Scaffolding the Music Listening and Music Making Experience for the Deaf

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1 Introduction

Music is an important part of our daily life. We listen to the radio, enjoy concerts or make music. However, 360 million people worldwide have limited access to music due to "disabling hearing loss" [63]. Deaf musicians, such as percussionist Evelyn Glennie [16] and opera singer Janine Roebuck [55], are extraordinary examples of individuals who made music their occupation. Initiatives such as "Music and the Deaf" [44], aim to encourage deaf people to make music through seminars, concerts and workshops. Moreover, educational approaches towards making music for deaf people have been investigated [18, 19, 38, 40] and assistive technology for music making such as MOGAT [67] and the Tac-Tile Sound System [50] have developed additional visual and vibrotactile feedback to compensate for the lack of hearing.

In this chapter we describe two assistive augmentations based on sensory substitution techniques for deaf people in the application areas of music listening and music making. Firstly, we discuss and compare existing assistive technologies that support musical activities for deaf people through augmentation of the ear or applying sensory substitution, in particular using visual and vibrotactile feedback. Secondly, we introduce the Haptic Chair system, a chair that provides audio information through a visual display and vibrations transmitted to different body sites, including hands, back and feet. An evaluation of the Haptic Chair shows that

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deaf people enjoy the vibrotactile music listening experience with the Haptic Chair. Additionally, it has been found that the feedback from the Haptic Chair could improve the regular speech therapy program. The third section transits from music listening to music making and introduces the VibroBelt, a reprogrammable music-to-vibrotactile belt worn around the waist. We discuss requirements for music making assistive technology based on an observational study, describe the technical development of the VibroBelt and present user sessions that indicate vibrotactile feedback as a potential modality for scaffolding the music making process for deaf people. We close this chapter with a conclusion and outlook on how we envision the future development of assistive augmentation technology that supports musical activities for the deaf community.

2 Related Work

2.1 Augmentation of the Existing Pathway

Hearing aids are one of the most common strategies for deaf people to experience sound. Hearing aids amplify sound and improve language recognition. However, they are known to distort music which limits its enjoyment [4, 11]. Cochlear implants are another way to augment the ear. A cochlear implant consists of an array of electrodes that is inserted directly into the ear's cochlea to stimulate the nerves with electrical signals. These signals are quite different from natural auditory signals. Hence, the success of a cochlear implant depends on the age of implantation [6]. The earlier a person gets the cochlear implant, the higher is the chance of success. Cochlear implants improve language recognition, however, they are less ideal for music perception [9]. Due to the limited bandwidth of cochlear implants, the perception and identification of melodies [13] and timbre [9] are poor, limiting the musical experience [33]. In addition, cochlear implants require an expensive surgery and can cause ear infections.

2.2 Augmentation of Alternative Sensory Channels

"*Sensory substitution devices (SSDs) convey information that is normally perceived by one sense, using an alternative sense*" [32]. Sensory substitution has been applied to compensate hearing loss for sound type detection [20, 37], direction cueing [24, 60], speech processing using the Tadoma method [54], and the enhancement of musical experiences [26, 28, 49]. The following section provides an overview and comparison of two different sensory substitution strategies for music.

2.2.1 Music-to-Visual Sensory Substitution Strategies

Mori et al. used animated lyrics to convey emotions of music [42, 53, 62]. In fact, signing the lyrics of a song by sign language is a common practice in the deaf community to translate sung music into visual form. Most music-to-visual sensory substitution strategies focus on representing musical information as animations on a screen. An overview is given in Table 1 (for more details see [51]). Common mapping for pitch is the vertical position of an object representing a note (e.g., circle or bar), its color or its angle relative to a reference point, on a screen. However, different instruments are also presented through different colors, which can interfere with the pitch mapping. Time is presented in two different ways: (1) along an axis, which makes past and future of the music visible or (2) as instantaneous events. Given the importance of real-time information, music making approaches mainly use instantaneous events for time representation. To our knowledge, an optimal mapping from musical information to animations has not been established yet. However, Fourney et al. found that visualizations with too much musical information tend to be boring for hearing impaired individuals [12]. Rather, the entertainment value seems more important for deaf music consumers.

2.2.2 Music-to-Vibrotactile Sensory Substitution Strategies

An overview of existing music-to-vibrotactile sensory substitution systems is given in Table 2 (for more details see [51]). We note that the use of pure audio signals is quite common for music-to-vibrotactile sensory substitution approaches. This is reasonable since the audio signal can be directly used as the driving signal for many actuators, such as speakers and voice coils. With this mechanism, pitch and loudness is directly translated to vibrotactile frequency and intensity, respectively. However, the frequency discrimination of the skin is poor compared to audio and the skin's frequency range is small (up to 1000 Hz) [61]. This limits the number of distinguishable frequencies for vibrotactile stimuli. Hence, some approaches combine vibration frequency with spatial location (point of feedback on the skin) to improve pitch discrimination. Furthermore, time is mainly presented through instantaneous events. The representation of instruments has not been the main focus of music-to-vibrotactile sensory substitution strategies. Nonetheless, Karam et al. have found, that an additional mapping of instruments conveys more information [28].

The use of vibrotactile feedback as a substitution strategy for auditory feedback can be challenging, since the properties and limitations of auditory and vibrotactile information are different: the ear can perceive frequencies between 20 Hz and 20 kHz, but the skin's perceptual frequency range is limited to 1000 Hz with a peak frequency at 250 Hz [5, 35, 59, 61]. Further, the spatial tactile resolution varies across different body parts. Some body parts, such as hands or lips, have a very high spatial tactile resolution (discrimination of a two point stimuli of less than 10 mm in average), but other body parts, such as calf or back, have a low resolution (larger

Table 1 Overview of visual sensory substitution strategies for music

Work	Focus (music-listening/music-making)	Audio source	Mapping (selected musical elements)			
			Pitch	Loudness	Instrument	Time
Piano roll view [12, 22, 43][a]	Listening	MIDI	Vertical position		Color	Horizontal position
Part motion view [12, 43][a]	Listening	MIDI	Vertical position		Color	Horizontal position
Tonal compass view [12, 43][a]	Listening	MIDI	Angle	Circle's size		Instantaneous
Motion pixels of music [12][a]	Listening	MIDI	Angle		Color, screen position	In-/outwards movements
MusicViz [52][a]	Listening	MIDI	Vertical position	Pipe's size + brightness	Color/shape[b]	Depth position[b]
MOGAT [67][a]	Making	Audio	Vertical position			Instantaneous
Movies from music [41]	Listening	N/A	Color + brightness			Distance from center
Seen music [30][a]	Making	[c]	Color			Instantaneous
Spectrogram [22]	Listening	Audio	Vertical position			Horizontal position
CAMLS for hearing-impaired [65][a]	Making	Audio	Written text, notation			Position inside the notation
Seeing sound [10]	Making	Audio	Angle	Vertical height		Instantaneous

[a]Designed or evaluated with deaf or hard of hearing individuals
[b]Uses a three-dimensional representation
[c]Exact pitch information is retrieved using an external trigger

Table 2 Overview of vibrotactile sensory substitution strategies for music

Work	Focus (music-listening/music-making)	Audio source	Actuator used	Mapping (selected musical elements)			
				Pitch	Loudness	Instrument	Time
MUVIB [31][a]	Listening	Audio	ERM motor		Intensity		Instantaneous
Tactilicious flute display [1, 36]	Listening	Audio	Voice coil	Frequency	Intensity		Instantaneous
Tac-tile sounds [50][a]	Listening + making	Audio	Speaker	Frequency	Intensity		Instantaneous
Emoti-chair (frequency model) [25–27][a]	Listening	Audio	Voice coil	Frequency + spatial location	Intensity		Instantaneous
Emoti-chair (track model) [25–27][a]	Listening	Audio (separated instrument tracks)	Voice coil	Frequency + spatial location relative to instrument	Intensity	Spatial location	Instantaneous
Emoti-chair (control model) [25–27][a]	Listening	Audio	Voice coil	Frequency	Intensity		Instantaneous
Vibrochord [2]	Making	MIDI	Voice coil	Spatial location + frequency	Intensity		Instantaneous
Mobile music touch [21]	Making	MIDI	ERM motor	Spatial location (finger)			Instantaneous

[a]Designed or evaluated with deaf or hard of hearing individuals

than 40 mm in average) [17]. However, these tests have been conducted with small single point actuators. Using larger area of stimulation could take the advantage of the skin's spatial summation and hence, could result in a better discrimination as proposed by Branje et al. [3] and Wyse et al. [64].

3 Music Listening: The Haptic Chair

In this subchapter, we present the Haptic Chair, a music-to-vibrotactile and music-to-visual sensory substitution system for listening. Technical details of the development of a vibrotactile and a visual display are discussed along with an evaluation with profoundly deaf children. The study provides evidences for the Haptic Chair's effectiveness for listening to music and its potential as an extension to speech therapy.

3.1 Motivation

The motivation behind the Haptic Chair was to enhance the experience of listening to music for deaf people. Deafness does not prevent a person from enjoying music. However, the interest displayed by a person with hearing impairment in music, depends on his or her affiliation with the hearing or deaf culture [8]. The Haptic Chair is inspired by Evelyn Glennie, a profoundly deaf musician, who wrote in her hearing essay: "*Hearing is basically a specialized form of touch*" [15]. She argues that sound is basically vibrating air molecules which are picked-up by the ear. However, sometimes the skin also picks-up these air-conducted vibrations, as they are for low frequency sounds. The idea behind the Haptic Chair is to amplify these vibrations and deliver them to different parts of the body. Evelyn Glennie also mentioned that she discriminates sound according to the location along her body where she feels the sound [16]. Palmer developed a theory that describes that low-middle- and high-frequencies can be felt in different parts of the body [48], which is consistent with the review on the tactile modality, carried out by the Army Research Laboratory, USA [45]. This suggests, that the body is able to pick-up and discriminate sound based on the different body parts through vibrations.

3.2 The Haptic Chair

The Haptic Chair consists of a densely laminated wooden chair that is widely available at relatively low cost (Poäng made by IKEA). Contact speakers (SolidDrive SD1 and Nimzy Vibro Max) were attached to four positions of the chair: one under each armrest, one under a rigid, laminated wooden footrest (also

Poäng by IKEA) that was securely fixed to the main chair, and one on the backrest at the level of the lumbar spine. To improve the contact of the hand with the chair, one hand doom at each side was mounted at the appropriate positions to the chair. An amplifier (SD-250 mini amplifier) takes the sound input from a sound source (e.g. mobile phone or computer), amplifies it and distributes it to the four contact speakers. The mechanism of providing a tactile sensation through this wooden structure is quite similar to the common technique used by deaf people, called ‘‘speaker listening’’ where deaf people place their hands or foot directly on an audio speaker. However, the Haptic Chair provides a tactile stimulation to various parts of the body simultaneously in contrast to speaker listening, where only one part of the body is stimulated at any particular instant and not necessarily within an optimal frequency range. A complete sketch of the Haptic Chair is shown in Fig. 1.

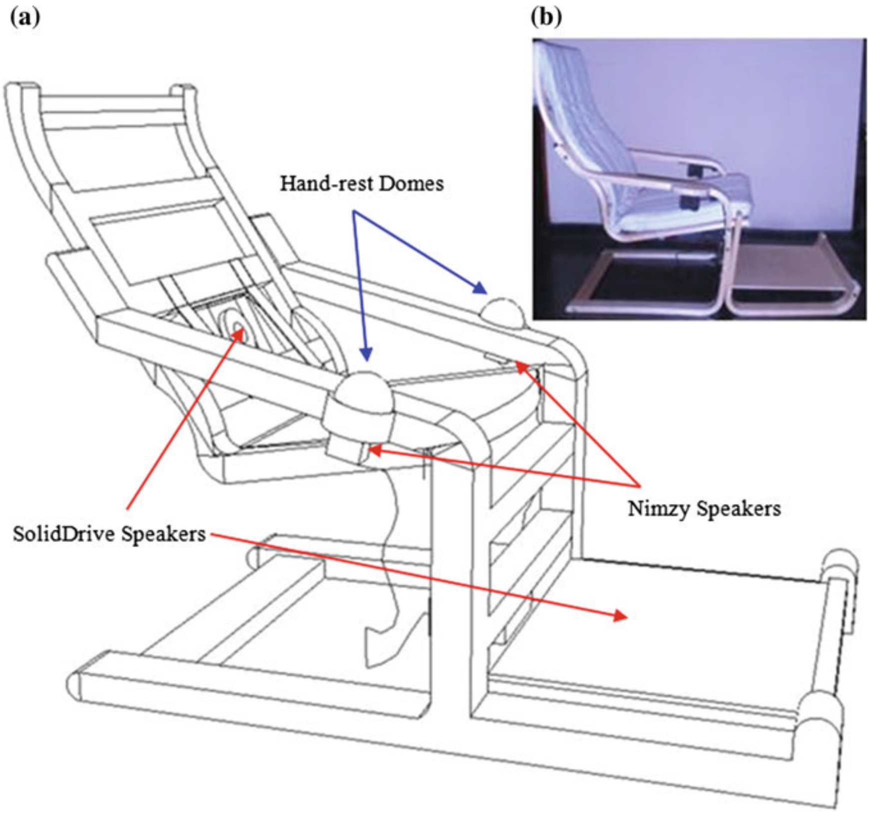

Fig. 1 The Haptic Chair: **a** diagram. **b** photograph

3.3 Visual Display

A visual display was developed to investigate the effect of additional visual feedback. A fundamental decision in designing a music-to-vision display is the type of visualization related to time: piano roll or movie roll (see Fig. 2). The piano roll presentation refers to a display that scrolls from left to right. The axis of scrolling represents time. Musical events occurring at a specific time are displayed in a single column. This enables the user to see the past, current and future of events. However, this does not relate to hearing, where the listener cannot hear future sounds neither past sounds, except from auditory memory. In contrast, the movie roll presentation shows only instantaneous events allowing more freedom of expression. The visual effect for a particular audio feature is visible on screen for as long as that audio feature is audible and fades away into the screen as the audio feature fades. This is closer to how humans hear sound events and was therefore chosen as the visualization type.

A further challenge was the design of the mapping from the auditory domain into visual effects. As a basic shape a sphere was chosen for each note produced by a non-percussive instrument. With the feedback of two deaf musicians (a pianist and a percussionist) the following auditory parameters were mapped to visual parameters changing the sphere's appearance:

- **pitch of a note**: vertical position (high pitch—top, low pitch—bottom) and size (high pitch—small, low pitch—big)
- **loudness**: brightness
- **instrument timbre**: color

Figure 3 shows a screen capture of the visual display but obviously cannot convey the effect of a visual display corresponding to a piece of music: this must be left to the imagination of the reader.

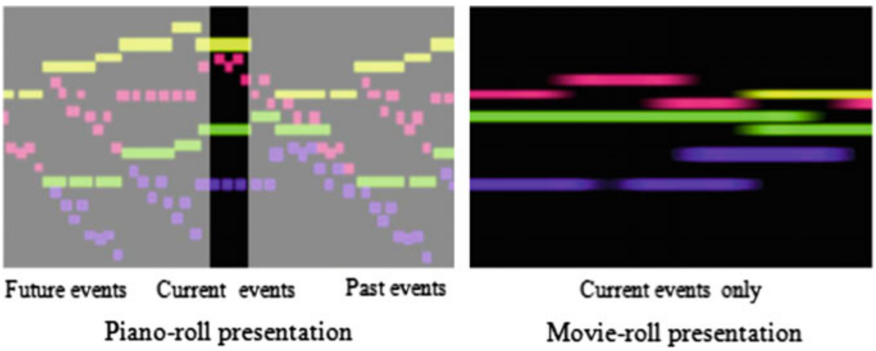

Fig. 2 Examples of piano-roll and movie-roll presentation

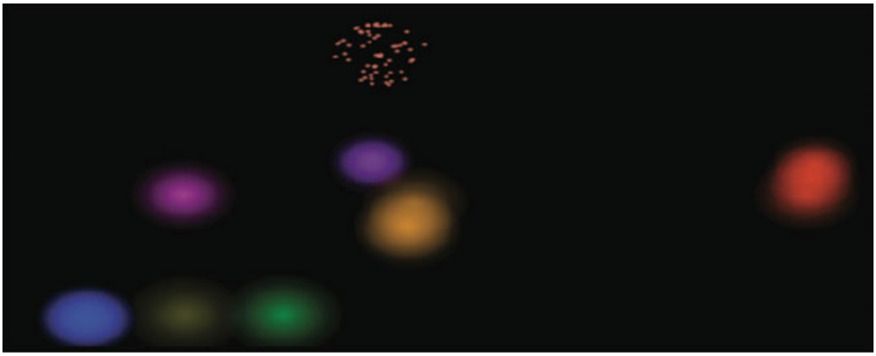

Fig. 3 Screen capture of the visual display with real-time abstract animations corresponding to music

3.4 Evaluation

We conducted a study with 43 hearing-impaired children (28 partially deaf, 15 profoundly deaf—see Fig. 4) ranging from 12 to 20 years to investigate the following questions:

1. Does the visual display enhance their experience?
2. Does the haptic display enhance their experience?
3. Does a combined output (visual and haptic display) enhances their experience?
4. What is an optimal configuration?—Visual display alone, haptic display alone, visual and haptic display together.

To evaluate the experience of a participant, we used Csikszentmihalyi's theory of flow [7]. Csikszentmihalyi describes "being in the flow" as the timelessness, effortlessness, and lack of self-consciousness one experiences. He described ''flow'' as a state in which people are so involved in an activity that nothing else matters: The experience itself is so enjoyable that people will do it even at a high

Fig. 4 Deaf children using the Haptic Chair

cost, for the sheer joy of doing it. To measure the flow, a questionnaire called the Flow State Scale (FSS) with 36 items was used [23].

In the study, the Haptic Chair was used as the haptic display and a 17″ LCD display for the visual effects. In addition, a normal diaphragm speaker system (Creative 5.1 Sound Blast System) was used to play the music. The experiment was a within-subject 4 × 3 factorial design. The two independent variables were music sample (classical, rock, beat only—each was 1 min in length) and the test condition (music only, music + visual display, music + haptic display, music + visual + haptic display). The samples were presented in random order. The task throughout the study was to follow the music on the activated displays.

3.5 Discussion

The FSS score was minimal when only the music was played and the visual and haptic display were turned off. Furthermore, there was no main effect for music genres and the level of deafness as well as no interaction between music genre and test condition. However, there was a main effect between the four test-conditions as shown in Fig. 5. The “music only” condition was significantly smaller than the other 3 conditions ($p < 0.01$). Furthermore, the “music + haptic” as well the “music + visual + haptic” conditions’ scores were significantly higher than the “music + visual” score ($p < 0.01$). When the participants were asked, which combination they preferred most, 54% preferred the “music + haptic” setup, 46% the “music + visual + haptic” setup and no participant one of the other two options. These findings suggest that the haptic display has a high contribution to the enhancement of the music listening experience.

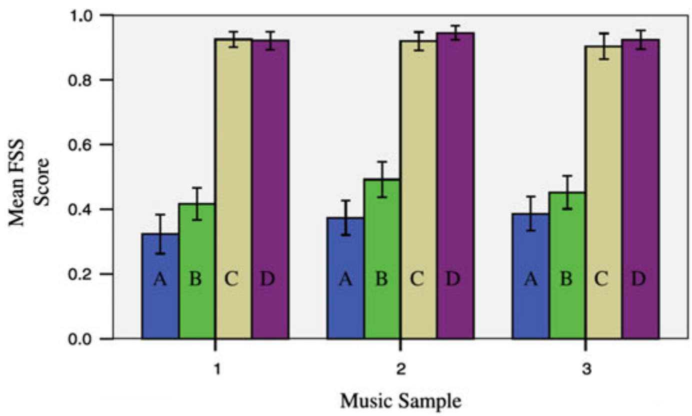

Fig. 5 Overall flow state scale (FSS) score for three music samples under all experimental conditions with error bars showing 95% confident interval (*A*—music alone, *B*—music and visual display, *C*—music and haptic display, *D*—music, visual and haptic display)

The current system, makes no attempt to electronically process speech in any way, but instead delivers the entire input audio stream to each of the separate vibration systems targeting the feet, back, arms and hands. This is not necessarily the optimal strategy for vibrotactile presentation [26–28]. In future work, we will explore the possibility of providing customized (e.g. separated by frequency bands) vibrotactile feedback through different vibration elements to different locations on the body. Moreover, we are focusing on extending the Haptic Chair concept into a wearable or portable device. We hope that these future works will lead to more effective uses of the vibrotactile channel for music as well as communication via speech for the profoundly deaf.

3.6 Extending to Speech Therapy

Prolonged use of single-user Haptic Chair unveiled the potential to be a useful tool in speech therapy—going beyond the original aim of enhancing the pleasure of ‘listening to music’. In a typical speech therapy session at the school, a deaf student and a speech therapist sit in front of a mirror. The student watches the speech therapist’s lip movement in the mirror and tries to mimic those movements. We observed that the students are often able to mimic lip movements, but either they generate no sound or they generate a sound that is very different from the example provided by the therapist. This is not surprising given the lack of auditory feedback. Furthermore, it was also clear that many profoundly deaf students did not enjoy the speech therapy sessions, which is a common problem worldwide.

Almost a century ago, Gault [14] proposed a method of presenting speech signals via a vibrator placed on the skin. This provided further motivation for exploring this kind of vibrotactile feedback for speech therapy and education. The design of the Haptic Chair was extended so that users would be able to sense amplified vibrations produced by their own voice as well as others such as teachers or therapists. With this modification, we observed immediate effects on the awareness the profoundly deaf users had and whether they were matching the sound production pattern accompanying the lip movements they could see.

We conducted a 12-week long pilot study and a 24-week long follow-up study to evaluate the effectiveness of the Haptic Chair in speech therapy sessions for profoundly deaf students (see Figs. 6 and 7). Our results suggest that this kind of display can, to some extent, function as an effective substitute for the traditional ‘Tadoma’ [54] method of speech instruction wherein students touch the throat or lips of their teachers. It would also open up a range of approaches for speech therapy aids that are independent of or complementary to the physical presence of a human therapist.

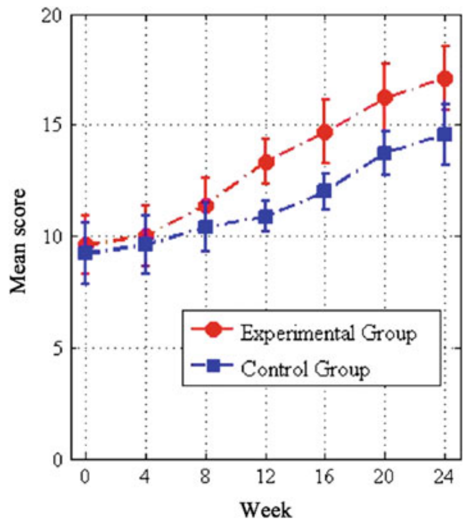

Fig. 6 Follow-up study: mean score (average number of words recognized by the **speech therapist**) after every 4-weeks with 95% confidence interval

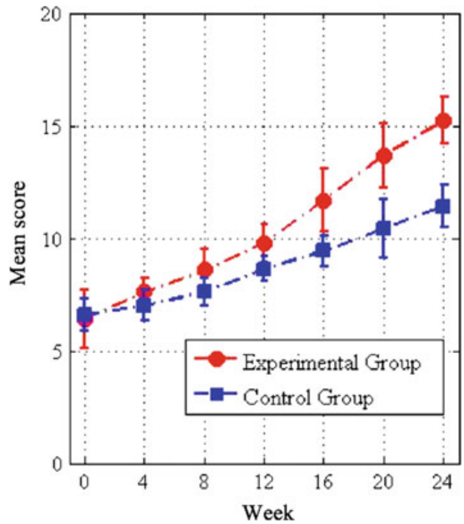

Fig. 7 Follow-up study: mean score (average number of words recognized by the **independent listener**) after every 4-week block with 95% confidence interval

4 Music Making: The VibroBelt

The previous sub-chapter provided a study of enhancing the music listening experience using a visual and a haptic display. In this subchapter, we focus on music making. We introduce the VibroBelt, a music-to-vibrotactile sensory substitution system to support deaf people in music making. We first conducted an observational study to understand the needs and requirements for music making systems for profoundly deaf children. We present the implementation of a wearable haptic display for exploring ways of scaffolding the music making process for deaf people and provide initial user reactions.

4.1 Motivation

Music making differs from music listening as it is "*more powerful […], transformative […], and a way to express yourself*" [34]. Furthermore, it depends on a "*strong coupling of perception and action mediated by sensory, motor and multimodal brain regions*" [56, 66]. Hence, music making requires a closed feedback loop (play-listen-evaluate-correct-play) that allows the control of musical elements, such as pitch, melody and rhythm. This can be challenging for people with hearing impairments for musical elements that mainly depend on tonal content, such as pitch and melody. These elements are almost impossible for them to perceive and tonal instruments, such as the piano and guitar, are therefore harder to play.

4.2 Need and Requirement Analysis

We conducted an observational study with 7 congenitally profoundly deaf children aging from 12 to 15 years. The aim of this study was to understand needs and requirements for music making. In particular, we were interested in the following questions:

1. How do profoundly deaf children interact with musical instruments?
2. Which musical elements do profoundly deaf children vary?
3. Which strategies do profoundly deaf children employ to compensate for their hearing loss?

The study had two parts: (A) an interview and (B) a musical activity. The latter consisted of two phases: (1) instrument exploration and (2) musical expression. The semi-structured interview focused on the children's prior experience with music and musical instruments. Following that, each child selected one instrument out of 5 for the musical activity. We brought 3 non-tonal instruments (Shakers, Thammettama Drum, and Bass Drum) as well as 2 tonal instruments (Guitar and Violin) as shown in Fig. 8. In the exploration phase, each child could familiarize himself or herself with the instrument. Initially, no instructions were given; but instructions were given if a child did not know how to interact with the instrument. In the musical expression phase, we asked the children to use instruments to express familiar

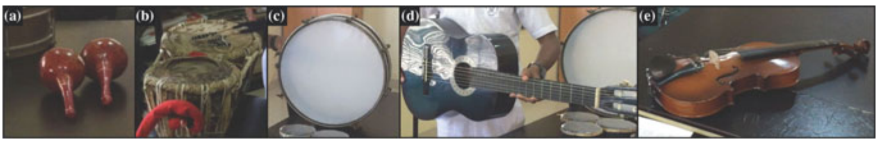

Fig. 8 The instruments we used: **a** shakers, **b** thammettama drum, **c** bass drum, **d** guitar and **e** violin

phenomena: (1) happiness and sadness, (2) a running rabbit and a crawling turtle and (3) a bird flying up to the sky and rain falling down to the ground.

The duration of each session was about 45 min. Each child tried 2–3 different instruments. The musical activity was video recorded for further analysis. Furthermore, 3 researchers observed and took written notes throughout the whole study. The data was coded iteratively after each session, resulting in 6 main categories.

4.2.1 Prior Experience

All children reported to have experience with non-tonal instruments, such as Cymbal, Thammettama Drum and Bass Drum. Furthermore, all children stated to enjoy playing those instruments. However, the children could not specifically say, what they like about playing the instruments: *"[I] feel happy when playing" (P1), "[It] makes [me] not sad, when [I am] playing" (P2).*

4.2.2 Challenges of Playing Instruments

Challenges were extracted through observations during the musical activity part. Some children reported to have doubts whether they played the instrument correctly: *"[I don't] know, if [I] did it correctly" (P5), others had no doubts: "[I] knew, [I] did it" (P6).* It seems, that some of the children care about what others, especially hearing people, may hear and are aware that they perceive more than them. On the other hand, some of the children focus on their own experience. As long as they enjoy this experience, there is no challenge.

4.2.3 Feedback Strategies

The deaf children showed several strategies to compensate for their hearing loss. We found two main visual feedback strategies: (1) focusing (see Fig. 9a) and (2) looking at the audience. A very strong feedback strategy employed by most of the children is to focus on the instrument and the area where the action happens, e.g. bow touches the strings for violin, fingers touching the strings on a guitar. This strategy was also reflected by the participants' feedback: *"[I am] seeing what [I am] doing" (P4).* In addition, P4 also uses the audience's reaction to verify if she is performing correctly: *"Other people's reaction to what [I] do confirms, what [I am] doing is right".*

A further strategy to get feedback from the instrument is to perceive its natural tactile feedback. We expected this to be a main strategy for them. However, only P2 mentioned to feel the Violin in his left arm and P6 said *"[I don't] know [where I felt*

Fig. 9 Pictures from the observational study: **a** participant is visually focused on the instrument, **b** participant replies to questions and **c** participant imitates finger movements on the guitar's neck while visually focusing on his action

the sound].” Furthermore, they used the feedback of their own motor movement to verify if they perform properly: *“[I] felt the [faster] movement of my hand” (P6).*

4.2.4 Feedback Interpretation

During the sessions the children often referred to hearing (as shown in Fig. 9b): *“[I] hear, but [I don't] know what [I] hear” (P1).* Even when we specifically asked, whether they *heard* or *felt* something on the skin, they referred to hearing: *“[I] didn't feel something in [my] hand, but [I] heard something” (P7).* Furthermore, P7 mentioned to hear vibrations: *“The vibrations of the [guitar's] string, that's what [I] heard”*. Based on these comments, we assume, that they refer to hearing as the result of processed visual and tactile feedback.

4.2.5 Playing Strategies

During their play, we observed two main playing strategies: (1) counting and (2) mimicking (see Fig. 9c). We observed, that the children quickly converged to a regular rhythm and did not vary any musical elements from that point onwards. To keep a steady beat they counted: *“[I] was counting: 3 and 1” (P1).* Moreover, we asked them to play without counting and saw that some children struggled. However, we also observed that they finally converged again to a different counting pattern. Another strategy we saw was mimicking. When we observed that they used their fingers on the Violin's or Guitar's neck, they said: *“[I saw] other people doing [it]” (P3), “[I] used [my] fingers, because [I] saw it on TV” (P2).* However, it would be interesting to see, if the strategies of play would change or further ones would arise when additional feedback is provided.

4.2.6 Musical Interpretation

Music making offers the possibility for self-expression. We were interested which musical elements profoundly deaf children can vary to express familiar phenomena.

Thus, the musical expression task gave us insights in the children's ability of varying musical elements. As an initial step, we focused on 3 different musical elements: Tempo, Loudness and Pitch. Happy and sad was mainly expressed through tempo and loudness. This was also the intent of the participants as they stated: *"Happy louder, sad softer" (P4)*. However, for P2 it was the opposite way when he was playing the guitar: *"When happy, [I] slowly play the guitar. When sad, [I] played fastly."* While most participants could exactly say what they changed in their play to express happiness or sadness, P2 and P7 applied another strategy: *"When [I] played, [I] imagined to feel sad" (P2), "For happiness [I] thought on [my] mother and played something" (P7).*

Since we saw only tempo and loudness variations for the interpretation of happy and sad for P1–P4, we introduced two new phenomena with clear contrast for P5–P7. The interpretation of a running rabbit and a crawling turtle were aiming for tempo variations only. The participants expressed the rabbit as fast throughout the experiment while the turtle was expressed as slow. This was also reflected by the participants' comments: *"[I will] play fast and slow" (P6)*. The interpretation of the picture of a bird flying up to the sky and rain falling down from the clouds were aiming for tonal variations. However, all participants expressed those pictures with tempo variations. For the bird the participants mostly started slow and got faster in tempo: *"Bird starts slow and accelerates [as it] goes up" (P5)*. For the rain, it was mostly the opposite way. However, P5 interpreted rain falling down as slow, then getting faster and becoming slow again. She commented that, *"Rain comes down and slowly floats away"*.

4.3 Opportunities for Scaffolding Music Making

4.3.1 Tonal Variations

Profoundly deaf children have the ability to express familiar phenomena with instruments as we reported. However, their dimension of expression was limited to tempo and loudness. We did not see any tonal variations even on tonal instruments throughout the whole study. This could be due to two main reasons: (1) they do not know that tonal variation exists since they are deaf or (2) they know tonal variation exists, but they do not know how to apply it on the instrument. We believe it is mainly due to the first reason; for example, we saw no effort in changing squeaking sounds that P1, P2 and P3 accidentally produced with the violin. Nonetheless, it seems that improving the feedback loop for tonal feedback, such as pitch or melody, has a lot of potential to enhance their music making experience.

4.3.2 Visual Feedback

Visually focusing on the area of action is a strong strategy to receive feedback from the instrument. Visual feedback as a sensory substitution strategy can interfere with or complement their current strategy. We speculate that visuals on a screen, as it has been done in prior work for music listening (e.g. [12, 22, 52]), interferes with their focusing strategy. However, enhancing the area of action with additional feedback (e.g. lighting up the keys of a keyboard as in [39]) could complement their focusing strategy. In summary, it is important to minimize attention switching.

4.3.3 Vibrotactile Feedback

Prior work has shown, that vibrotactile feedback is an effective channel for music making [15, 40, 50]. In our study, we did not see our participants relying much on that channel. However, we think that vibrotactile feedback is still an important channel for music making, since previous studies [29, 57] found that some deaf people process tactile sensations in parts of the brain that are associated with hearing in hearing people. Furthermore, as discussed in the previous subchapter, the haptic display of the Haptic Chair has a high contribution to the music listening experience at least.

4.3.4 Other Considerations

Music making requires free limb movement. Since most instruments are played with hands or feet they should not be restricted in any way. Using limbs for the perception of feedback, such as vibrotactile feedback on the fingertips, could be distracting and disrupting the music making experience. Furthermore, music making assistive technology should be comfortable, since music making is an activity that can range from minutes to hours.

4.4 The VibroBelt

Based on prior work regarding music making for deaf people [30, 65, 67] and the results of our observational study, we decided to focus on conveying tonal information. To avoid interference with the children's visual focusing strategy, we decided to use a music-to-vibrotactile sensory substitution strategy. We developed a wearable vibrotactile belt (see Fig. 10) that provides vibrations to the human's back. This allows free limb movement and a comfortable use over a longer period of time. Though, the back's sensitivity is not that high, it provides a large surface allowing us to make use of spatially-encoded information. The VibroBelt consists of 8 light weighted coin vibrator motors (ERM motors—Model 310-101 from

Fig. 10 Participant wearing the VibroBelt. The prototype consists of 8 stripes with attached vibrator motors

Precision Microdrive). Each motor is attached to a 200 × 16 × 2 mm acrylic stripe to enhance vibrations and to allow spatial summation by the skin. The motors are connected via a 1 m long cable to the VibroBelt-Controller, consisting of a multi driver board (DRV2605L Multi-Driver Board from Texas Instruments) and an Arduino Mini Pro (3.3 V). The motor-stripes were attached to a commercially available belly-belt in a horizontal arrangement with a distance of 20 mm between two stripes. We connected the VibroBelt with a keyboard (Yamaha SY22 MIDI-keyboard with semi-weighted keys) to understand if vibrotactile feedback allows profoundly deaf children to make tonal variations. An overview of the system is shown in Fig. 11.

4.5 Evaluation

We conducted 3 user sessions with 4 profoundly deaf children to investigate whether vibrotactile feedback has the potential to scaffold the music making process. In particular, we were interested whether the VibroBelt supports

- discrimination of tones
- identification of tones and
- reproduction of tone sequences.

4.5.1 Setup

We connected the VibroBelt to a keyboard and used it as an initial prototype. Since the children had no experience with a keyboard so far, we only used 8 white keys (C4–C5) to simplify the tasks. Furthermore, we implemented three music-to-vibrotactile mappings:

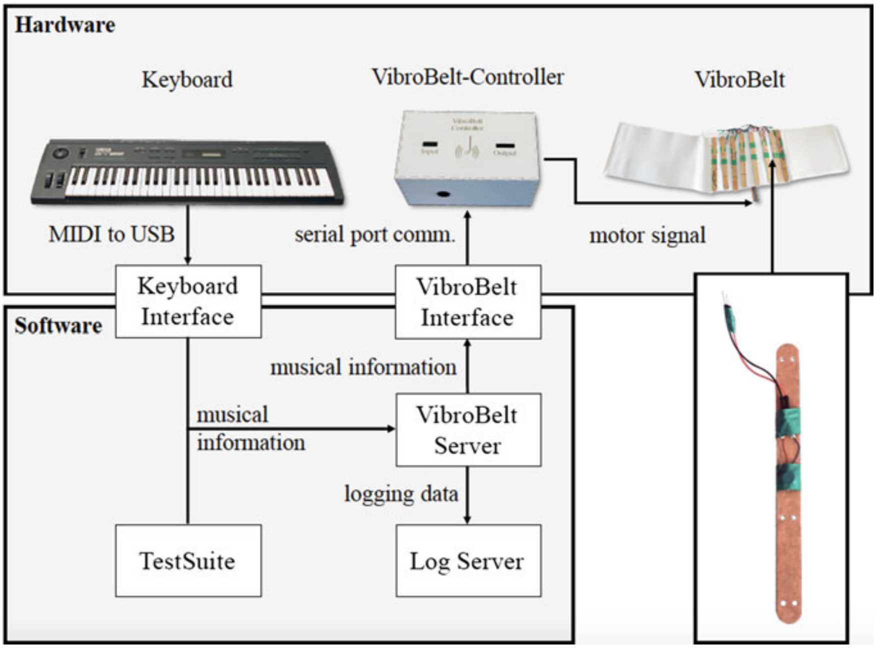

Fig. 11 The VibroBelt system

- Mapping A: Inspired by the Emoti-Chair [25, 28], each of the 8 keys is spatially mapped to one of the 8 motors on the VibroBelt.
- Mapping B: This mapping activates all motors at the same time with a "tapping"-pattern related to the key's representative frequency.
- Mapping C: Inspired by David Eagleman's work [47], this mapping uses left-to-right moving spatiotemporal patterns related to the key's representative frequency.

For mapping B and C the key's original frequencies (C4–C5: 261.63–523.25 Hz) were shifted down to a tactile perceivable frequency range (C0–C1: 16.35–32.70 Hz).

4.5.2 Stimuli and Procedure

User Session 1—Tone Discrimination: Two tones (each 1000 ms in duration) with a break of 1000 ms were presented through the VibroBelt to the participant's back. The stimuli set consisted of 8 same-tone pairs (e.g. C4 and C4) and 7 adjacent-tone pairs (e.g. C4 and D4). Each pair was tested 3 times and the order of tone-pairs was randomized. Each stimulus was played from a computer and no visual cues were available to the participant. After the participant perceived a tone-pair, he or she had to decide whether the two tones were the same or different. Their response was recorded and the next tone-pair was played. For each mapping the whole set was played before moving to the next mapping. The order of the mappings within a participant was randomized.

User Session 2—Tone Identification: The stimuli set consisted of 8 tones (C4–C5). Each tone was played for a period of 1000 ms. The order of the tones was randomized. Throughout the whole session mapping A was used. The stimulus was played from the computer and no visual cues were given. Before a session started, the participant had time to explore the keyboard wearing the VibroBelt. After the participant perceived a tone, he or she tried to find the tone on the keyboard. The participant reported when he or she had found the right tone and the next tone was played. The participant could try as long as he or she wanted, to find the right tone and could ask the experimenter to play the tone again.

User Session 3—Reproduction of Tone Sequences: Short tone sequences (between 4 and 8 tones) were presented to the participants. The participant was asked to find and repeat the sequence on the keyboard. To ease the process of reproduction, the first tone of all sequences was C4 and was marked on the keyboard. The stimulus was presented from the computer without any visual cues. Mapping A was used throughout the whole session. The session started with 4 tone sequences. The participant was given unlimited time to figure out the sequence on the keyboard and could ask the experimenter to play the sequence again. After the participant indicated that he or she had found the sequence, he or she was asked to play the sequence again. The response (including the exploration) was recorded on a computer. The same procedure was repeated for 5-, 6-, 7-, and 8-tone sequences. If the task became too difficult, the participant had the option to drop out.

4.5.3 Results

User Session 1—Tone Discrimination: We found that participants performed above chance for mapping A, but around chance for mapping B and C (see Fig. 12). To get deeper insights in the performance of mapping B and C, a confusion table was created. It revealed that 79% of all responses were *"same"* for mapping C indicating that participants perceived most tone pairs as same, independently of a same- or different-tone-pair stimulus. Based on these result we used mapping A for the following sessions, since these require the ability to discriminate.

User Session 2—Tone Identification: We observed, that the participants were able to find the right key in at least 50% of the trials on average (see Fig. 13). Further analysis revealed that if a participant selected a wrong key, he or she would mainly be one key above or below the correct key (93 out of 96 trials). There were 2 instances of selecting a wrong key that was 2 keys apart and 1 instance of selecting a wrong key that was 3 keys apart from the correct key. Even the first guess was observed to be quite close to the correct key.

User Session 3—Reproduction of Tone Sequences: This task was difficult for some participants. Only one participant completed all tone sequences. We analyzed

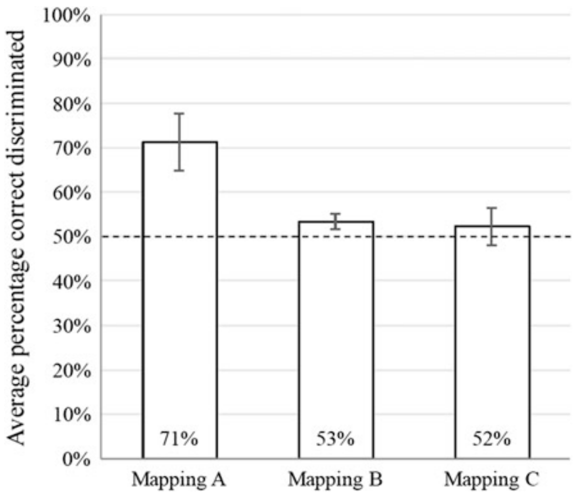

Fig. 12 The average percentage of correctly discriminated tone-pairs across 4 participants (95% confidence interval)

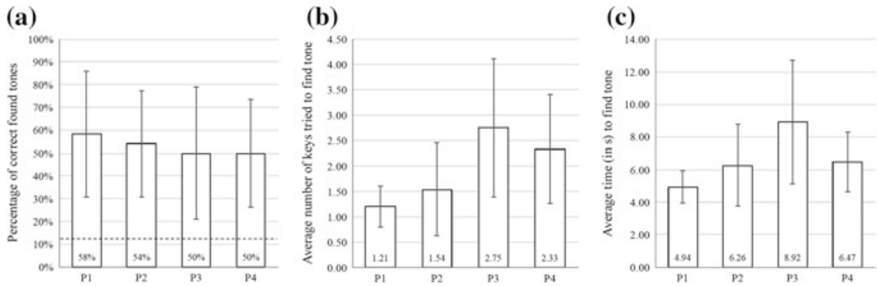

Fig. 13 Tone identification test: **a** percentage of correct identified tones per participant, **b** average number of keys pressed and **c** time needed to find a key (The *dotted line* represents the chance level to hit the right tone)

the recorded melodies of the participants and compared them to the actual presented melodies. Even for hearing people, finding the exact tones of a melody might be difficult. However, getting the contour of a melody (*up* and *down*) right should be possible. Exact tone-hits ranged from 35 to 70%. Regarding identifying the contour of a melody, participants were able to achieve 60–85% of accuracy. This is also in accordance with our second session (tone identification), where exact hits were around 50% and wrong keys mainly one key apart.

4.5.4 Discussion

Mapping A performed better compared to mapping B and C and allowed the children to determine a given key quite accurately. This could be due to the fact that the haptic stimulation had the same spatial arrangement as the keys on the keyboard. In addition, the vibrotactile feedback was perceived as positive by the participants: "[I like] the vibrations" (P2), "When [I am] playing, it vibrates. That is good" (P4). Once the participants got familiar with the instrument, we asked them to interpret the familiar phenomena from the contextual enquiry: (1) happy and sad, (2) a running rabbit and a crawling turtle and (3) a bird flying up to the sky and rain falling down from the clouds. P1 and P4 only varied tempo similar to what they did in first study. In contrast, P2 and P3 used multiple keys simultaneously to express happiness and the running rabbit and only one key at a time for sadness and the crawling turtle. This change in their interpretation could be a first indicator for the effect of scaffolding via vibrotactile feedback. Furthermore, we also observed the visual focusing strategy throughout all participants and all tasks.

4.6 Limitations of the Current System

The motors we used have a lag time (time until the vibrations can be felt) of 47 ms and a rise time (time until the motor reaches half of its maximum intensity) of 91 ms. This limits the range of "tapping"-frequencies that can be presented. The frequency range we choose to operate on (16.35–32.7 Hz) was representable due to summation of the motor's speed. However, this results in a lower intensity contrast. This could be one reason why mapping B and C performed at chance. We are building a second prototype with new motors (Model 307-103 from Precision Microdrive), which have a lag time of 8 ms and rise time of 28 ms. Furthermore, these motors have a higher maximum intensity of 7G compared to the old motors (1.34G). This should improve the vibrotactile contrast.

We aim to investigate new music-to-vibrotactile mappings that are more closely related to music, such as including harmonics or using audio compressed information to mitigate potential cognitive overload. Moreover, other body sites, such as the ear or shoulder, could be also a good place for vibrotactile pitch feedback. Evelyn Glennie mentioned in her Hearing Essay [15] that she discriminates tones via the body sites or organs where she can feel the vibrations most.

5 Conclusion and Outlook

In this chapter, we presented two assistive augmentation approaches for deaf people to experience music. These two systems are one step towards assistive music making augmentation systems. The Haptic Chair uses a vibrotactile and a visual display to enhance the music listening experience and found that the vibrotactile display has a high contribution towards this experience. The VibroBelt uses a wearable vibrotactile display to explore ways of scaffolding the music making process. Both approaches showed the importance of vibrotactile feedback as it provided an intuitive understanding of music for profoundly deaf children.

As discussed in the related work, there are several sensory substitution strategies for the deaf for music listening as well as music making. These approaches focus either on visual or vibrotactile feedback. We also pointed out, that pitch representation in visual and vibrotactile feedback can lead to challenges. Ambiguous visual representations (such as color for pitch and instruments) or the limited number of distinguishable vibrotactile frequencies limits the amount of information conveyed via these channels. A multi-modal assistive augmentation system, embodying both, visual and vibrotactile feedback, could improve the perception of musical elements and has the potential to enhance music listening and improve music making activities.

However, it is important to note that deafness occurs in very different varieties (e.g. unilateral/bilateral, level of deafness, congenital/deafened). Hence, one generalizable solution for music listening or music making cannot be expected. The same has been found by Shinohara and Tenenberg [58] for the design of assistive augmentation systems for blind people. The current approaches for music listening and music making, even developed with hearing impaired users, provide mainly one fixed mapping for every user. We think it is important to design assistive augmentation system that can be calibrated and customized by the user to allow him or her to explore sound in general and music in particular. A deafened user with severe hearing loss, might use vibration feedback differently than a congenital profoundly deaf user. Catering for individual requirements could be the next step towards building assistive music augmentation system for the deaf community.

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