Co-Designing Haptic Instruments With Deaf and Hard-of-Hearing Children

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ABSTRACT

This paper explores haptic art and tactile experiences as an independent form of artistic expression, distinct from audio-visual (AV) technologies. Haptic technologies have seen significant advances in gaming, virtual reality training, and as an auxiliary output in select music performance and playback systems. However, there are currently no stand-alone haptic music/art systems that allow for the easy creation and distribution of haptic music/art. Despite the convergence of haptics research and music technology, the perspectives of the Deaf and Hard-of-Hearing (DHH) communities remain underrepresented in the field of creative haptic technology development. Recognizing the potential of more readily available haptic art creation and sharing systems for the Deaf and/or Disabled community, we conducted a co-design workshop with 27 DHH middle school children, focusing on their experiences with haptic vibrations, creating low-fidelity prototypes for haptic art presentation devices, and composing short pieces of haptic music. Through a mixed-methods analysis of survey responses, reflections, and thematic analysis of the prototypes and haptic art compositions, we gained valuable insights into the aesthetic possibilities and considerations for future haptic art instruments. By elevating haptic music/art as a distinct category of work not always subservient to auditory music, we hope to pave the way for more inclusive and accessible technologies in the realm of artistic expression and enrich the experiences of diverse communities in the world of art and creativity.

Author Keywords

Haptic Art, Inclusive Design, Deaf Haptics, Musical Haptics

CCS Concepts

• **Human-centered computing** → **Empirical studies in accessibility;** Accessibility design and evaluation methods; • **Applied computing** → *Sound and music computing;*

1. INTRODUCTION

Musical and artistic expression are part of every day for many, with several related research fields producing technologies to facilitate both the creation and experience of these artistic expressions. While the majority of these advances have focused predominantly on audio-visual (AV) technologies, there have been many recent strides in haptic technologies to provide nuanced dynamic feedback while gaming or simulate the tactile feeling of surgery in virtual reality training [9, 12]. However, far fewer technologies exist to create and experience stand-alone haptic art [1] that is not paired with a larger AV experience. Haptic art and tactile experiences present a variety of aesthetic possibilities but are notably of interest to members of the Deaf and/or Disabled community as it provides another sensory channel to perceive and create artistic experiences.

Within the field of haptics, there exist two major groups of technologies, namely force haptics, which use motorized systems to provide physical resistance or assistance while interacting with an object, and vibrotactile (VT) haptics, which comprises of vibrations that are felt by parts of the body in contact with the medium, such as the sensation of holding a mobile phone in one's hand while it receives an incoming call. Given the similarity of the techniques and technologies used, VT research and artistic practice [14]. Within the field of designing new interfaces for musical expression (NIMEs), the perspectives of D/deaf and Hard-of-Hearing (DHH) communities are often under-considered. In a 2019 review article on developments in accessible digital musical instruments (ADMIs), only 6% of ADMI research and development focused on the DHH community [6]. Gunther and O'Modhrain proposed the term "tactile composition" referring to a "system that facilitates the composition and perception of intricate, musically structured spatiotemporal patterns of vibration on the surface of the body" [8]. This was done to highlight the need to consider the somatosensory system and haptic art on its own terms with its own aesthetic possibilities as opposed to only considering it in a support capacity, such as in the audio-to-haptic translation of music.

In this paper we present the findings of a three-session co-design workshop where 27 DHH children (1) reflected on their previous experiences of haptic vibrations, (2) created a low-fidelity prototype to artistically present VT signals, and (3) composed several short pieces of VT art. The contributions of this work include an analysis of survey responses and reflections, a thematic analysis of prototypes and VT art compositions, and a list of considerations for the design of future interfaces for VT art experiences and creation.

[1]Please note that we use the term haptic art as a broader term that includes haptic, vibration, and touch-based musical experiences.

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2. BACKGROUND

2.1 Vibrotactile Perception

Humans can perceive VT information through various touch, pressure, motion, and temperature-related sensory organs all over the body [2]. Through these various sensory organs in and around the skin, we are generally able to perceive VT signals that are in contact with the skin from frequencies of about 0.1 Hz - 800 Hz, where 0.1-3 Hz is perceived as kinesthetic motion, 10-70 Hz as rough or fluttering motion, and 100-800 Hz as smooth vibration [21]. In addition the frequency of a pure sine wave signal, rapidly changing the intensity of these signals through amplitude modulation is an additional characteristic of VT signals that are readily perceivable [22], and can effectively convey sensations of roughness [23].

2.2 State of The Art VT Systems

Haptic feedback technology has been implemented in a variety of applications, from feedback while playing video games [5] or the piano [13], to trying to convey semantically meaningful information through emulation of established touch-based languages used within DeafBlind communities such as social-haptic communication or protactile [16]. While some technologies have incorporated novel haptic technologies, many share common underlying haptic components that are then utilized to achieve a specific effect. Regardless of the combination of haptic technologies used, similar considerations regarding the spectral, spatial, temporal, and dynamic profile must be made.

Sound-to-Haptic Translation and VT Art: There are a variety of solutions in which the user holds a device in their hands or against their body to receive increased haptic information during a musical performance. The practice of holding balloons during concerts to provide richer vibrotactile feedback is not uncommon in DHH communities and can often be seen in many Deaf studies writings [4]. Artist and scholar Wendy Jacobs created a large-scale installation consisting of various sub-woofers and a vibrating floor to establish a shared tactile experience of sound among DHH and hearing audience members [10], while David Bobier has explored haptic and sound art through activating taut ropes using vibrotactile drivers [1] The *SoundHug*[2] consists of a 1-foot diameter plastic sphere that uses a mix of colored light and haptic feedback to augment musical experiences.

Controllers and Surface Simulators: Video game controllers and controller pads are a common entry point to haptic feedback for many, and there has been significant progress from the early days of rumble-enabled controllers. The field has progressed considerably since vibrotactile feedback was first added to commercial game controllers in 1997 when *Nintendo* released the *Rumble Pak* for the N64 controller [5]. Current commercial video game controllers have expanded the rumble technology, from the *Xbox One's Wireless Controller* utilizing localized vibrotactile feedback on the back triggers [20], to the *PlayStation 5 DualSense* controller using force-feedback in the large triggers on the back of the controller as a form of haptic communication to players [17].

Wearables Wearable haptic feedback devices have been employed in a variety of application areas. The *HaptX DK2*[3] glove utilizes a combination of microfluidics and restive-force haptics to emulate technology that emulates the haptic sensation of holding an object. A variety of multi-driver vests and shirts have been designed primarily for immersive gaming experiences or as an augmentation to music listening, such as the *SoundShirt*[4], *Woojer Vest*[5], and the *BHaptics Tactsuit*[6]. Wearable haptic technologies have also been used in a variety of sensory substitution research, such as a haptic wristband that has been used to augment experiences of verbal speech and showed significant improvement in speech intelligibility [15]. While sensory substitution remains an exciting application, ensuring many members are actively involved in the design process is crucial but not widely practiced in the field [7].

Non-contact: The *Ultra Leap Stratos*[7] utilizes a grid of 256 ultra-sonic speakers to render contact-less haptic feedback on the user's skin, provided they are within the interaction zone. The system tracks the position of the user and modulates the amplitude and phase of the pressure waves emitted by the ultra-sonic speaker array. *Disney's* experimental *AIREAL* system emitted strongly-timed, concentrated air vortexes which the user experienced as a feeling of localized pressure [19].

2.3 Participatory Design with DHH Children

Participatory design (PD) is a framework for human-centered research that engages participants to be active agents and partners in the designing of research related artifacts or prototypes rather than engaging only with end users during the later stages of the design process [18]. These methods are particularly effective for communities who have been under-engaged with by prior research and may experience additional socio-economic marginalization, such as the DHH community, as the embodied knowledge and lived experiences they have are not often included in the academy. Korte et al. highlight in the importance of establishing clear, robust communication with young DHH children participating in PD research in their "YoungDeafDesign" framework to ensure the highest degree of participation possible [11]. Both PD and YoungDeafDesign highlight the importance providing structure and support while working with co-designers, but remaining flexible to respond to their needs, concerns, and goals, which may change throughout the course of the study.

3. METHODS

This participatory design study occurred over three workshop sessions held at Metro Deaf School, a charter school for Deaf, DeafBlind, and Hard-of-Hearing students located in St. Paul, MN that uses American Sign Language (ASL) as the primary language of instruction. We employed a mixed methods approach that combined survey data, observational data, as well as the creation and analysis of workshop artifacts in the form of VT display prototypes as well as short exploratory VT compositions (etudes).

3.1 Participants

Participants were comprised of 27 middle school students aged 11-14 who were enrolled at Metro Deaf School, DHH, fluent in ASL, and students of the science class in which the workshops took place. Due to the fixed time window of the workshop as well as the difference in time required by different participants to complete the activities, not all participants completed every part of each session. Of the 27 participants who took place in at least one of three workshops,

[2] https://pixiedusttech.com/soundhug/en/index.html
[3] https://haptx.com/dk2-release/
[4] https://cutecircuit.com/soundshirt/
[5] https://www.woojer.com/pages/vest
[6] https://www.bhaptics.com/tactsuit
[7] https://www.ultraleap.com/haptics/

17 participants completed all parts of all three workshops. Not all participants completed every session or survey due to time constraints, illness, or other factors. The composition of each workshop session had the same participants as the science class the participants would normally attend at that same time. Additional participant demographics can be found in Table 4

3.2 Workshop Overview

Three workshop sessions were conducted over the course of one week. Each workshop lasted approximately 50 minutes and took place during the science class period at Metro Deaf School. These workshops were primarily facilitated by Lloyd May, a hearing music technology researcher fluent in ASL, with support provided by an experienced science educator at Metro Deaf School, during every session. Additional support during classes 2 and 5, as shown in 5, was provided by trained professionals employed or contracted by Metro Deaf School. The supports offered included one-on-one support, particularly for the two DeafBlind participants, an additional educator trained in accessible education practices, as well as an ASL interpreter with experience signing with additional clarity that has previously benefitted participants in this class. Other members of the research team who were hearing and not fluent in ASL were present during approximately half of the workshops and assisted with documentation and set-up.

Participants completed the survey worksheets and exit surveys throughout the workshop session with assistance from the facilitation team as needed. All workshop activities were conducted in ASL. Enlarged survey worksheets printed on colored paper were prepared for the two DeafBlind workshop participants.

3.2.1 Session 1: Introduction and Exploration

Introductions include who the researchers are, why they are visiting, and what we hope to achieve together. This was then followed by an overview of the workshop and an ideation icebreaker activity asking participants to discuss what superpowers they would have if they could have any superpowers. Researchers then presented a 5-minute mini-lecture on introduction to vibrations, which included a level-appropriate introduction to waves and pressure and a worksheet activity asking participants to report three examples of vibrations they have experienced before noting where and when they happened as well as any emotions they remember experiencing during the vibration. The research team then introduced the concept of VT playback to participants, including an overview of the hardware setup and playback software as shown in Figure 1. Additionally, participants were provided with a Dell laptop that ran both pieces of Max MSP standalone programs described below and output the VT signals via an 1/8" stereo cable to the amplifier. All equipment was set up and tested before participants arrived for each session. Participants were invited to explore the four vibration data types presented (brainwave, earthquake, train, and heartbeat), explore the placement of the transducer on their bodies, and note their observations on the survey worksheet. Heartbeat and train passing signals were manually recorded using a piezo surface microphone, the 'brainwave' signal was a single channel of an electroencephalogram (EEG) of a member of the research team at rest, and the earthquake signal was obtained from an earthquake sound effect video publicly available on YouTube [8]. These signals were selected to convey a diversity of sources, amplitude profiles, and levels of assumed experience with the vibrations.

3.2.2 Session 2: Display Prototype Building

The session began with an overview of the agenda for the session, a review of the VT components, and an overview of the various materials they would have access to during the session. Participants were then invited to select one of the four vibrations they experienced in session one and build a prototype of a device to best display that specific vibration. Participants had access to the same VT playback interface as session 1. Upon completion of their own prototype, participants were randomly paired with a partner with a completed prototype and asked to complete a survey worksheet analyzing their partner's display prototype. Each participant had access to all of the materials listed in Table 2.

3.2.3 Session 3: VT Composition

After a recap of the previous session and an overview of the session's agenda, the research team presented an introduction to composing (i.e. placing things intentionally in time and/or space) as well as an overview of the composition interface, as shown in Figure 2. Participants were able to generate a continuous tone by holding the space bar, stopping by lifting the space bar up, and adjusting the frequency (20 - 400 Hz) and roughness (depth of 20 Hz amplitude modulation) using either the arrow keys or mouse button. Four short (approximately 4 seconds) samples were available, namely: heartbeat, rumble (constant noise), riser (noise with an exponential increase in volume), and impact (noise with an exponential decrease in volume). Samples could be triggered using the corresponding numbered keys on the keyboard or using the mouse. Multiple samples could be triggered simultaneously and would play polyphonically with the tone if one was being generated when the sample was triggered. Global volume was adjusted via a slider using the mouse. Participants were able to record VT signals by pressing the 'R' key on their keyboard or clicking the large red button. This would trigger a three-second countdown, displayed in the grey box beneath the "Timer" label, which then transitioned into a 20-second countdown, during which the VT signals were recorded. After the 20-second window, the recordings became available for playback using the buttons labeled 1-3, which would each turn green once they were associated with a recording. Only three recordings could be recorded using this software, encouraging participants to approach the recordings with a degree of intentionality. Once all three slots were full, no more could be recorded.

Participants were asked to select either an emotion (e.g. anger, excitement, etc.) or a situation (e.g. petting a cat, riding the bus, etc.) that they would like to communicate through their VT compositions. Participants were then asked to record three 20-second-long etudes [9] communicating that emotion or situation. Participants then paired up, experienced a single VT etude selected by their partner, and completed a survey worksheet analyzing their partner's etude.

3.3 Analysis

We inductively analyzed both the VT display prototypes as well as the VT etudes through a grounded theory approach with two researchers to identify both general cate-

[8] https://www.youtube.com/watch?v=mgLBmLoL2Aw

[9] Short, exploratory compositions.

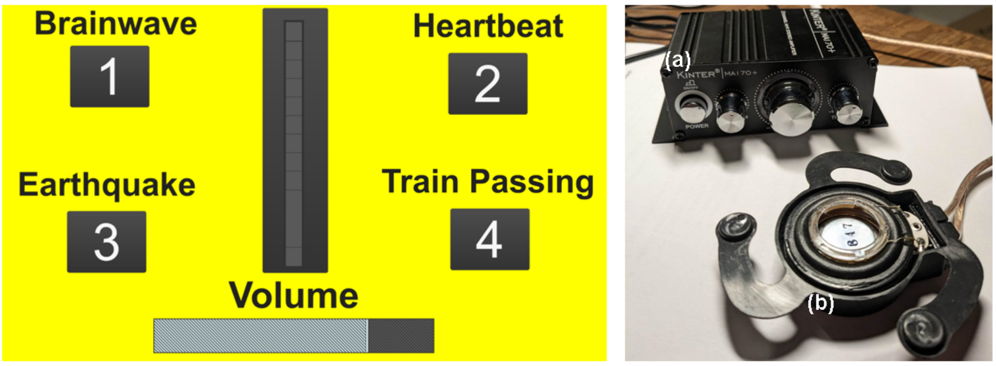

Figure 1: (Left) The user interface used to control VT signal selection and playback. (Right) the (a) signal amplifier and (b) VT transducer each participant had access to during the workshop.

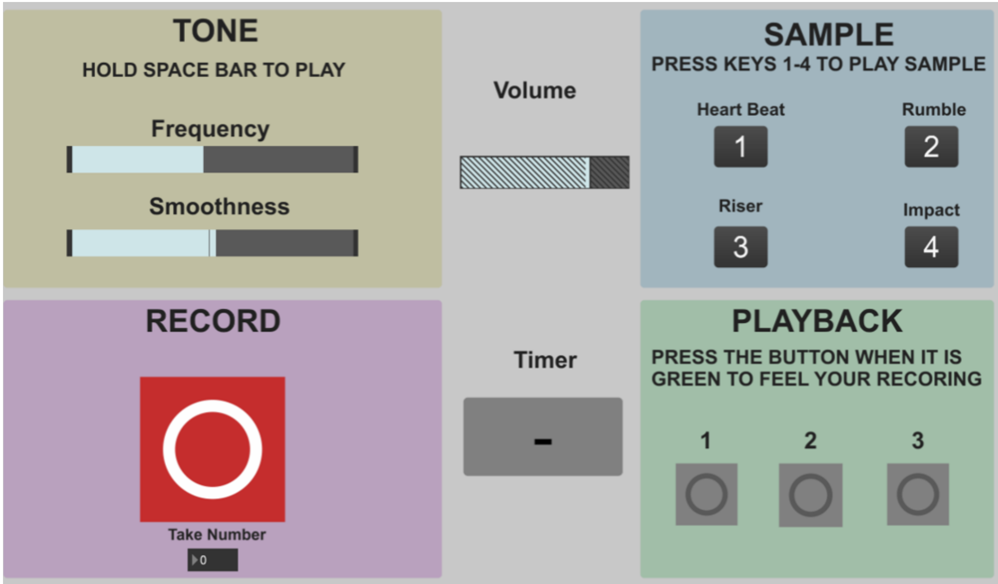

Figure 2: The user interface used to compose, record, and playback VT signals.

gories and specific themes created across display prototypes and etudes [3]. For the VT display prototype analysis, researchers constructed a table of material characteristics and design patterns (seen in Table 2), and independently analyzed each prototype to determine which of the characteristics and design patterns each instrument used. The research team then viewed the picture(s) of each of the n=24 prototypes as well as any related observational notes in the digital sticky note software *Miro*. We discussed what physical attributes and design patterns were present in each prototype and grouped them based on this content. Axial coding was then performed by dividing these initial groups into smaller, detailed, cohesive categories. This was repeated until no smaller categories could be found, with each category being subsequently labeled. Artifacts that prompted disagreements between researchers were put aside and discussed again at the end of the analysis. These artifacts were either placed into an agreed-upon category or placed into the "Other" category.

The VT etudes were analyzed in the same fashion, with notes in *Miro* containing a codename for each etude used for grouping. Each researcher had access to a VT playback system consisting of a Kinter MA170 18W amplifier and a Dayton Audio DAEX 25 VT transducer. The researchers performed gain matching before every VT etude analysis session.

4. RESULTS

4.1 Vibrotactile Exploration

During session one, participants completed a vibration exploration activity where they used the interface and equipment outlined in 3.2.1, and explored short 3-5 second excerpts of earthquake, train passing by, raw brainwave (EEG) data, and heartbeat VT signals. Participants were encouraged to move the VT transducer onto various parts of their body and note the various sensations they experienced. Participants were asked to select their favorite VT signals and locations, with results shown in Figure 3. Participants were additionally asked to name which vibration they would like to record and experience as a VT signal, the answers are summarized in Table 1.

4.2 VT Instrument Prototypes

Participants were asked to select a signal, from the four they explored in the previous session, to create a low-fidelity prototype for the device they would like to use to experience their selected VT signal using various crafting materials, such as cardboard and fabrics, and a single VT transducer. 10 selected brainwave, 4 heartbeats, 3 train passing by, and 5 participants selected the earthquake sample. In total, 24 instruments were prototyped by 25 participants, as one pair

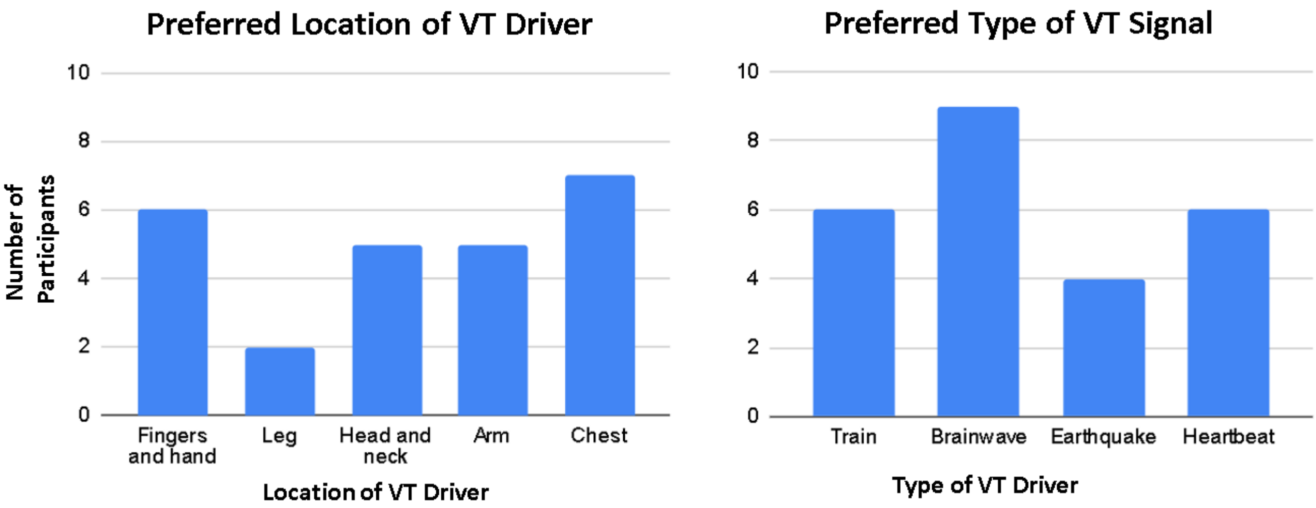

Figure 3: Participant's top selection for (left) their favorite location on their body to experience the VT signals, and (right) their favorite VT signal.

Table 1: Participant's selection of a vibration they would like to record and experience as a VT signal.

Category	**# of Selections**	**Examples**
Fictional	2	Sound effects from a sci-fi movie
Non-fictional, natural	5	Car purring, rain
Personal	6	Heartbeat, brainwaves
Non-fictional, synthetic	12	The inside of a computer, airplane engine

of participants preferred to collaborate.

The frequency of design characteristics and materials used are summarized in Table 2. The categories of materials and design patterns used were: (1) the placement of the driver relative to other prototype components, (2) the use of a receptacle or container-like component that could hold other components inside, (3) the use of free objects which were not firmly secured and allowed to move freely or semi-freely in response to vibration, and (4) the use of fixed, non-receptacle objects. The prototypes are illustrated in Figure 4

A thematic analysis was performed on these artifacts and produced two primary themes, namely prototypes that used materials to provide **additional visual feedback** of the vibrations, and those that relied primarily on **tactile stimulation alone** and did not contain any components that responded to vibrations in a visible manner. Two sub-themes were noted across prototypes grouped into these main themes, namely the utilization of three or fewer components to create a **minimal design** and others that used more components to employ a more **embellished design**.

Within the group of prototypes that provided additional visual feedback and utilized a minimal design, it was noted that some elected for the free objects to be in direct contact with the driver, leading to more noticeable free object movement, while others preferred to have free objects rest on another surface attached to the driver. The embellished designs however used a variety of both free objects and objects fixed at one end that vibrated in a visible way, such as feathers, popsicle sticks, and pipe cleaners.

The group of prototypes that relied primarily on tactile stimulation alone had three types of primary texture present, namely parchment-type texture of paper and cardboard, plush-type texture of fuzzy materials, and mixed-textured which combined parchment, rubber, and plush-type textures. Prototypes from all three of these texture groups contained both minimal and embellished designs. Notably, P16's instrument did not make use of a driver but was required to be physically shaken to create the participant's desired haptic sensation.

4.3 VT Composition

Participants were asked to select an emotion and/or situation and compose three 20-second VT etudes that explored their selected theme. Selected themes (Table 4 ranged from the recreation of real-world experiences such as "blissfully petting a cat" (P1) or being "surprised inside an airplane" (P29), to involving some degree of narrative such as feeling "happy in a video game, then I get killed, then I get mad" (P16), as well as abstract concepts such as "electricity" (P3), or "fear, uncertainty, a sense of foreboding" (P4). Etudes illustrated a variety of characteristics and employed VT compositional elements ranging from amplitude modulation, to sustained tones, to repetition, to silence, as shown in (Table 3).

17 etudes were completed by 19 participants, as two sets of two students independently decided to work together on the compositions. The thematic analysis resulted in two primary themes, namely compositions that employed largely static textures (*Textural*) and those that used VT material in a strongly rhythmic way (*Rhythmic*). Within these themes, two axes of sub-themes were identified: (1) if the piece used the same compositional motifs/patterns for the duration (*Constant*), or if it employed multiple (*Multiple*), and (2) if the piece consisted of silence for a total of more than 50% of its duration (*Sparse*) or contained less than 50% silence (*Dense*). Figure 5 displays a 0-600 Hz frequency-limited spectrogram of each participant's preferred VT etude, grouped by both primary theme and sub-theme.

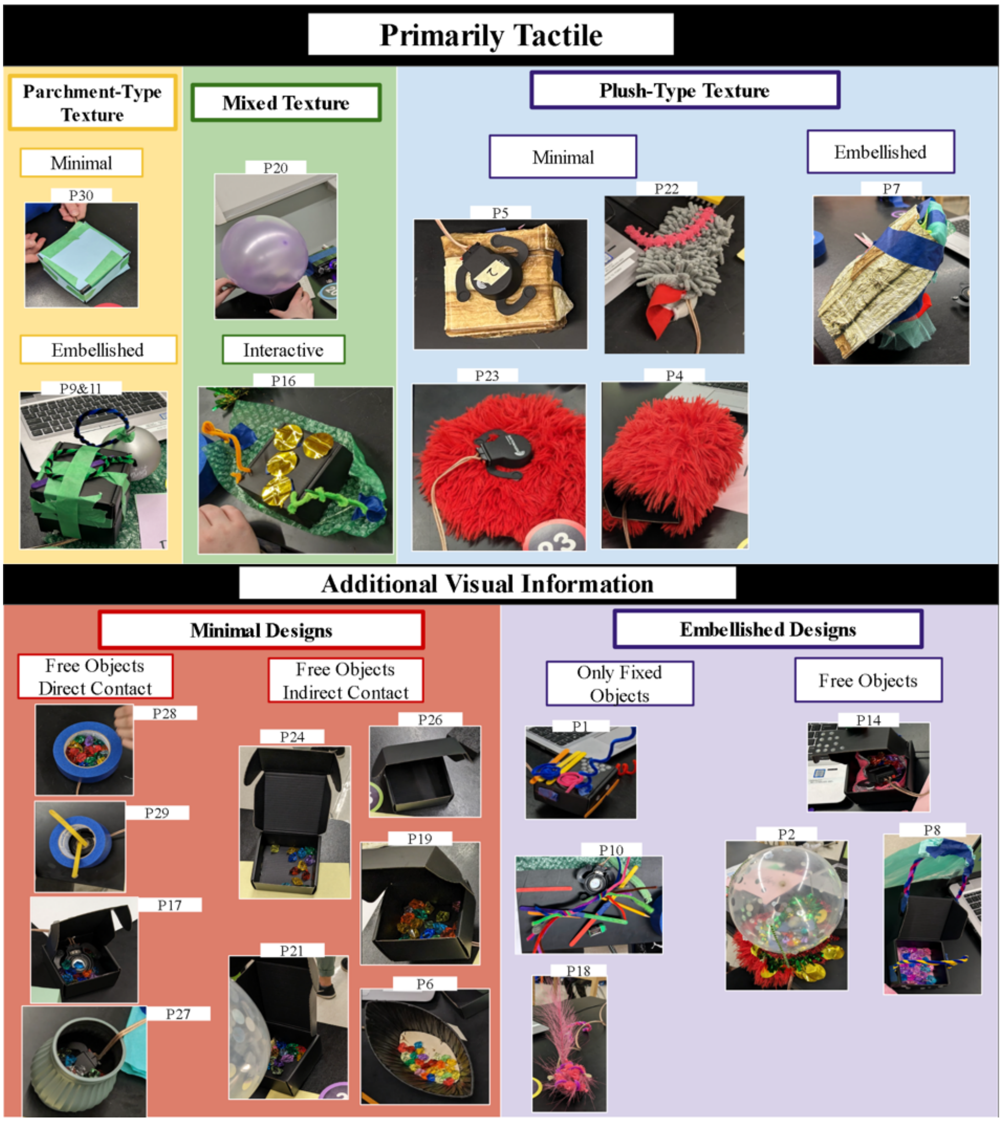

Figure 4: Images of the 24 prototypes produced by participants, divided into primary themes (Primary Tactile, Additional Visual Information), as well as sub-themes related to the type of texture, number of design elements used, and the relationship between elements.

5. DISCUSSION

5.1 Exploration

As shown in figure 3, participants indicated a mix of location preferences, including ones rarely designed for in general VT haptic devices such as the face and head. Participants noted that these areas were more sensitive to VT stimulation and it provided a more intense experience, such as P 27 noting "it feels like... woah!" when placing the driver to their cheek. Most participants noted broad rationale such as it felt "nice" (P1) or "fun" (P12), some participants mentioned connections to previous VT haptic experiences, such as P27, whose favorite VT location was "in my pocket, because it is [the] place for my phone", alluding to the familiar experience of having a phone vibrate in their pocket. Two participants who selected the hand as their preferred area made a similar connection to video game controllers providing VT stimulation. While every future VT instrument user might not want their cheeks or forehead stimulated, allowing for these playful, exploratory engagements allowed more participants to engage with the VT art and devices on their own terms and lead to more varied positive interactions with the technology.

The majority of participants selected the raw EEG data as their favorite, noting it was "intense" (P27) and "buzzy and nice" (P2). The earthquake and train VT signals possessed elements that were more easily interpreted as narrative due to their connection to events that participants have previously experienced, such as P12 noting the heartbeat VT signal "feels the same" as their heartbeat.

The mean enjoyment rating of the exploration workshop was 2.94/3 ($\pm$ 0.2, N = 17), on a 1–3 scale. While there was undoubtedly a large degree of novelty bias given the niche nature of the technology used and the excitement that comes with having external people visit a school classroom, these findings support the conclusion that participants enjoyed exploring both VT driver placement and VT signal types. There was no clear or consistent preference among all participants, indicating that personal choice, exploration, and customization are important factors to consider in the future design of VT instruments.

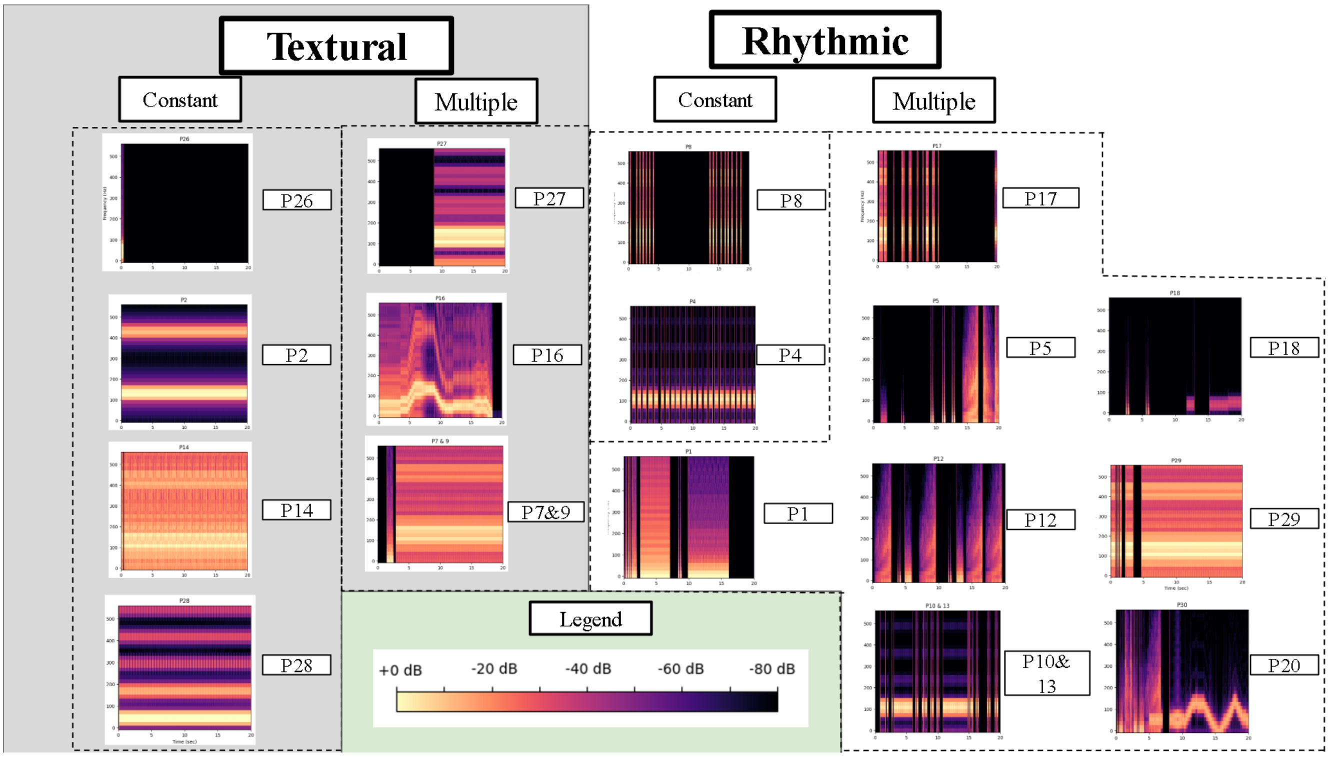

Figure 5: Images of spectrograms of the 17 etudes produced by participants. Each etude is 20 seconds in length. The spectrograms are frequency-limited to only display 0-600Hz and are divided by major theme (Rhythmic or Textural), and by sub-theme (Constant Motif or Multiple Motifs).

5.2 Personalization and Referential Signals

The variety of configurations and materials used in the prototypes that did not directly impact the VT signal, such as visual decorations, illustrates a desire for personalization in VT instruments, with some participants even anthropomorphizing their prototype such as P1 referring to their prototype as a "little buddy". This theme of personalization extended to some etudes, as P17 used the Morse code embedding of their name as a point of inspiration when constructing their very rhythmic, staccato piece.

Creating representational touchpoints through the incorporation of familiar signals that relate to lived experience appeared to help some participants acclimate to the use of VT signals in a creative way. Upon reflecting on the prototype they had created to display a heartbeat signal, P3 noted the similarity to a real-world experience they had created, reflecting that their prototype "feels like an actual heart", while P4's feedback on P2's instrument highlight the use of materials to create a similar experience, noting that the "balloon amplifies [the signal and] gives the heartbeat a real feel". P18 noted that this representation of a heartbeat held aesthetic symbolism, enjoying that P14's prototype "gave it a heartbeat". The signals could additionally reference stages of a narrative, such as P18's etude which captures the feeling of being "happy in [a] video game, then [getting] killed, then [getting mad]." Additionally, the ability for abstraction and composing with non-referential signals allowed users to explore varied compositional questions that are not strictly narrative or referential. This could be seen in, for example, P4's choice to explore the imagined sensation of feeling electricity or P5 expressing a feeling of "fear, uncertainty, a sense of foreboding" in their respective VT etudes.

5.3 Physical and Compositional Textures

Both the results of the prototype thematic analysis and workshop notes illustrate the importance of the physical texture of the prototype to many participants. For example, P1 "liked the fluffy" texture of P4's instrument. Participants noted the textures of materials, from silky lace to smooth paper, in their reflections on their own instrument and their feedback on the instruments of others. However, a clear favorite physical texture did not emerge, with a variety of textures incorporated, as shown in Figure 4. Therefore, having multiple physical textures available for VT instruments appears highly desirable.

Aside from the tactile texture of the physical prototype, participants used a variety of compositional textures, meaning the creation of a sustained sensation as opposed to rhythmic information, in their VT art, ranging from smooth sustained sine tones to perceptually rough amplitude-modulated tones. VT art and technologies are generally employed to communicate strongly rhythmic information, however, 7 out of 17 etudes demonstrated a clear use of compositional textures, indicating a strong desire from participants to incorporate abstraction and texture into their VT work.

5.4 Design Recommendations

The results of the surveys, workshop notes, and thematic analyses were analyzed in totality to derive four design considerations for the development of new VT instruments, particularly those looking to actively include DHH children in their user base. These recommendations are:

5.4.1 Flexibility of VT Driver Placement:

One size does not appear to fit all in VT display preferences. Therefore, the flexibility to move and adjust drivers

Table 2: The number of prototypes that used each of the available materials.

Prototype Element	Number of Prototypes
Driver:	
Driver outside receptacle	12
Driver inside receptacle	9
Attached to other object	5
No driver	1
Receptacle :	
Box	13
Roll of tape	2
Balloon stacked on top of boxes	2
Balloon	1
Boat shaped wooden box	1
Vase	1
Two boxes stacked	1
Free Objects:	
Rocks - inside receptacle	11
Sand - inside receptacle	1
Other Materials:	
Pipe cleaners	8
Popsicle sticks	6
Bumper dots	4
Fluffy fabric	3
Tinsel	2
Baige foam	2
Rubber worm	2
Car wash glove	2
Feather	1
Bubblewrap	1
Craft paper	1
Lace	1
Felt fabric	1
Microfiber cloth	1
Googly Eyes	1

Table 3: The number of etudes that used the identified compositional strategies and elements used by the 48 etudes created by 19 participants.

Category	Characteristic	Count
Arrangement	Constant Motif	24
	Multiple Motifs	24
Element	Riser	9
	Impact	9
	Heartbeat	6
	Silence	18
	Tone - Constant Freq.	20
	Tone - Constant Freq.	11
	Tone - Amplitude Modulated	19
	Tone - Sub 60 Hz	9
	Tone - Over 300 Hz	4
	Tone - Rhythmic	17
Density	Sparse	16
	Dense	14
Dynamics	Mix of Low & High Intensity	2
	Low Intensity	4

to different parts of the body and/or to different external objects should be considered.

5.4.2 Allow for Multiple Forms of Compositional Input:

Instruments should allow for both representations of real-world VT signals, such as through playback of recordings, as well as allowing for abstraction through signal and compositional controls.

5.4.3 Actively Encourage Personalization, Narrative, and Decoration:

VT instruments should encourage personalization and decoration through the incorporation of intuitive locations on the objects to apply both visual decorations and materials of varied textures.

5.4.4 Provide Options for Multi-sensory Feedback:

Visual displays of VT signals, particularly through analog means, provide an additional entry point to VT art while also offering a useful mode of feedback.

5.5 Limitations

The current study and workshop possessed several limitations. These include time constraints imposed by the structure of fitting into a standard middle school class time of 50 minutes as well as the compressed nature of a 3-day workshop that did not offer participants as much time to process information and reflect on themes of the workshop over time. As a result of this, participants did not have an opportunity to revise or expand on the design of their prototypes or etudes. Additionally, the composition software was designed before the workshop based on previous VT perception literature. However, additional forms of compositional input and user feedback could be explored, such as sequencers or timeline editing, to offer additional creative possibilities aside from the current plan-then-perform/improvise structure the current compositional system affords. A feature set with increased robustness would allow for more in-depth review and revision would allow for a greater degree of nuance to be uncovered in these workshops.

6. CONCLUSION AND FUTURE WORKS

We presented the methods and results of a multi-day co-design workshop with 27 DHH children in middle school where participants (1) reflected on their previous experiences with vibrations, (2) designed and fabricated a prototype of a low-fidelity VT display, and (3) composed three 20-second pieces of VT art. After exploring various VT vibration types and driver placement, participants indicated a wide variety of preferred locations for the VT driver, including the head and neck. Participants' low-fidelity prototypes were divided into prototypes that provided additional visual feedback regarding the VT signal (15) as well as those that relied primarily on tactile interactions and textures (9). The various short VT compositions that participants composed were analyzed in a similar way that highlighted the compositional theme of composing with primarily rhythmic or textural motifs. Finally, we concluded with several design insights that could be incorporated into the design of future VT instruments, namely: (1) flexibility of VT driver placement, (2) allow for multiple forms of compositional input, (3) actively encourage personalization and decoration, and (4) provide options for multi-sensory feedback.

Future work includes the design and creation of a medium-fidelity, modular, customizable prototype based on these findings and conducting another co-design workshop. Future workshops could include a more prolonged engagement with a smaller group of participants in an attempt to capture additional nuanced design insights and the evolution of co-designers perspectives over multiple engagements.

7. ETHICAL STANDARDS

This research was conducted with the approval of the internal review board (IRB) of the University of St. Thomas. All participants were under the age of 18 and were therefore asked to provide written, informed assent, while each participant's legal guardian provided written and informed consent. Participants were informed that their choice to participate had no impact on their academic standings or extra-curricular activities, was purely voluntary, and that they could stop participating at any time with no repercussions. Researchers were available to answer questions about the assent or consent process in written or spoken English as well as ASL.

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APPENDIX

A. PARTICIPANT INFORMATION

Table 4: Demographic information of participants

PID	Class ID	Age	Gender	Selected VT Signal	Etude Description	Note
1	1	12	F	Heartbeats	Blissfully petting a cat	
2	1	12	F	Heartbeats	Not sure, it just feels good	
4	1	13	M	Heartbeats	Electricity	
5	1	12	Genderfluid	Earthquake	Fear, uncertainty, a sense of foreboding	
6	2	11	M	Brainwave	N/A	
7	2	13	M	Earthquake	Video game, excited, ps4 or xbox one, vibrates	
8	2	11	F	Earthquake	Happy video game	DeafBlind
9	2	14	M	Earthquake	Cat sits feel chill, going visit, excited, my heartbeats	DeafBlind
10	2	13	M	Brainwave	Happy video game	
11	2	12	M	Earthquake	N/A	
12	2	13	M	N/A	Video games, ps4 black, excited	
13	2	12	F	N/A	Happy video game	
14	2	12	F	Heart	Excited on a roller coaster	
16	3	11	M	Train	Cat and chill	
17	3	14	M	Heart	(None)	
18	3	14	F	Train	Happy in video game, then I get killed, then I get mad	
19	4	11	F	Brainwaves	N/A	
20	4	11	F	Heart	N/A	
21	4	13	F	Brainwaves	N/A	
22	4	13	M	Brainwaves	N/A	
23	4	13	F	Heartbeat	N/A	
24	4	13	M	Brainwaves	N/A	
26	5	13	F	Train	Happy in airplane	
27	5	13	M	Heart	Excited while playing videogames	
28	5	12	M	Brainwaves	Scared in a plane	
29	5	12	M	N/A	Surprised inside an airplane	
30	5	12	M	Brainwaves	(None)	

Table 5: Additional information regarding the five classes groupings used in the study

Class ID	No. participants	Notes
1	4	Advanced class
2	9	Several participants with additional Disabilities and/or learning differences. Two additional teaching staff and an interpreter were present
3	3	
5	6	
6	5	