Co-designing Haptics for Deaf and Hard-of-Hearing Music Education with a Reconfigurable Prototyping System

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Abstract

Music education for Deaf and hard-of-hearing (DHH) learners remains challenging because access to auditory cues is constrained and instruction is often shaped by hearing-centered pedagogical and communication structures. Prior work has explored haptics for music, yet offers limited situated knowledge of how haptic cues should be designed and negotiated within authentic instruction. We address this gap through a co-design method centered on reconfigurable haptic prototyping. Using modular tactors that can be rapidly repositioned and retuned, we conducted four co-design workshops with educator–learner dyads in South Korea. The workshops involved hands-on trials, bodystorming, and mock teaching enactment to explore music-to-haptic cues within realistic instructional interaction. We show that haptics can support pedagogical fit, make musical concepts tangible as formative in-the-moment support, and function as a shared reference in instruction. We contribute a co-design method, empirical insights into haptics in music instruction, and design implications for DHH music education.

CCS Concepts

• **Human-centered computing → Accessibility design and evaluation methods**; **Haptic devices**.

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Deaf and Hard-of-Hearing (DHH), Music Education, Haptic Interaction, Co-design, Accessibility, Inclusive Learning

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1 Introduction

Music education can be an important experience for Deaf and hard-of-hearing (DHH) learners, not only for developing musical skills but also for supporting language-relevant perceptual and cognitive development (e.g., phonological awareness and prosodic focus) and psychosocial growth (e.g., peer relationships and emotional regulation) [38, 51, 59, 78]. It is also emphasized as an important context in which learners' longer-term motivation and attitudes toward musical participation can take shape [17]. Yet music education remains challenging for DHH learners because access to auditory cues is constrained by sensory–perceptual differences. In addition, classroom instruction is often shaped by structural constraints such as communication with predominantly hearing teachers and hearing-centered pedagogical approaches [42, 82]. In response, researchers have increasingly pursued assistive technologies and inclusive design approaches that move beyond audiological models to actively leverage visual cues and bodily engagement [12]. Such approaches help learners embody foundational concepts such as rhythm and tempo in their own way and frame musical understanding as something that emerges through multisensory participation and interaction within classroom routines [74, 75].

In this context, haptic technologies have been explored as a promising means to support DHH music education [41, 53, 79]. Previous evidence also suggests that haptic stimulation can support aspects of music perception for DHH listeners [24]. Vibrotactile feedback shares physical qualities with sound and can convey musical cues such as rhythm and accent through direct bodily sensation, which aligns well with embodied approaches to teaching and learning [5, 32, 46, 67]. Haptics can also communicate timing and expressive cues without taking up additional visual attention, which is often already heavily loaded when learners must coordinate notation, their instrument, and instructors' gestures or sign language [11, 23, 33].

However, many existing haptic music systems have been driven primarily by technical feasibility and vibrotactile designs motivated by engineering goals such as improving perceptual accuracy [2, 25]. As a result, there is often limited attention to what teachers are actually trying to communicate during instruction and to what DHH learners can realistically sense, interpret, and regulate while performing in situ. This gap is compounded by a research emphasis that has frequently privileged "music listening" results over the situated demands of teaching and learning. In response, the Human–Computer Interaction (HCI) community has increasingly adopted DHH-centered approaches, using co-design methods to respect DHH identity and culture and to reflect users' sensory preferences and values [13, 21, 41, 68]. Despite these advances, haptic interaction remains challenging for non-experts to imagine and articulate without hands-on experience, often limiting the depth of participatory practices. This is particularly evident in educational settings, where instructional needs are constantly redefined through educator–learner dynamics, moment-to-moment negotiation, and constraints of classroom routines.

To address this gap, we present a co-design method centered on reconfigurable haptic prototyping for DHH music education. Our workshop approach enables educators and DHH learners to rapidly try, compare, and iteratively refine music-to-haptic cue candidates through direct haptic experience and rapid reconfiguration in instructional settings. Applying this method in four co-design workshops, we provide empirical insights into how haptics can support music instruction and derive design implications for integrating haptics as pedagogically meaningful support.

This paper makes the following contributions:

- **A co-design method using reconfigurable haptic prototyping:** We contribute a co-design method centered on reconfigurable haptic prototyping, combining modular tactor configuration, bodystorming, and mock teaching enactment to support in-context exploration, negotiation, and refinement of haptic cues in DHH music instruction.
- **Empirical insights from reconfigurable haptic co-design:** We provide empirical insights into how haptic cues are interpreted, negotiated, and refined through educator–learner interaction under real instructional constraints.
- **Design implications for music haptics in DHH education:** Grounded in these empirical insights, we derive three implications for DHH music education: haptics for pedagogical fit, haptics for making musical concepts tangible, and haptics as a shared reference in instruction.

2 Related Works

2.1 Music Education for DHH Learners

For DHH learners, music education is a critical process that not only fosters the development of auditory attention and linguistic abilities [77] but also facilitates social integration with hearing peers [18, 80]. However, the essence of such education extends beyond mere auditory training to encompass a fundamentally embodied experience. Sutela and Ahonen [75] argue for challenging the traditional hierarchy of senses in music education, advocating a pedagogical shift toward bodily movement and vibration. This view is further supported by cognitive science research linking rhythm perception to the vestibular system and physical movement [54]. From this perspective, DHH music education can also be understood through Universal Design for Learning (UDL), which emphasizes designing instruction through multiple means of representation, engagement, and action/expression so that classroom participation is not restricted to a single sensory pathway [44].

However, this educational context presents sophisticated design challenges from an HCI perspective, as it involves not only technical assistance but also a complex interplay of social interactions and power dynamics among individuals with heterogeneous hearing backgrounds [18, 63, 68, 80]. While prior HCI research has predominantly focused on passive engagement such as music appreciation [52, 53], the field is increasingly expanding toward active participation, including singing, performance, and creation [10, 13, 14, 33, 41]. This shift reflects the fact that moving beyond passive listening toward active performance and collaborative music-making entails higher-order challenges that require seamless integration of sensory and social cues [14, 83]. To better characterize these challenges, prior work has shown that DHH music activities vary not only by task but also by social configuration and coordination demands. For example, Yi et al. [82] systematized DHH individuals' music activities into six dimensions and highlighted the latent potential of interactive experiences within mixed social groups, where participation often depends on real-time alignment of cues, roles, and expectations. Building upon this framework, we posit that the educational context represents a critical design space for HCI, as it is a primary venue where real-time sensory calibration and multimodal collaboration between learners and educators are indispensable, yet remain underexplored [58].

2.2 Haptic and Multimodal Systems for DHH Music Experiences

To broaden access to music for DHH people, HCI and music technology research has long explored multimodal systems that combine visual and haptic modalities. Visual approaches have ranged from representing emotional and structural cues through animated lyrics [45] to ambient data visualizations designed for children with hearing impairments in educational settings [33]. In parallel, haptic approaches have aimed to deliver musical information through bodily sensation, reframing music as something to be *felt*. Representative systems include the combination of a visual display and a haptic chair [46, 47], as well as interactive, public-facing installations that provide vibrotactile music experiences [31]. These trajectories are also reflected in review work that surveys the technologies and methods used to convey musical information through touch [25, 50, 58].

Across this body of work, *signal mapping* has been a central design concern—that is, deciding which musical attributes should be translated into which vibrotactile parameters. Rhythm and accent are often encoded as temporal vibrotactile patterns or pulses, whereas pitch and melodic contours are mapped to vibration frequency or spatial location via arrays of actuators [5, 32, 46]. Actuator *placement* is likewise treated as consequential, given differences in bodily sensitivity and task demands. As systems moved toward wearables, prior work explored sleeves and band-like form factors for delivering musical vibrations [27, 79] and proposed leveraging the collarbone as a site for whole-body vibrotactile presentation [61]. More recently, systems have targeted task-oriented outcomes such as improving pitch perception and performance accuracy with wearable vibrotactile support [66, 67], and have offered modular, constructive formats (e.g., block-based sensor-display elements) that enable users to explore sound-to-sensation mappings [52, 53].

Despite these advances, haptic effects are difficult for users to preview, imagine, and articulate without direct experience [84]. As a result, many systems begin from engineer-defined mappings and device forms, with user needs incorporated only through limited post-hoc refinement. This is particularly limiting in education, where situated practice determines what vibrotactile cues are needed, when they should occur, and how they should be tuned.

2.3 Co-design with DHH People

In accessibility and inclusive design research, participatory and collaborative approaches have been emphasized to counteract expert-driven assumptions and to ground technology in the lived experience of people with disabilities [28, 35, 57, 60]. Informed by disability studies, this work positions people with disabilities not as passive recipients but as epistemic partners who can shape problem framings, priorities, and design values. It also critiques accessibility research that excludes people with disabilities or relies on proxies [4, 29, 40, 72]. Together, these perspectives emphasize self-determination and motivate approaches that treat design as negotiating what counts as a meaningful outcome—and who has the authority to define it.

These motivations are particularly salient for Deaf communities [19, 36], where language, cultural norms, and histories of audist and medically framed interventions make Deaf-centered participation not only ethically important, but also methodologically necessary [1, 2]. De Meulder et al. [43] further caution that work framed as co-creation or inclusion can still reproduce hearing-centered outcomes when decision-making power remains asymmetrically distributed, underscoring the need for participatory engagements that genuinely foreground Deaf identity and communication practices. Recent HCI research has begun to develop such Deaf-centered participatory approaches, including workshops and co-design activities grounded in Deaf communication and community priorities [21]. Within music-related contexts, researchers have similarly involved DHH in co-design to explore accessible musical interaction and expression; for example, through sign-based expression [83], user-tunable cross-modal mappings [13], ideation of multisensory music experiences [41] and touch-inclusive interactive systems that broaden what "listening" can entail [10]. Building on this trajectory, studies also examined equitable participation in mixed-ability music collaboration, highlighting how collaboration structures can redistribute participation opportunities across hearing differences [37]. Collectively, these efforts shift accessibility from optimizing a predefined technical solution toward co-defining what counts as meaningful musical interaction and expression.

2.4 Summary

Previous work positions music education for DHH learners as an embodied and socially situated practice. In response, HCI research has developed haptic and multimodal systems to support non-auditory music experiences. However, non-experts often struggle to imagine and articulate haptic interactions without direct experience, causing design decisions to default to engineer-driven assumptions. Although participatory and DHH-centered design approaches aim to address this limitation, it remains difficult to surface concrete, in-situ judgments about how haptic interactions should be used. Our work therefore foregrounds hands-on co-design to examine how haptics are experienced and negotiated within educator–learner interaction, and to derive situated design implications for haptics in DHH music education.

3 Reconfigurable Haptic Music Prototyping System

We implemented a reconfigurable haptic prototyping system to support co-design workshops by letting participants rapidly experience, iterate on, and articulate music haptics in an instructional context. Our system consists of three integrated layers, a modular hardware hub for physical flexibility, a graphical user interface (GUI)-based configuration tool for logical mapping, and a runtime engine that translates MIDI data into expressive vibrotactile feedback. Although we retain a common approach in prior work—using actuator arrays to encode musical features such as rhythm, accent, and pitch—our system departs from fixed-form devices by prioritizing two workshop-oriented goals: reconfigurable tactor placement across wearables and instrument-related artifacts, and immediate, performance-based testing through on-the-fly mapping adjustments.

3.1 Hardware: 20-Channel Tactor Hub

The system (Figure 1, Hardware) is centered on a hub device enclosed in a compact case that integrates the control module and a multi-channel output board. The output board exposes 20 independently addressable channels via 3.5 mm ports, allowing users to connect custom tactor assemblies based on linear resonant actuators (LRAs; nominal resonance ~170 Hz; $2.7G_{rms}$ at 2.5 V) using standard 3.5 mm audio cables. Each tactor is mounted with a Velcro-based attachment, enabling participants to flexibly attach, remove, and reposition tactors on physical artifacts. This setup allows users to scale the number of tactors as needed and reconfigure placements.

The hub is connected to a Windows laptop for real-time haptic control and synchronizes the per-channel tactor connection status with the GUI. This supports rapid reconfiguration during workshop

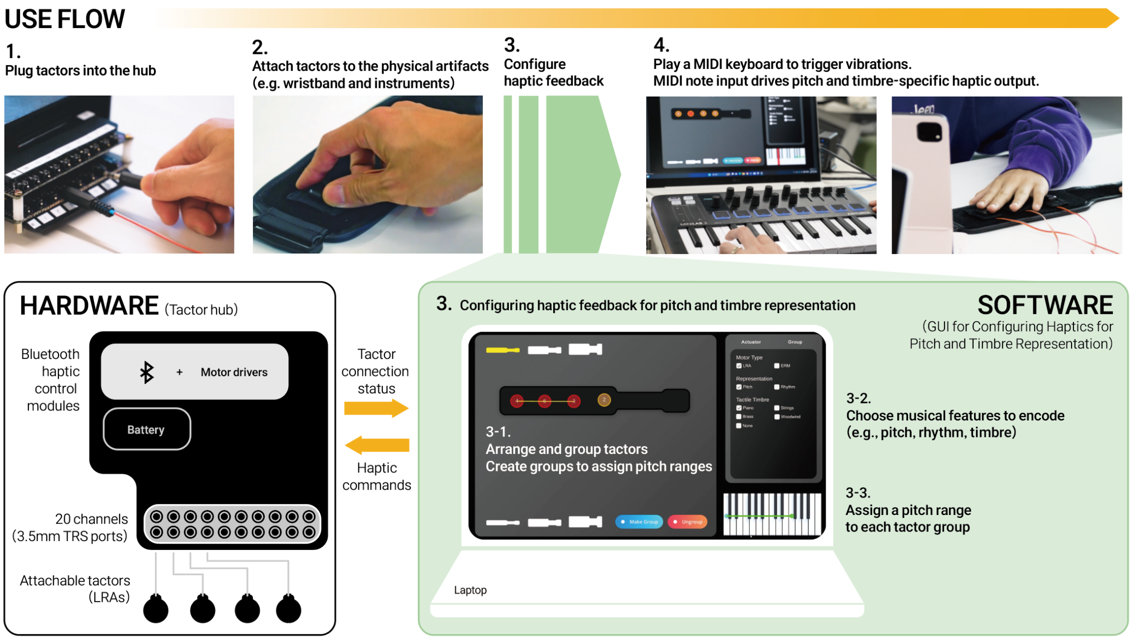

Figure 1: System overview and use flow. The hub drives up to 20 wired tactors, syncs connection status with a laptop GUI for grouping and mapping musical features (e.g., pitch, rhythm, timbre), and uses MIDI input to trigger the configured haptic output on attached artifacts (e.g., wristbands and instruments).

activities, where tactors are frequently attached, detached, and moved across artifacts. For communication between the hub and the laptop, the system uses an nRF52833-based control board that coordinates channel updates and drives tactors through AW86225 motor driver chips.

3.2 Software: GUI for Configuring Haptics for Pitch, Rhythm, and Timbre Representation

We implemented the software in Unity 2022.3.12f and built a GUI to support rapid configuration and testing of music-to-haptic mappings. The GUI was designed around three core activities: (1) inspecting connected tactors and arranging or grouping them, (2) assigning musical features (pitch, rhythm, timbre) to individual tactors or tactor groups, and (3) testing the resulting configurations using real-time input.

Specifically, users can view connected tactors and optionally group them as a unit for mapping (Figure 1, Software). These groups serve as an intermediate layer for assigning musical features and applying shared encoding rules. For pitch, users configure spatial pitch-to-haptic mappings, following a commonly used approach in prior works that represent pitch through distinct tactor locations (or tactor groups) [50, 66]. Higher and lower notes are thus differentiated by where vibration is felt across the mapped locations. Rhythm mappings trigger tactors based on temporal musical events, independent of pitch. Timbre mappings allow users to select vibrotactile modulation presets designed to evoke instrument-like qualities (piano, string, brass, woodwind), or to disable timbre modulation entirely.

3.3 Runtime Mapping: MIDI-Driven Pitch Output and Timbre Modulation

At runtime, the system receives MIDI note input and activates the tactors (or tactor groups) mapped to the corresponding pitch ranges, with MIDI velocity controlling the amplitude of the vibrotactile output. In addition to pitch-based activation, the system renders an instrument-like vibrotactile texture by modulating vibration amplitude with an ADSR-like envelope [7]. Specifically, amplitude is updated at 25 ms intervals to finely control perceived ascents and descents in intensity over time. When users select an instrument preset (piano, string, brass, woodwind, or none), the system applies a corresponding amplitude contour to approximate instrument-like articulation through vibrotactile feedback. This choice is motivated by previous evidence that temporal-envelope cues, such as attack time, are highly salient for perception of musical timbre [34]. This does not aim to reproduce acoustic signals, but to offer an expressive repertoire that participants can perceive, compare, and discuss during co-design.

3.4 Workshop Use Flow

In our workshops, participants followed a repeatable loop: (1) they attached LRAs to artifacts such as wristbands or instruments and plugged them into the hub, (2) verified connectivity and arranged or grouped tactors in the GUI, (3) configured pitch ranges and encoding options, and (4) played a MIDI keyboard to immediately trigger the configured haptic output. This iterative loop helped participants move beyond abstract discussions and articulate situated needs and constraints based on tangible haptic experiences.

4 Co-Design with Reconfigurable Haptic Prototyping

A core challenge in participatory haptic design is that existing approaches tend to separate direct haptic experience from iterative design exploration. Fixed prototypes allow participants to feel actual haptic cues, but they are difficult to modify during co-design, whereas more open-ended ideation requires participants to imagine sensations they cannot directly experience. To address this limitation, we designed a co-design workshop method using reconfigurable haptic prototyping to explore music haptics in DHH education. We conducted a series of workshop sessions with educators and DHH learners. Through hands-on exploration with the reconfigurable haptic prototyping system, the workshops brought pedagogical and lived sensory perspectives into the design process and were intended to support situated exploration grounded in instructional practice.

4.1 Procedure & Methodology

We framed each session as a situated co-design process that embedded haptic ideation into the routines of DHH music education. To support a gradual progression from grounding and reflection on lived instructional experiences to focused ideation, we structured each session as a sequence of phases that increased engagement and specificity over time.

Methodologically, our approach was grounded in bodystorming [8, 49] and role-playing [30, 71, 76]. Participants externalized ideas by enacting instructional interactions, while we supported rapid, experiential iteration through immediate reconfiguration and testing of haptic feedback designs. This structure allowed ideas to emerge through repeated cycles of discussion, bodily trial, adjustment, and enactment within realistic instructional constraints.

Detailed participant roles and procedures for each phase are described in the following.

4.1.1 Session Role Structure. Each workshop session involves four primary roles, which can be grouped into two categories: facilitation roles and participant roles. The facilitation roles consist of a facilitator and an engineer. The facilitator moderates the session, manages time and turn-taking, and supports ideation and convergence during discussions. The engineer introduces the reconfigurable haptic music prototyping system, assists the participants during hands-on trials, and addresses technical questions related to haptic technology. The participant roles consist of an educator and a learner. The educator contributes expertise in DHH music instruction and guides discussions based on pedagogical goals and instructional practices. The learner is a DHH participant with prior music learning experience who contributes sensory feedback, interpretations, and reflections grounded in lived experience.

4.1.2 Phase 0 (5 min): Role Alignment and Warm-up. Each workshop session begins with role confirmation and a brief ice-breaking activity using lightweight prompts (e.g., preferred music genres or favorite artists) to establish rapport. This opening phase supports early participation and open exchange, aligning with facilitation practices that help build trust in participatory settings [15].

4.1.3 Phase 1 (20 min): Instructional Moment Recall and Needs Surfacing. Participants are invited to recall positive and challenging moments from their previous music lesson experiences. To support recall, facilitators introduce prepared instructional materials and instruments as memory cues. Educators and learners reflect on specific instructional situations and discuss which musical elements are difficult to explain, perceive, or assess. These conversations help surface initial needs and prepare participants to explore how such moments might be supported through vibrotactile cues.

4.1.4 Phase 2 (20 min): Sensory Grounding Through Hands-on Trials. The engineer introduces the reconfigurable haptic system and guides the participants through hands-on trials. Tactors are attached to different targets, including body locations, instruments, and classroom props. The engineer demonstrates how musical features such as pitch and timbre can be mapped to vibrotactile parameters, and how participants' emerging audio-to-haptic scenarios can be rapidly configured and experienced in situ. The system is framed as an exploratory tool for quickly authoring and feeling candidate vibrotactile cues, rather than as a constraint on ideation.

4.1.5 Phase 3 (30 min): Bodystorming and Iterative Co-configuration. Participants engage in bodystorming by attaching tactors to instruments and wearable bands (e.g., forearm or wrist) and enacting how these cues might be used during music lessons. Educators typically propose an initial instructional idea, while learners provide feedback on the cues' perceptibility and interpretability. This exchange enables iterative refinement of vibrotactile configurations. The engineer supports rapid adjustments to the haptic feedback and, when needed, employs a Wizard-of-Oz approach [16] to temporarily manipulate timing or expression to clarify interaction possibilities. Throughout this phase, the facilitator actively manages participation to ensure that learners are not excluded during negotiation and decision-making.

4.1.6 Phase 4 (10 min): Mock Teaching Enactment and Reflection. Participants role-play a short mock teaching interaction using the refined haptic idea. This enactment focuses on assessing how the configuration might function within real instructional routines, including feasibility, instructional flow, and learner comfort. Rather than fine-grained tuning, discussion centers on what additional design support would be required for adoption, such as attachment stability, guidance and feedback mechanisms, or teacher control.

4.1.7 Phase 5 (10 min): Interview and Consolidation. Each session concludes with a brief semi-structured interview focusing on perceived value (who the ideas would help and in what situations), conditions for classroom adoption (e.g., setup effort, teachability, learner acceptance), and potential concerns such as confusion, overload, or social exposure. Session outcomes are consolidated into structured notes that capture scenarios, placements, cue parameters, and design rationales, and these summaries are linked to photo and video records for later analysis.

4.2 Participants

We sought to recruit educator–learner dyads to ground the co-design process in established instructional relationships. We prioritized dyads with pre-existing rapport, specifically those with

Figure 2: Overview of the co-design workshop. Across phases, educators and DHH learners recall instructional experiences, explore haptic feedback through hands-on trials, and iteratively co-configure vibrotactile cues through bodystorming and mock teaching enactment. The figure highlights representative moments from each phase.

prior or ongoing experiences of teaching and learning together. This pairing strategy was intended to support open exchange and negotiation during design activities that reflect real educational settings [15, 69]. However, this strategy also carried a risk of reproducing educator–learner power asymmetries in who initiated ideas, validated interpretations, or steered decisions. To mitigate potential educator dominance, we incorporated participation-oriented facilitation strategies across phases, including warm-up activities (Phase 0), facilitator-managed turn-taking during bodystorming (Phase 3), learner-first prompts before convergence, and end-of-session interviews (Phase 5) that gave learners additional space to articulate their own perspectives.

Participants were recruited through community-based outreach at social welfare centers and special schools in South Korea. A total of four educator–learner dyads (eight participants) participated, resulting in four co-design workshop sessions. Table 1 summarizes participant demographics, including educators' instructional backgrounds and learners' degree of hearing loss (categorized as *severe* or *mild* according to the South Korean registration system), Deaf identity, and primary communication method. Educators (T1–T4) represented diverse instructional contexts, including music for auditory rehabilitation, after-school programs at Deaf schools, and special schools where music was part of the curriculum. Learners (S1–S4) ranged from adolescents to adults, including elementary and middle school students and an adult leisure learner, enabling examination of haptic support across varied learning stages.

4.3 Workshop Setup and Accessibility

All sessions took place in a dedicated studio environment organized around a shared worktable. The seating arrangement prioritized continuous visual access among participants (e.g., faces, hands, and gestures) to accommodate mixed communication practices such as signing, speech, and gesture.

Communication and Accessibility Accommodations. To support communication between DHH participants and hearing facilitators, we arranged a professional sign-language interpreting team following accessibility-oriented study practices [39, 56]. Interpreters were briefed on workshop goals and terminology in advance and arrived before each session to align on key terms and interactional conventions, helping reduce role ambiguity and improve conceptual consistency during interpretation [65]. Also, a secondary display was placed in front of the DHH learner to provide real-time captioning during each session.

Materials and Props. We prepared four categories of materials: (1) music-activity instruments, (2) ideation materials for rhythm, motion, and externalization, (3) fabrication and attachment materials for building haptic teaching aids, and (4) the reconfigurable haptic music prototyping system.

Ethical Considerations. This study was approved by the Institutional Review Board (IRB) of KAIST (IRB No. KH2024-234) for all study procedures, including recruitment, study materials, and data collection. All participants provided informed consent and received approximately US$37 in compensation.

4.4 Data Analysis

All workshop sessions were audio- and video-recorded and transcribed. Transcripts, including sign-language interpretations, were cross-verified by stenographers and interpreters. Our analysis dataset comprised verified transcripts, observational notes, and physical artifacts such as ideation worksheets and documented haptic configurations.

We conducted thematic analysis [6] to examine participants' design decisions and pedagogical rationales. Three researchers collaboratively coded the data using ATLAS.ti [3], focusing on recurring interaction patterns, instructional scenarios, and rationales for mapping vibrations to musical elements such as pitch and

Table 1: Demographics of workshop participant dyads.

Educators			DHH Learners					
Alias	Age	Instructional Background	Alias	Age	Deaf Identity	Degree	Learner Status	Language
T1	53	Music teacher (auditory rehabilitation)	S1	16	Bicultural	Mild	Middle school student	Bilingual (Sign, Spoken)
T2	47	After-school music teacher	S2	32	Deaf	Severe	Leisure learner	Sign Language
T3	29	Teacher at a special school	S3	12	Bicultural	Severe	Elementary school student	Bilingual (Sign, Spoken)
T4	31	Teacher at a special school	S4	12	Deaf	Severe	Elementary school student	Sign Language

Note. All educators identified as hearing. Deaf identity was self-identified by learners and does not necessarily correspond to the degree of hearing loss.

timbre. A fourth researcher who did not participate in the workshops reviewed the codebook, and discrepancies were discussed and resolved through iterative team discussion until consensus was reached.

5 Findings from the Co-design Journey

We report our findings by framing the workshops as a *co-design journey*, as key insights emerged through how ideas were developed, negotiated, and transformed across workshop phases. Although all sessions followed the same phased structure, participants' focal points and outcomes differed depending on their educational contexts and individual profiles. Viewing the workshops through this session-specific journey allows us to trace how design ideas evolved over time while attending to differences in participants' profiles that shaped each session. In what follows, we describe each session by outlining the participant dyad and co-design outcome, followed by synthesized findings showing how haptic experiences reshaped the ways participants sensed, learned, and made sense of music together. For each finding, we draw from representative quotes or observation notes that integrate participants' utterances and actions within their situational context.

5.1 Session 1: Reframing Pedagogical Challenges Through Embodiment

Session 1 involved an educator (T1) working in a music-based auditory rehabilitation context and a learner (S1) with multiple years of training in this domain. Unlike music education centered on Deaf identity, this workshop was situated in a context where music is used to support auditory development for students using hearing aids or cochlear implants. This context shaped the workshop dynamics, with T1 approaching activities from a strongly pedagogical perspective and raising practical questions about how haptic feedback could be integrated into existing musical instruction.

Co-design Outcome: Spatialized Cues for Embodied Pitch Learning. The co-design outcome converged on a pitch learning setup using spatialized vibrotactile feedback. Participants arranged seven tactors along the forearm in an ordered sequence so that the lower notes were felt closer to the wrist and the higher notes closer to the upper arm, supporting an embodied sense of pitch ascent and descent. In Phase 4, T1 enacted a quiz-like activity: after having S1 feel a full scale from low to high notes, T1 played isolated notes and asked S1 to identify the corresponding note name only by haptic sensation.

Figure 3: Outcome of session 1. A forearm-mounted haptic configuration that spatializes pitch using multiple tactors to support pitch learning.

5.1.1 *Making Pitch Teachable Through Tangible Haptic References.*

> T1 asks S1 to close her eyes while arranging the tactors along her forearm. After playing a single note, she pauses and asks, *"Does this feel high or low?"* They repeat the action with another note, comparing sensations. T1 then reflects later, *"If they can feel high and low like this, then pitch becomes something we can actually teach."*

This note captures a broader pedagogical shift observed across this session. In Phase 1, T1 had described pitch and melody as among the most difficult concepts to teach in DHH music education. Phase 2 introduced a new possibility by giving pitch a bodily reference through haptic exploration, suggesting that pitch change could be taught through haptics rather than explanation alone. This resonated with T1's instructional experience that pitched percussion (e.g., xylophone-like instruments) often supports pitch learning more effectively because striking naturally produces tangible vibration. Building on this insight, Phase 3 focused on establishing a teachable haptic reference: T1 and S1 repeatedly tried our system with melodic instruments (e.g., recorder and ukulele), asked each other how the vibrotactile feedback felt, and refined placements and mappings to arrive at a shared, discussable distinction between high and low pitches. The Phase 4 mock lesson then provided a brief and situated confirmation that such haptic cues could be pedagogically mobilized to support pitch concept learning.

5.1.2 *Haptics Complementing Visual Scaffolds.*

> *"For these students, hearing doesn't really work, so they prefer relying on visual cues instead. These days, with platforms like YouTube, the score shows up on screen with the beats clearly marked. They follow along by watching—doing it this way feels much more vivid and engaging for them."* (T1)

In Phase 1, T1 questioned the need for haptics in DHH music education, emphasizing that visual cues already function as core classroom infrastructure and that additional channels could increase instructional overhead. Through Phase 2, however, participants came to recognize that haptics could address aspects of music learning that remain difficult to support visually. This led to a clearer positioning of haptics not as a replacement for visual elements but as something that should work alongside them. This view was grounded in classroom practice, as T1 described how ensemble activities can quickly fall apart when a learner makes a mistake requiring the teacher to visually indicate *"this part, start here"* to support re-entry. Within this context, haptics were discussed as a complementary layer that could reinforce timing or provide brief, on-body cues at critical moments, without demanding continuous visual monitoring.

5.2 Session 2: Haptic Cues for Intangible Musical Features

Session 2 involved an adult DHH participant (S2) in the learner role and her former music teacher (T2) in the educator role. Unlike sessions focused on current classroom practice, this workshop drew on S2's retrospective learning experiences. Having strong interest in music and prior exposure to haptic music technologies, S2 took a highly active, learner-driven role, frequently initiating exploration and steering ideation. As she was not currently in formal instruction, the conversation centered less on pedagogical use and more on concrete preferences for how haptics should represent specific musical elements.

Co-design Outcome: Watch-Like Wearable for On-Body, Real-Time Voice Quality Cues. The co-design outcome converged on a minimal wearable form, namely a single tactor worn on the wrist like a watch, intended to provide immediate vibrotactile feedback to produced sound. Participants envisioned this device as supporting two kinds of feedback. They proposed a pitch mapping in which musical pitch would be conveyed through differences in vibrotactile frequency rather than spatial location. They also proposed timbre-modulated feedback for vocal practice to differentiate voice production qualities, such as breathy versus pressed voice. Because these two forms of feedback were not directly supported by the current system, Phase 4 explored pitch through hypothetical exploration and vocal quality through a Wizard-of-Oz approach.

5.2.1 *Reframing Haptic Pitch Through Felt Experience.*

> S2 presses piano keys and pauses to reflect on the haptic sensation. After repeating the same note several times, S2 compares what she feels to her prior listening experience and remarks, *"It's not what I originally wanted. When I press 'do,' the feeling (haptic) is different from the 'do' I sense when wearing hearing aids."*

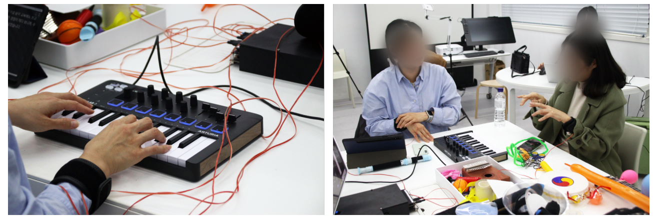

Figure 4: Outcome of session 2. A wrist-worn haptic device supporting immediate, parametric vibrotactile feedback for pitch exploration and vocal production.

This note shows how S2 began to articulate what pitch should feel like through haptics. In Phase 1, S2's prior exposure to haptic music technologies through media had generated strong curiosity, but her expectations remained abstract. In Phase 2, hands-on trials made those expectations tangible by directly contrasting assumed mappings with felt sensations, revealing a pitch-specific mismatch. Rather than aligning with her learned auditory associations, pitch felt different when translated into vibrotactile cues, prompting a reassessment of how pitch should be represented haptically. At the same time, S2 responded more positively to timbre-modulated vibration, which felt richer and easier to interpret through texture. This contrast led her to reframe what an effective pitch mapping should prioritize. Instead of relying on spatial relocation, she argued for a form of haptic differentiation that would directly express "high" and "low" through sensation itself. While the current system could not implement this proposal because it relied on fixed-frequency LRAs and spatial pitch mapping, a discussion with the session engineer raised the possibility of alternative wideband haptic actuators that could support frequency-varying cues. This allowed participants to continue Phase 4 as a hypothetical exploration of how pitch might be conveyed through haptic feel.

5.2.2 *Embodied Regulation of Vocalization Through Haptics.*

> *"'Ah,' 'uh,' and 'oo' are all different sounds. Can the vibration feel different when producing 'ah,' 'uh,' or 'oo'?"* (S2)

This question reframed vocal practice as an embodied regulation problem. Throughout the discussion, both participants emphasized that producing clean vocal quality is difficult for many DHH learners because sound production lacks immediate, perceivable feedback during action. Without reliable auditory cues, it becomes difficult to monitor breath initiation, airflow control, and sustained phonation in real time, and vocal practice often breaks down over time. Through the exploration of Phase 2, haptics were imagined as a way to restore this missing feedback loop by making aspects of vocal production perceptible through the body. Instead of treating voice as an outcome to be evaluated, participants considered haptics as on-body feedback that could support real-time awareness and regulation of vocal action. This frame was especially notable because existing compensatory strategies, such as touching the throat, are impractical during singing or during the performance of wind instruments that rely on active breath support. Because the system could not recognize vocalization directly, this idea was simulated using a Wizard-of-Oz approach in which S2 produced different vocalizations while the engineer selected the closest timbre modulation preset to represent the vocal quality. This exploration reinforced the idea that haptics could support the embodied learning of vocalization by helping learners sense and adjust their own sound production as it unfolds.

5.2.3 *Simple, Repositionable Form Factors.*

> *"The wrist is enough. When I got an Apple Watch, just that vibration alone was enough for me."* (S2)

This statement encapsulates how hands-on exploration led S2 to prioritize simplicity and everyday wearability in haptic form factors. Throughout Phase 3, since participants were invited to imagine and physically reposition tactors at different locations and scales of the body, S2 consistently rejected bulky or body-encompassing configurations, describing them as uncomfortable and undesirable for sustained use. Instead, she repeatedly returned to a lightweight, watch-like wearable as a sufficient and realistic baseline. Importantly, this preference was not driven by comfort alone, but by a desire for flexibility and control in everyday contexts. S2 emphasized that haptic devices should be usable on demand rather than continuously worn, and easily repositioned depending on the musical activity at hand. In this framework, a simple wrist-worn device functioned not as a fixed interface but as a modular resource that could be removed, reattached, or temporarily placed on instruments as needed.

5.3 Sessions 3 and 4: Building Shared Haptic References under Classroom Constraints

Sessions 3 and 4 involved in-service special school teachers (T3, T4) in the educator role and their current DHH students (S3, S4) in the learner role. In contrast to the auditory rehabilitation context of Session 1, these workshops were situated in special DHH school contexts, where music education is framed as part of inclusive education, rather than as a means of improving auditory perception. Based on everyday classroom practice, the participants focused on how music haptics could support inclusive instruction within real school constraints, and how such systems might fit into existing routines without increasing the orchestration burden of teachers.

Co-design Outcome: Shared Haptic Setups for Timbre and Harmony Learning. In Session 3, the co-design outcome took the form of a shared monitoring setup for instrumental practice. S3 held a handheld object composed of four tactors, while T3 wore a matching set on the wrist. The system mapped instrumental pitch differences to spatially distributed vibrotactile feedback, with additional timbre modulation designed to convey the characteristic sound qualities of the instrument. In Phase 4, participants treated the provided ukulele as a stand-in for a violin and used mirrored haptic cues as a common reference: T3 explained the sound characteristics of the violin, while S3 described what the violin-like vibrotactile felt like, allowing instruction to proceed through a shared haptic basis.

In Session 4, the outcome converged on a compact pitch-and-harmony learning aid. Five tactors were arranged in a line and mapped from Do to Sol. In Phase 4, T4 introduced harmony by progressively layering notes (Do, then Do–Mi, then Do–Mi–Sol),

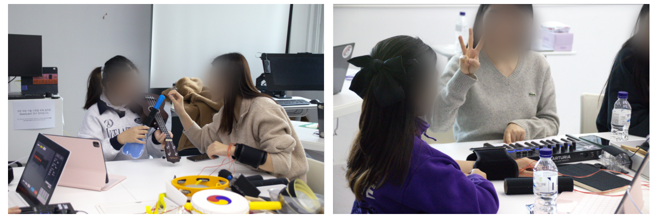

Figure 5: Outcomes of sessions 3 and 4. A shared haptic setup enabling (Left) participants to jointly sense and discuss instrumental performance through timbre modulated vibrotactile and (Right) supporting the exploration of pitch and harmony through layered vibrotactile cues.

inviting S4 to compare how the haptic sensation changed as the tones accumulated. This stepwise stacking interaction allowed T4 and S4 to discuss harmony as a felt difference in density and layering.

5.3.1 *Shared Haptic References for Negotiating Musical Meaning.*

> T4 first plays single notes (Do, Mi, then Sol), asking whether the sensations feel the same or different. T4 then plays Do–Mi–Sol together and asks how the combined vibrotactile feels. After S4 describes the sensation, T4 frames this felt difference as harmony, explaining that Do, Mi, and Sol together form a C chord.

Throughout Sessions 3 and 4, both educators foregrounded *expression* as a core goal of music education in DHH special schools. They described relying heavily on body-based activities such as movement and percussion, as well as expressing musical experience through sign language, to help students externalize what they feel in music. While such approaches support shared participation, they also reveal a persistent constraint: beyond rhythm and intensity, many musical concepts remain difficult to express and negotiate together. Pitch, in particular, was repeatedly described as challenging to teach, as students cannot reliably access pitch differences through hearing alone.

Through hands-on exploration and enactment, haptics emerged as a way to expand this expressive space by providing a shared haptic reference for musical meaning. In Session 3, this took the form of using instrument-specific vibrotactile modulations, allowing T3 and S3 to talk about instruments through felt differences in haptic sensation. In Session 4, the same logic was applied to harmony in music. By alternating between single and combined tones and inviting S4 to compare how they felt, the participants jointly negotiated the meaning of harmony through haptics. Rather than defining harmony verbally, they used haptic comparison to arrive at a shared understanding, treating haptics as a common experiential ground for expressing and discussing musical structure.

5.3.2 *Haptics as a Continuous Channel for Musical Attention.*

> *"When music lessons rely on visuals, the moment they turn their head, the music is gone."* (T3)

This remark emerged as the participants reflected on the limits of visually dominant music instruction. In everyday classrooms, musical information is often conveyed through visual materials, gestures, and demonstrations, requiring students to keep their gaze fixed on the teacher or the screen. T3 and T4 noted that when students momentarily look away—whether due to distraction, fatigue, or classroom dynamics—the musical experience itself is interrupted. In this context, haptics were discussed as a way to maintain a musical presence through the body, even when visual attention shifts. T3 and T4 envisioned haptics as allowing students to continue feeling musical elements while listening to explanations, enabling instruction and musical experience to unfold in parallel rather than sequentially. This was seen as particularly valuable in listening activities, where haptic cues could make qualities such as tempo and intensity perceptible without demanding constant visual focus. Together, these discussions positioned haptics as a continuous attentional channel that supports uninterrupted engagement with music.

5.3.3 *Teaching Across Heterogeneity Without Exclusion.*

> *"In one class, some students can hear a little with their devices, some rely mostly on sign, and some lose focus very quickly. When you start following the ones who can hear a bit better, it's easy for the others to be left behind."* (T3)

Sessions 3 and 4 foregrounded heterogeneity as a defining condition of music education in DHH special schools. Participants described classrooms composed of students with a wide variation in hearing levels, language modalities, and attentional capacities, where instructional focus can easily become uneven. As T3 explained, responding to students who show faster auditory or musical uptake often happens unintentionally, but risks excluding others who engage differently or require more support. To manage this diversity, teachers already rely on a dense combination of modalities, including visual materials, spoken language, sign language, gesture-based cues, and even environmental signals such as turning lights on and off. This results in a high orchestration burden, especially given that teachers' hands must remain free for signing and guiding students. In this context, haptics were initially discussed as a potential source of additional overhead if they required a complex setup or constant attention.

At the same time, the teachers articulated an alternative possibility. If designed to be simple, wearable, and low-effort, haptics could function as a shared sensory channel that reaches all students simultaneously, regardless of individual differences. Rather than adding yet another modality to manage, haptic feedback was valued for its potential to reduce the reliance on constant visual monitoring. As T4 put it, *"If it can be felt without having to look, it would be much easier to teach,"* pointing to haptics as a way to support inclusive instruction while easing the practical burden of teaching in heterogeneity.

6 Discussion

This section interprets and extends what our co-design journeys revealed about how vibrotactile cues are designed and used within the realities of DHH music education. By reflecting on participants' hands-on exploration of haptics within instructional interaction, we articulate design implications grounded in educational practice. Alongside these implications, we reflect on how our reconfigurable haptic system and co-design approach shaped what participants were able to experience, articulate, and negotiate, highlighting both enabling aspects and areas for improvement.

6.1 Design Implications for Music Haptics in DHH Education

6.1.1 *Haptics for Pedagogical Fit.*

Across sessions, educators repeatedly questioned whether haptic feedback was necessary, noting that visual cues already function as core classroom infrastructure and that adding another modality could increase instructional overhead. As the enactments progressed, participants began to identify moments where "feeling it" seemed genuinely helpful. This shift reframed "why haptics" from a question of novelty into a question about instructional purpose. Given that DHH people often rely on visualized information to engage in music activities [12, 20, 48], the discussion turned to what educators might aim to convey through haptics and what learners can realistically perceive and learn from haptic cues. This implication also resonates with UDL, which emphasizes supporting instruction through multiple means rather than relying on a single modality [44]. Within this framing, haptics can contribute when it helps represent musical information, sustain engagement, or support self-monitoring during performance. In this sense, the value of haptics lies not in simply adding another channel, but in helping educators and learners coordinate modalities in ways that fit lesson goals, learner needs, and classroom constraints.

One practical approach is to offer a small repertoire of sensory symbols that can be tuned to fit objectives and individual differences, instead of prescribing a single fixed mapping. For example, prior work shows that users can construct personally intuitive cross-modal representations by adjusting both visual parameters (e.g., size, color, texture, shape, spacing) and vibrotactile parameters (e.g., sensitivity, intensity) [13]. Such customization can be structured at two levels: (1) selecting which sensory symbol corresponds to a target musical feature, and (2) tuning parameters (e.g., intensity, sensitivity, spacing) of the chosen symbol. This two-level framing can accommodate both learner variability and shifts in pedagogical goals (e.g., discrimination accuracy versus engagement), while also turning the act of adjustment into a meaningful form of participation.

Overall, we suggest answering "why haptics" through a structured combination of instructional goals, candidate sensory symbols, and supported forms of adjustment. Designers can start by specifying the target goal, then offer symbols that educators and learners can select and explain within instruction, and finally support adjustment at both the mapping-selection and parameter-tuning levels. Evaluations should likewise extend beyond accuracy or preference to include pedagogically aligned outcomes such as adjustability during learning, self-efficacy, practice persistence, and changes in educators' instructional workload. With this notion of pedagogical fit, haptics can be positioned not as a substitute for visualization, but as an educational tool integrated into lesson design.

6.1.2 *Haptics for Making Musical Concepts Tangible.*

Session 2 and the instructional moment recall activities across sessions similarly highlighted that participants tended to describe activities such as singing, playing wind and string instruments as comparatively difficult, especially when haptic feedback during performance felt ambiguous. In contrast to percussion, they noted that it was harder to *"tell what I am doing right now"* through the body, which in turn made it difficult to establish a basis for fine-grained adjustment while performing. These reflections suggest an opportunity for haptics to function as supportive feedback: not as a replication of auditory information, but as cues that help learners monitor actions and outcomes through the skin in the midst of performance.

In line with this, participants discussed haptics as a way to externalize bodily states that are otherwise difficult to self-check during performance, such as the intensity and steadiness of phonation while singing, or breath pressure and blowing strength when playing wind instruments. This points to the role of haptics beyond "information delivery," as a means to intervene in the process of embodied skill formation. Prior work has suggested that real-time haptic feedback can support kinesthetic learning in regulating bodily processes such as muscle activity and breathing [55], and haptics have also been explored for supporting singing-related performance feedback [66, 67]. However, how to map fine-grained vocal or instrumental actions into haptic cues, and how to deliver such feedback in real time without oversimplifying the action–sound relationship, remains an underexplored design space.

Accordingly, we argue that haptics in DHH music education should be designed as *formative, in-the-moment support* rather than a one-size-fits-all channel. A central role of haptics is to make otherwise intangible musical concepts tangible by re-constructing them as sensory cues that learners can reference during execution. Concretely, phenomena that are often accessed through listening or verbal explanation—such as timbre-related qualities, dynamics, breath stability, or vocal effort—can be transformed into vibrotactilely perceivable cues that help learners "hold onto" a concept and connect it back to their own action. Importantly, these cues should be designed not as post-hoc indicators, but as the basis for an embodied feedback loop that supports ongoing adjustment and internalization during performance [64, 70]. In this framing, haptics becomes formative feedback that shapes performance in the moment, rather than an output reserved for retrospective evaluation.

6.1.3 Haptics as a Shared Reference for Music Instruction. In bodystorming and enactment, we repeatedly observed moments where educators and learners needed to communicate musical intent while the performance was unfolding. In these moments, haptics were discussed less as an output that "accurately reproduces" musical features, and more as a medium for quickly confirming a shared assessment of what is happening now—and what should be adjusted next. Put differently, haptics can support a shared reference that participants can point to together. When haptic cues become a shared reference, they can support more inclusive instructional interaction by making feedback easier to point to, discuss, and act on in real time. This implication also resonates with prior findings on mixed-ability music collaboration, where equitable participation depends on how interaction structures distribute opportunities to interpret, respond to, and shape ongoing musical activity [37].

This framing highlights an important design consideration that haptic cues should remain interpretable and sharable in the instructional context. Interpretability does not mean enforcing a single "correct" mapping principle. Instead, educators and learners should be able to describe what a cue stands for in simple terms, connect it to what to adjust next, and revise or renegotiate that meaning as the lesson progresses. Related discussions in the haptics community similarly emphasize the need for common ground and shared ways to talk about, compare, and carry forward haptic encodings across settings [62]. Recent work on collaborative vibrotactile pattern design further shows how teams iteratively produce and refine patterns to align intent and evaluation criteria, effectively building shared references through design iteration [81]. Together, these accounts support our implication that haptic meaning is more likely to become shared when it is sustained through classroom interaction rather than pre-defined as a one-way mapping.

Together, we suggest approaching music haptics not only as a support for an individual learner's perception, but also as a coordination resource that helps educators and learners align their understanding of what is happening during performance and what to adjust next. From an inclusive design perspective, the value of haptics lies less in improving an individual's accuracy and more in sustaining shared sense-making and interaction as learning unfolds.

6.2 Methodological Reflections

6.2.1 Enabling More Inclusive Participation Through Reconfigurable Prototyping and Enactment. A central strength of our approach lies in how hands-on engagement and bodystorming enabled participants to generate concrete, situated insights while meaningfully contributing to design. Working with a functional, yet reconfigurable, haptic system allowed participants to move beyond abstract expectations and engage with haptics through direct experience. Throughout the sessions, this supported participants in developing a more grounded understanding of what haptic feedback could do in practice and how it might operate within instructional settings. In Session 2, repeated trials and exploration helped deepen the participant's understanding of haptics, supporting participant-led ideation that moved beyond surface-level preferences. As a result, some proposed ideas aligned closely with ongoing directions in haptic research, particularly mapping strategies that transform audio-frequency information into discriminable vibrotactile representations [50]. Similarly, in Sessions 1, 3, and 4, participants progressed from articulating general needs toward proposing more concrete configurations of where and how haptics could be used in context.

Previous co-design research cautions that participatory processes can still devolve into "participation as consultation," where minoritized partners are positioned primarily as testers of pre-built systems and decision-making authority remains unevenly distributed [43]. Against this backdrop, our methodological contribution lies in how the co-design process supported knowledge production rather than opinion harvesting. This concern is particularly salient for haptics, as sensations are difficult to imagine and underlying technologies can be hard to grasp without direct experience. By deploying a functioning but reconfigurable haptic system that participants could try and adjust in the moment, the workshops enabled participants to build a concrete sense of how the feedback felt and how it operated. Over time, participants asked increasingly specific technical and design questions and took a more active role in shaping ideas. This hands-on engagement also made critique more actionable, allowing participants to ground proposals in concrete instructional scenarios and constraints, rather than leaving collaboration at the level of symbolic or performative participation.

6.2.2 Reflecting on Children's Agency in Co-design. To align the workshops with everyday educational practice, we worked with educator–learner dyads who had existing teacher–student relationships. However, in early-stage education, interaction is often organized around educator-led guidance, with teachers setting goals, pacing, and directions, while learners' opportunities to initiate or steer activities remain limited [22, 26]. This pedagogical structure also shaped participation in our co-design sessions, and we acknowledge that teacher-led bias was not fully eliminated. While we used facilitation strategies to broaden participation, learners—except in Session 2—still tended to take a more reserved role in proposing ideas and steering discussion. Rather than claiming equal participation, we interpret this asymmetry as both an empirical finding and a methodological constraint. This asymmetry is analytically meaningful because it reveals how pedagogical hierarchy enters co-design, but it also limits how strongly we can interpret learner-led ideation.

Building on this reflection, future methodological refinements can more directly support learner agency. Our observations suggest two concrete directions. First, dyad composition could be diversified while retaining pedagogically meaningful role structure. Session 2 illustrates why this may matter, as a softened teacher–student hierarchy, shaped by time and the learner's adult status, coincided with comparatively stronger learner initiation. This indicates that varied relationship trajectories may help rebalance participation without sacrificing educational realism. Second, building on our observation that Phase 4 often elicited more focused and active learner participation, it could be extended with role-switch enactments in which learners explain their own musical interpretations to educators, rather than only responding within teacher-led mock lessons. This draws on pedagogical practices that invite learners to articulate their own understanding and may help foreground learners' perspectives while supporting more active participation in ideation and negotiation. In addition, future protocols could formalize learner-first rounds, separate learner reflection checkpoints, and auditable facilitation criteria for turn distribution and decision closure. These directions are also consistent with prior work on children's agency, including age-appropriate ideation scaffolds and session formats that support more confident and proactive participation in co-design [9, 73].

6.2.3 Method Transferability. Beyond the specific findings in DHH music education, our workshop process suggests a transferable methodological structure for designing and evaluating embodied haptic interaction in context. Across sessions, this process consistently followed four connected steps—(1) sensory grounding before ideation, (2) role-based enactment in situated interaction, (3) rapid reconfiguration during negotiation, and (4) post-enactment consolidation of rationale and configuration—which can serve as a practical scaffold for other domains where users must coordinate meaning around embodied cues. Potential application contexts include speech training, motor rehabilitation, special education, and broader multisensory coaching settings. In this sense, the contribution is not only the domain-specific insights reported, but also a reusable workflow for haptic co-design in settings where interpretation, adjustment, and coordination must unfold together. Unlike approaches that separate ideation, embodied enactment, and prototype evaluation into distinct stages, this workflow keeps sensory experience, role-based interaction, and rapid reconfiguration coupled within a single session.

7 Limitations and Future Work

This study engaged a limited range of participant configurations within DHH music education. In practice, DHH music classrooms often include learners with additional disabilities, and engaging such learners would allow future studies to examine how haptic co-design supports more complex and intersecting access needs. This heterogeneity may also apply to educators. As interest in music among DHH people continues to grow, DHH people increasingly take on roles as music educators, and involving DHH music educators in co-design processes may surface pedagogical perspectives and design considerations grounded in lived experience.

Beyond individual participant characteristics, heterogeneity also manifests in how participants interact during learning and design activities. While this study focused on educator–learner relationships, educational practice also relies heavily on peer interaction among learners, and workshop formats centered on learner–learner interaction may reveal complementary insights into collaboration, agency, and shared musical understanding.

In addition, this work was situated within South Korean DHH music education, with a limited number of educator–learner dyads. Accordingly, the empirical findings and cue interpretations reported here should be understood as context-bound rather than directly generalizable across DHH education settings. Future studies should therefore test these findings across countries and Deaf cultural contexts to examine which patterns remain stable and which are context-sensitive. Comparative replications across different classroom ecologies, facilitation styles, and participant compositions would help establish stronger evidence for the boundary conditions of these results and for how haptic co-design outcomes vary across settings.

8 Conclusions

This paper contributes a co-design method using reconfigurable haptic prototyping for investigating music haptics in DHH education. By enabling rapid reconfiguration of tactors across body- and instrument-related contexts, the method allowed educators and DHH learners to directly experience, discuss, and iteratively refine vibrotactile cues during instruction-oriented design activities. Building on this method, we provide empirical insights into how cues are interpreted, negotiated, adjusted, and stabilized in educator–learner interaction, and derive implications for designing haptics for pedagogical fit, for making musical concepts tangible as formative in-the-moment support, and as a shared reference in instruction. Finally, we contribute methodological lessons on how reconfigurable prototyping, hands-on exploration, bodystorming, and mock teaching enactment can surface fine-grained sensory requirements together with practical and pedagogical considerations that emerge in instruction.

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