research, we examine the potential of wearable haptic devices for artistic expression and musical performance and discuss the potential of patterns or textures as vibration signals for haptic communication.

5.1 Designing Wearable Haptic Communication for Artistic Expression and Musical Performance

Despite recent developments in wearable haptics for communication [2, 5, 19, 22, 29, 31, 52], limited research has explored applications for creative expression and musical performances. Our findings, along with those of others [5, 29, 50, 52], suggest that haptic wearables can replace visual cues, such as head nods and facial expressions, with vibration signals. This can facilitate synchronization among all musicians (including sighted and BLV musicians) and enable real-time communication in improvisational settings such as a Jazz performance. We, along with others [5, 29, 52], found that simple, timely vibration signals can effectively convey contextual information to BLV musicians such as cueing to perform an action at the right moment in the music. We also found that musicians with preexisting relationships with one another can more intuitively communicate contextual information through vibration signals without ever needing to establish predefined meaning. This insight was best illustrated during the first observation session between T4 and S5, who seamlessly adapted and interpreted the music instruction using vibration signals without explicitly defining their meanings. Additionally, we, along with others [22], found that creating binary codes, such as long and short vibration signals or strong and weak vibration intensities, could convey simplified binary commands, such as playing louder or softer and going faster or slower. T1 described this application as "working in gradients, a little more of this and a little less of that".

When designing these systems, we, along with others [7], discovered that both their placement on the body and the ways people interacted with them varied significantly depending on the context. Even within a musical setting, different instrumentalists favoured positioning the wearable haptics on distinct parts of their bodies. Furthermore, we found that the choice between one-way and two-way communication varied with the context as well. In more instructive scenarios, such as one-on-one music lessons, one-way communication was typically sufficient, whereas group performance settings might call for a one-to-many design.

This remains an under-explored area of research with open-ended questions for future researchers to explore: 1) Our preliminary findings on designing vibration-signal pairs suggest they can convey binary instructions. However, the ideal configurations and their suitability within various contexts remain unexamined; 2) Refining wearable haptic communication systems requires deeper inquiry into ideal body placement, considering interaction methods, dexterity demands, and the perceptibility of vibration signals; 3) Designing wearable haptic systems for one-to-many communication raises more complex challenges, including how to identify individual command senders and developing interfaces that support intricate exchanges among multiple users. We argue that sensory substitution through wearable haptic communication systems can significantly improve the musicianship, confidence and learning experience of BLV musicians and also support music learners with other needs, including deaf or hard of hearing as well as deaf-blind musicians.

5.2 Patterns and Textures as Vibration Signals

Despite advancements in assistive technology design, non-verbal cues, including eye contact, facial expressions, and gestures, remain a significant challenge for BLV musicians and their sighted teachers [7, 27, 45].

Over the course of our ten-week study, we found that both students and teachers wanted to use vibration signals to communicate intricate and nuanced information accurately. Meaning from vibration signals was derived from the timing, the context and through pre-agreed codes. Our findings, along with others [46, 50], agree that vibration signals were effective in communicating time-coded musical information such as rhythm, tempo and musical cues. This was articulated by S6, who noted that she tends to rush certain sections in the music but feeling the rhythm through vibration signals made her understand when she was rushing. Our findings and others [29] suggest that a combination of long and short vibration signals can communicate pre-agreed instructions, similar to Morse code. S1 offered a key observation by associating their most commonly used instructions with the simplest vibration signals they could make. We also found that some students and teachers bypassed the need for pre-agreed codes, instead trusting their musical intelligence to make sense of vibration signals. Our findings, along with others [29, 47], indicate that variations in vibration intensity can effectively communicate specific musical elements like dynamics and articulation. We found that by feeling changes in vibration intensity, BLV musicians can perceive subtle musical details that might otherwise be unclear. As S5 remarked, "Not all crescendos are linear. The dream would be to feel a smooth curve of things, not just the timing."

However, we found some limitations with our haptic wearable system, reducing the accuracy and intricacy of the information being conveyed. Firstly, the real-time nature of musical instructions limits how lengthy or complex a coded message can be. For example, a coded message that takes a few seconds to tap out could cause the student to lose track of their playing while trying to interpret the instructions being given. Secondly, vibration signals were more effective for certain musical instructions but less intuitive for others. For example, a strong vibration signal was easily understood as a cue to play louder, whereas a soft vibration signal wasn't as intuitively interpreted as a cue to play softer. As T1 described, "poking them with the device to play louder worked well, but getting them to play softer was much harder". Additionally, sending coded vibration signals required teachers to perform complex tasks while continuing to play their instrument or focus on their students' performance.

We argue that these limitations can be addressed by exploring pre-programmed repeating vibration patterns or textures to create meaning and communicate instruction. This idea was articulated by S3, who said, "When we listen to a game show, a particular sporadic sound indicates something is wrong, it's very intuitive. To depict something as right, we could use a continuous, soft buzz that feels pleasant and smooth. When you make an error, the buzz could fluctuate in intensity very fast". We see wearable haptics for communication as an emerging area with considerable potential and we recommend further exploration into meaning-making through repeating vibration patterns or textures.

6 LIMITATIONS AND FUTURE WORK

The overarching purpose of our research was to explore how wearable haptics can make non-verbal communication more accessible and investigate how BLV musicians and sighted teachers can derive meaning from vibration signals. However, our insights and findings do come with caveats. Our research took the form of a ten-week-long study with a small population of BLV musicians and sighted music teachers with experience primarily in Western classical music. The subtleties of non-verbal communication in music learning may vary for BLV musicians in different genres, particularly in highly improvisational styles like Indian classical music and Latin Jazz. Working with BLV musicians and teachers who specialize in these different genres may lead to alternative research questions or unique findings. Many of the student-teacher pairs in our study also had years of experience working together, making our open-ended system compatible with their existing communication methods. However, this approach might function quite differently for pairs who are less familiar with each other. Also, this research focused solely on one-on-one music lessons between two individuals, though music learning also occurs in various other settings, such as group lessons, in schools, or in mixed classrooms with both sighted and BLV students. Additionally, our initial study design focused on simple vibrotactile alerts with a constant vibration intensity. However, we discovered that participants wanted more control over the vibration signals being sent through intensity modulation. However, this study was limited to only simple over-the-internet software updates offering preliminary exploration of this complex and interesting topic area. Future research should investigate how variations in vibration signal intensity can be utilized to convey more nuanced musical information. Furthermore, researchers should examine additional contexts for wearable haptics, including mixed classroom settings, improvisation, and live performances.

7 CONCLUSION

Non-verbal communication, like gestures and facial expressions, is fundamental in music teaching but largely inaccessible to blind and low-vision musicians, especially in practice and performance settings. Wearable haptics offers the potential for conveying non-verbal communication through predefined codes, but we lack an understanding of how BLV students and sighted teachers want to use vibration signals to convey information in real-time. Through a ten-week-long study which comprised observations, interviews and group meetings, we explored how students and teachers derived meaning from particular vibration signals, including time-coded meaning, mutually agreed and intuitive meaning, positive and negative perceptions, and the development of haptic metaphors. We also reported on the impact of wearable haptics on the overall music-learning experience and introduced specific design ideas to improve the future design of wearable haptics for communication. We believe this is a promising, yet under-researched area with the potential to greatly improve the experiences of BLV individuals in music and other fields.

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