Multisensory Integration Design in Music for Cochlear Implant Users

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MULTISENSORY INTEGRATION DESIGN IN MUSIC FOR COCHLEAR IMPLANT USERS

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ABSTRACT

Cochlear implant (CI) users experience several challenges when listening to music. However, their hearing abilities are greatly diverse and their musical experiences may significantly vary from each other. In this research, we investigate this diversity in CI users' musical experience, preferences, and practices. We integrate multisensory feedback into their listening experiences to support the perception of specific musical features and elements. Three installations are implemented, each exploring different sensory modalities assisting or supporting CI users' listening experience. We study these installations throughout semi-structured and exploratory workshops with participants. We report the results of our process-oriented assessment of CI users' experience with music. Because the CI community is a minority participant group in music, musical instrument design frameworks and practices vary from those of hearing cultures. We share guidelines for designing multisensory integration that derived from our studies with individual CI users and specifically aimed to enrich their experiences.

1. INTRODUCTION

While cochlear implants (CI) have achieved a high level of complexity in terms of hardware and ergonomics, training and rehabilitation programs for cochlear implant users are still lacking. This technology is quite advanced for facilitating speech perception, but music appreciation and rendering prove to be underwhelming. Specifically, most CI users report the inability to properly recognize the timbre and pitch of musical instruments, or have issues of sound localization [1, 2]. Additionally, they state to struggle with segregating the individual instruments in multi-instrument mixing [3]. In this paper, we describe a participatory design approach to designing novel technologies to help hearing impaired users' experience and appreciate music.

The hearing abilities, profiles, and perceptions significantly vary among people experiencing hearing impairments. This diversity is even wider among cochlear implant (CI) users due to "age, cognitive processing residual hearing, hearing aid use, and musical training" [4]. When approaching musical experience design for CI users, the assessment and evaluation might need to be process-oriented and individual-specific. Over the course of explorative workshops with CI users, we developed design practices and guidelines for integrating multisensory modalities to enrich their experiences with music. Our motivation derives from providing them with tools to better understand and enjoy musical features that many participant report difficulties.

2. RELATED WORK

2.1 Accessible and Inclusive Design in Music

When designing accessible digital musical instruments (ADMIs) or accessible music technologies (AMTs), researchers differently approach this design and collaboration / participation process, ranging from participatory approaches to performance and improvisation.

Schroeder and Lucas discuss the process and evaluation of bespoke design approach to accessible music technologies [5]. The authors describe how bespoke designs are vital to provide access for disabled artist to music making. Lucas et al. investigate the evaluation methods for bespoke designs for music and provide their observation on assessing these designs for future ADMI designs [6]. Samuels and Schroeder study improvisation possibilities among performers of different background and abilities for increased inclusion [7] and emphasize the performance aspect in accessible and inclusive design for music.

Dickens et al. practice participatory methods to investigate real life musical interactions for people with complex disabilities and to explore potentials of embodied interactions with gesture-based technology [8]. Another participatory approach by Marti and Recupero [9] focuses on design of smart jewels beyond functionality for Deaf and Hard of Hearing (D/HoH) people with hearing aids. Similar participatory practices and their implications for rehabilitation are explored by accessibility researchers [10]; however their application to musical experience design, specifically for Deaf and Hard of Hearing participants are significantly limited. Like participatory design with D/HoH, community-engaged research with focus on music and hearing impairments is even more limited in this field. Gosine et al. discuss the importance of community building through inclusive music making and its benefits to disabled people through music theraphy [11]. They created collaboration possibilities among persons with physical disabilities and local community musicians following a workshop format.

Frid highlights that the majority of ADMIs focus on addressing users' complex needs in terms of physical and cognitive disabilities, rather than users' experience of music who live with vision and hearing impairments [12]. By 2019, only 6% of ADMIs focused on hearing impairments, even less studied specific cases of cochlear implant use and music.

2.2 Cochlear Implant Use and Music

Cochlear implants have witnessed an impressive evolution in the last 30 years, restoring hearing to more than half a million profoundly deaf people. Their success is usually measured through speech recognition tests. Common implant systems achieve 50% - 60% accuracy after 24 month of use when tested on monosyllabic words, and close to 100% on sentences [13]. Some patients achieve spectacularly high results providing proof of what is possible with a neuroimplant in an otherwise totally deaf cochlea. Variability is high though, with standard deviations ranging from about 10% to 30%, for various studies, but results are improving, especially in patients using bilateral implants [13].

The CIs available today still have significant limitations, offering a severely impaired pitch and timbre perception. Another known limitation is the difficulty users have when presented competing sounds; CI users struggle to discriminate musical events when multiple instruments are playing, or long reverberations are present [14, 15]. Furthermore, there is a general weak representation of the fundamental frequencies (F0) for complex sounds, with difference limens ten times lower than hearing without no impairments, even when signals are below that of the CI pitch saturation limit (300Hz) [13]. As a result of these cumulative factors, the evaluation of music experience is not included as a measurement of success for the implants, as the general music experience for CI users is poor.

2.3 Multisensory Integration in Music

At the core of this project lies the principle of multisensory integration that explains how humans form coherent experiences by merging information from multiple senses [16]. For this integration to occur, the only requirement is that the stimuli are temporally overlapping; this will produce a perceptual enhancement that is strongest for the stimuli which are least effective [16].

In the specific case of auditory-tactile stimuli, recent studies demonstrate that multisensory integration can in fact occur at very early stages of cognition, resulting in supra-additive integration of touch and hearing [17–19]. This is especially useful for CI users that are shown to be better multisensory integrators []. Furthermore, research within auditory-tactile interactions has shown that tactile stimulus can influence auditory stimulus perception when presented in unison [20, 21].

Multisensory integration has been exploited extensively in previous research focusing on tactile augmentation of music; in 2009 Karam et. al. drew inspiration from previous sensory substitution vocoders and aimed to increase the audio-tactile resolution through the skin [22]. Their project resulted in a chair that provided 4 pairs of voice coil actuators arranged in an array along the back rest, following the cochlea metaphor - lower frequencies are reproduced lower than the higher ones. Each one of the actuators could reproduce one octave of the piano, from 27.5Hz to 4186 Hz [22]. They evaluated their design with respect to emotional reaction and concluded that participants enjoy the two proposed techniques more than the audio signal alone. Further upgrades to the chair resulted in a a wide spectrum of feedback, mostly positive [23].

Another chair installation was designed by Nanayakkara et al. with the help of the hearing impaired community [24]. Initially, their haptic chair had two contact speakers as haptic transducers placed under the armrest that was upgraded later with actuators directed at the lower back area and a footrest, providing a *whole body stimulation* [25]. The actuators were reproducing an amplified version of the auditory stimuli, and was always used in conjunction with sound. The chair was used successfully in long term studies (12-24 weeks) to enhance the music listening experience, as well as speech therapy for deaf children, and underlying the importance of training when users are expected to adapt a novel haptic system [25].

In 2015 a collaboration between the Deaf arts charity organization *Incloodu* and Queen Mary University resulted in an installation in the shape of an armchair and a sofa [26]. The devices used voice coil actuators placed in the backrests and armrests, and a subPac [1] under the seat. The auditory signals were spatialized from low to high areas of the backrest, and a noisy component correlated to timber was reproduced through the armrests. The structure was designed by a profoundly deaf architect, specialized in developing interiors for hard-of-hearing customers [26]. Their evaluation shows that the type of music has a great impact on the experience, with highly rhythmic music eliciting more positive reactions than music where harmonic motion was most important [26]. When music with less transients was presented, users seemed to observe the therapeutic value of vibrations. This emphasizes an important aspect of vibrotactile musical devices: they should be designed in manner that places the musical context in the spotlight.

3. RESEARCH APPROACH

The goal of this study was to (1) invite CI users into the early stages of designing novel audio-tactile displays by introducing several multisensory installations and (2) to understand the limitations of presented configurations. We performed an exploratory study, collected by a triangulation of methods: think aloud protocol, observations, and enter and exit interviews [27].

3.1 Workshop Format

Each meeting followed a predefined structure and lasted 60 - 120 minutes; for the entire duration there was one of the authors taking notes and recording the conversations. Before the meeting, the participants were requested to fill an

[1] https://subpac.com/

online survey, focusing on demographics and their past and current music listening habits. The answers from this survey formed the foundation for an semi-structured interview that was conducted before any installations were introduced; the focus was on exploring further the music engagement habits. Subsequently, the participants were guided to explore and experiment different installations described in section 4, and concluded with a shorter exit interview, summing up their feedback. Throughout the whole meeting, the participants were in contact with at least one of the authors, and were encouraged to *think aloud*.

3.2 Participants

Three participants voluntarily participated in the study, invited via open invitation on the national CI user's Facebook [2] group or via email.

Participant 1 (P1) is 52F and started losing her hearing at the age of 3, currently with no residual hearing. In 2017, she got bi-implanted with Kanso CI, experiencing a positive transition from hearing aid to cochlear implants. She likes *Fleetwood Mac*, *Dolly Parton* or *The Beatles*, but dislikes techno, classical music and heavy metal. She has background in piano and dancing (in African and Danish dances). She sings in a choir but is challenged in distinguishing and synchronizing with accompaniment, misidentifying when to start singing. She reported using a water bottle or glass in her hands to feel the vibrations in concerts.

Participant 2 (P2) is 69M with genetic hearing disability, uses a cochlear implant in his left ear, and a hearing aid in his right ear. He has experience from a musician family, in singing in a church choir, and performing competitive dancing. He likes opera, waltzes, church and classical music, and dislikes rock. More recently, he rarely listens to music. When listening to familiar music, he expresses: *"[...]my memory was another [...] I have this sort of feeling of something is in another way."*

Participant 3 (P3) is 41M. He uses a Nucleus Cochlear implant in the right ear, and near deaf in the left ear, with hearing threshold at +95dB. He has been using hearing aids since the age of 3, frequently upgrading them to higher amplification ones. When listening, he can identify when music is playing, the sex of the singer, and the instrument if the music is performed live on stage. He regularly attends to festivals, mostly for the social reasons. Lately, he enjoys listening to music for short periods of time (5 minutes) since after about 10 minutes it becomes exhausting. He mostly likes rock, especially the band *Dizzy Mizz Lizzy*.

4. DESIGN AND IMPLEMENTATIONS

4.1 Installation 1

CI users experience significant difficulties in identifying individual instruments in a musical piece [28]. In this installation, we addressed this issue by creating a multi-channel listening experience. The installation tested CI users' instrument segregation process through reproducing multi-channel recordings in a four channel speaker setup. We encourage the listeners to freely move around the room and hear individual sound sources to compare and contrast the single and multi-instrument mixings.

4.1.1 Setup

The experiment was conducted on campus at Aalborg University Copenhagen, in an anechoic room in order to prevent room reverberation altering or reducing loudspeaker directionality. The setup consisted of four *Dynaudio BM5 MKIII* loudspeakers connected to a laptop through an *Steinberg UR44C* audio interface. Each loudspeaker was fed with a dedicated output from the audio interface with only one instrument. We played multi-track recordings using Reaper - a Digital Audio Workstation (DAW) to route the instruments to independent speakers: (1) drums, (2) bass, (3) vocals, (4) keyboard or guitar alternating.

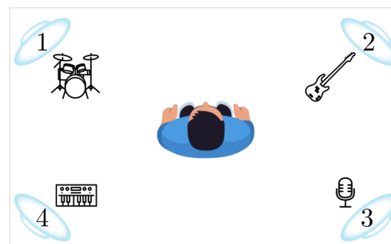

Figure 1. Scheme of installation 1.

For all the three sessions with the participants, no routing changes were applied to maintain consistency between the experiences. The dB level of each channel was set to obtain a balanced mix that allowed a hearing person to perceive all the instruments with perceived equal loudness in the center of the room by the authors. The single recordings were played without any effect such as reverberation or compression to avoid any possible confusion in the listener.

4.1.2 Experience

Once entered the room, we explained briefly what the experience was about and we let the test subject choose which music they preferred between three famous Rock, Soul and Reggae songs. Later, we proceeded setting a proper loudness level that was agreed together with the user. For all the test we set all channels to a *conversation level*.

For the first part of the experiment, we asked the subject to stand in the middle of the room and try to identify which instruments were played and from which loudspeaker they were coming from. After collecting the answers, we asked the user to walk around the room moving close to each loudspeaker to confirm or correct his/her statement about which and where instruments were played. For the second and last part, we let the subject find a sweet-spot in the room where the music sounded best for him/her. During the whole experiment the test subject was free to comment or explain at any moment their thoughts and perception of the experience.

[2] Facebook CI Group

4.2 Installation 2

A design process was undertaken to explore if and how audio-tactile feedback might be integrated into a seating installation to enhance CI users' music listening experience. We focused on providing low-frequency enhancement since CI users experience poor auditory resolution in this range.

We tested two mock-ups with 3 CI users and 3 hearing participants (including the designers). Each mock-up consisted of three components, a seat, a footrest and a hand held device, used both independently and simultaneously. All users accessed to the gain control for each actuator, through a headphone splitter used to feed the same signal to the amplifier for each transducer. Only the first user chose to manipulate the gain balance herself, while the last two provided verbal instructions to the researchers. The audio was played through either a pair of *B&W 800D* speakers for the first user, and a pair of *Mackie SRM450* + *Mackie SRM1550* for the second and third participant. The users had access to the master volume knob that controlled the audio level, as well as the signal feeding the headphone amplifier (used here as a multi-channel signal splitter), thus coupling the auditory and the tactile volume.

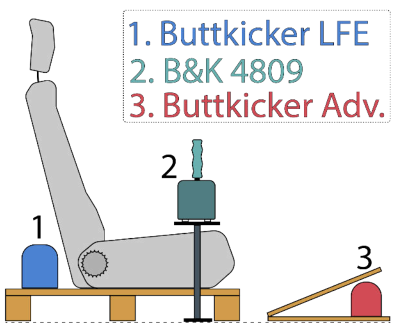

Figure 2. One configuration experienced by all participants

4.2.1 Hardware

Three types of seated installations provided different experiences: The first installation was a tactile car seat actuated by a *Buttkicker* [3] LFE that was initially powered by a *Buttkicker BKA1000* and later StageLine ST600 in bridge mode. The *BKA1000* amplifier was found to limit the higher frequencies. Both the chair and the actuator were bolted onto a wooden EUR-pallet platform, with the actuator behind the seat(see Figure 2). The actuator provided strong enough tactile feedback throughout the entire body, including the headrest. P1 and 3 hearing participants reported that it could easily felt overwhelming with higher gain.

The second and third type of seated experience shifted from a low seating position to a more upright one through a bar stool instead of the car seat, based on P1's feedback that rated the first design overwhelming. We chose the bar stool design since it affords control over the amount of weight the user applies onto, linking to the amount of feedback received. A *Buttkicker Advanced* powered by a *Buttkicker BKA300* actuated this seating. As a much smaller actuator compared to the one from the car seat, this setup required less power. The authors noticed a substantial difference between the frequency responses of the two, with a high frequency emphasis for the setup with *Buttkicker Advanced*.

P2 and P3 experienced different configurations; for P2, the actuator was bolted perpendicular to the seating area, while for P3, the actuator was fixed parallel to the ground on the side of the seating area. The side actuator configuration aimed to conduct more tactile stimuli, as P2 commented on the low intensity of the bar stool (possibly in comparison to the car seat). We observed an unexpected phenomenon in P3's setup that loud transients laterally shook the bar stool, feeling like a small "kick in the back of the chair", potentially due to the loose joints.

The footrest was designed according to H. Dreyfuss measurement recommendations and featured an inclined plane at 22° [29]. In order to have clearance for the actuator underneath the inclined plane, the footrest measured 45cm length and 60cm width. The same *Buttkicker Advanced* + *BKA300* combination was used, as with the bar stool. The transducer was bolted underneath the footrest, perpendicular to the ground (see Figure 2). All participants experienced the same setup.

Two handheld devices were used. A cylindrical handheld grip measuring 204mm in length and 110mm in diameter was fabricated by stacking 51 laser cut slices of 4mm HDF, following design recommendations from H. Dryeyfuss [29]. This grip was was attached to a *Brüel & Kjær(B&K) Type 4809 portable vibration exciter* (see Figure 2). The second interface, VAM (Vibrotactile Actuator for Music), was built around the Tactuator BM1C [4] [30] with an ovoid shape measuring 84mm in width, 58mm in height and 89mm depth. P1 individually tested the cylindrical grip and the VAM in combination with the seat and footrest, but the latter was deemed "not adding much" and abandoned for P2 and P3.

4.2.2 Audio Stimuli

The first audio stimulus, *Peggy Lee*'s *Fever* was presented in every Installation 2 configuration due to its clear instrument separation and the prominence of the female vocal track, matching CI users' appreciation [31]. Firstly, two different signals were sent to the handheld grips in consecutive renditions: the first identical to other actuators' signal and the second filtered to isolate the female vocal range and pitch shifted to one octave lower to skin's sensitivity range [32, 33], only applied to P1's experiment. P2 and P3 heard solo bass improvisation of *Fever* on the double bass or ukulele bass. The performance presented different playing styles (pizzicato, slapping, staccato, etc.), using the full range of the instrument, and experienced in bar stool and car seat setups. The drums accompanied to P3's experiment.

Participants selected extra audio material for their preferred setup. All three preferred the setup in Figure 2. P1 listened to *Fleetwood Mac - Dreams*, P2 *Vienna Philharmonic - An der schönen, blauen Donau* (excerpts), and P3 *Dizzy Mizz Lizzy - Silverflame*.

[3] https://thebuttkicker.com/

[4] http://tactilelabs.com/

4.3 Installation 3

We also studied participants' experience with embodied interactions using movement-based performance and in-air haptics. To simulate this experience, we discussed excerpts from a previous inclusive performance study, Felt Sound, designed for both D/HoH and hearing audience members [34]. Originally, Felt Sound, consisting a digital musical instrument, a performance setting, and a user study, was performed in-person with an 8-subwoofer speaker setup where the participants sat close to or touched the speakers. Due to time and space restrictions and COVID-19 precautions, performance excerpts [5] [6] were individually shared with the participants with two subwoofers enclosing their sitting area and facing the participant. The participants were still encouraged to interact with the speakers and feel the vibrations through touch.

We briefly described Felt Sound's motivation, concept, and performance practice. After providing the participants with its context, we presented its excerpts. Following the performance, we discussed their experience both with Felt Sound and with their own movement and music practices. Presenting a new movement-based musical concept led participants to share their own associations and experiences with movement practice and music.

5. EXPERIENCES AND RESULTS

We audio recorded the discussions with each participant and transcribed them after the study. This chapter will present a summary of these discussion sessions, focusing on their appreciation of the installations and their overall experiences.

5.1 First Participant

P1 listened using 4 vibrotactile devices: car seat, footrest, hand grip, the VAM, in 2 cases (processed and unprocessed signals) as detailed in Section 4.2.1. The audio volume was tied to the overall actuator amplitude. The researchers initially set the individual tactile amplitudes to "perceptually equal" and the listening volume to "comfortably loud", slightly over conversation level.

In the first case (listening to the processed audio), she reported how it was *"fun to feel the vibrations in the entire body"*, re-iterating her experience with the water bottle during concerts (see Section 3.2). She did not understand the mapping of the vocals to the haptic feedback, stating that she could already hear the voice through the speakers, and would not need extra stimuli representing the vocals. Additionally, she only adjusted the volume of the hand grip up several times.

When presented with the second case (listening to the unprocessed audio), she seemed more engaged in the song, grooving with the rhythm and moving to music. Similar to the first case, she experimented with slightly turning up the hand grip, footrest, and seat. When the song was over, she stated that she preferred this listening method over the first case because she can feel the melody in the footrest. She also expressed that listening to the vibrations through the chair setup could sometimes feel overwhelming.

Her perception changed over the course of the experiment. She reported that she could feel the vocals through the hand grip and the bass line (initially she assumes it was a keyboard) through the foot pad and the seat, expressing that it was fun. Although all actuators reproduced the same signal, different haptic experiences where perceived at different locations on the body, that amplified their perception of pitch and instrument type. She answered to whether she would use such a device at a concert as *"I would like to have some help from vibrations"* and explained how she sits very close to the speaker at concerts to get the haptic feedback. Furthermore, she said she would use them if *"it is trusty"*. She less emphasized her experience using the VAM compared to the other haptic listening tools, stating that it was not strong enough. We interpreted her articulations about the VAM as "not strong, relative to other actuators".

After listening to Installation 3, she discussed her experience with music and movement. This installation led her to articulate her movement practice and more embodied experiences with music such as singing. She reported that when she sings in a choir, she experiences the difficulty of identifying the onsets, specifically knowing when to start singing only by listening to the piano. She stated that she would be interested in incorporating gestures to her singing practice to assist her and to support her conductor's assistance for her. Additionally, she expressed that seeing a gesture-based performance was supporting her understanding and enjoyment of music.

5.2 Second Participant

P2 listened to *Ain't No Mountain High Enough* by *Marvin Gaye & Tammi Terrell* with Installation 1. When listening to the piece in the middle, he correctly identified the left and right channels of the instrument sources. However, he guessed the incorrect instruments at each channel. After we asked him to move closer to each speaker, he correctly identified all the instruments, including the male and female voice alternating, not being able to distinguish the lyrics. Similar to the voices, he was able to identify that the guitar and keyboards were playing together in the same channel. He was very unsure of his answers, stating that *"it's always about guessing"*. He always directed his non-implanted ear towards the speakers, making use of his hearing aid.

We lastly asked him to freely select a spot where the music sounds the best for him. He chose a spot in the middle of the 1-2 3-4 speaker pair, closer to the 1-2 speakers, and said *"... I think this must be the ideal (spot) for this kind of music that all of it is, is possible to hear."* After being exposed to all instruments individually he said that they became clearer once he separately heard and identified them. Similarly, when identifying the lyrics, he could follow them once he was told what the chorus lyrics were.

The second installation consisted of the car seat, the bar stool (with vertical actuator) the footrest and the hand grip powered by the *B&K* actuator, with the same volume settings as initially set for P1. The setup was split in two: (1) bar stool with footrest and had hand grip and (2) car seat

[5] https://tinyurl.com/2p8axhwp
[6] https://tinyurl.com/yck63zbz

with footrest and hand grip. We played the same music without any processing for the actuators. After approximately 90 seconds of listening through the first setup, we paused the listening for intermediate discussion and the participant described where he most significantly felt the vibrations: in the thigh, ankles, and up to the elbow. He provided verbose feedback regarding the locations and intensities of perceived vibrations, but limited in terms of perceptual qualities of the stimuli. He could identify the female voice and the deep bass. He also stated he could easily identify the melody.

When we asked him how the music made him feel, he said: *"It was more like a little bit sad music."* and stated how there should be more happiness in it for him to appreciate it. Furthermore, when one of the researchers played the double bass solo, P2 appreciated the live music aspect but he stated that he does not like the bass (as an instrument). He further reported that the installation was more involving but influenced by the choice of music since the music piece was not a style of music he enjoys; thus, becoming and enhancement of something he does not prefer. He requested listening to *An der schönen, blauen Donau* composed by J. Strauss. From the very first chord, the participant said *"... yeah this is much better, much better, yeah and I can feel it supports the music. So, if you like the music, this gives extra power"*. The second setup was experience only with the waltz playing, but the discussion diverted towards commercial value of musical experiences, and no feedback on the second setup was noted. He mentioned that he would not use such system (setup 2) in an concert environment, stating that *"[he] is rather conservative, and he'd prefer a regular chair, unless explicitly invited to try on in a concert hall"*.

His experience with Installation 3 varied from P1's. He less enjoyed the low frequency content of the music. He reported that he could feel the vibrations on his body but this form of listening did not enhance his experience of music. He finally stated that the gestural performance aspect of the music was effective.

5.3 Third Participant

P3 selected to listen to *Don't stop be now* by *Queen* in Installation 1. By standing in the center, he correctly identified the voice and mentioned that there was a lower volume coming from the speaker that was playing the bass line. After getting closer to each speaker, he quickly identified the voice correctly, and mislabeled the piano as guitar. When he approached the speaker playing the bass line, he experienced difficulty in identifying the instrument, asking if it was a tuba. He correctly distinguished the drums.

When we asked him to choose a favorite spot in the room he walked for several minutes, moving between speakers and overall listening area. The chosen spot spot was equally distant from speakers 1 and 2, and much further from speaker 3 and 4 that he was facing. At this spot, he stated that he could hear "a bit of everything", but only mentioning the drums, bass, and vocals. During the post-experiment discussions, we observed that he enjoyed listening to instruments separately since he could make sense of them on his own terms. He further shared his discussions with other people about the sound of bass (at concerts) that *"[he] could never distinguish [the individual instruments] because everything sounds like "mush", but it was a bit easier in this case, after hearing each instrument separately"*.

The second installation followed a similar structure to experiment with P2, only difference being the orientation of the actuator on the bar stool as described in Section 4.2.1. After about 90 seconds (before the second verse), the music was stopped and the participant rapidly mentioned that he mostly felt the hand and the bar stool did not add anything to the experience. When asked, he could not identify the valence of the song. Before resuming the music, all actuators were turned down and we slowly increased their amplitude one by one while we instructed the participant to focus on preference over actuated areas. The results were the same; he preferred the hand grip and the footrest (especially when it was turned up more). He mentioned that it's difficult to identify the mood of the song claiming that on one side it's *"slow and heavy, but the singing (voice) sounds happy"*. For the live ukulele bass performance all actuators were set to initial amplitudes; for feedback, P2 said that he preferred the lower frequencies from the footrest, but when the frequency gets higher, it's better through the hand handle. Additionally, when short and fast notes were played, he reported that it was easier to *"feel what happens"* through the hand grip. Similar to the first case, the bar stool *"did not have much to offer"* in this experience.

Moving to the second setup, the participants mentioned that *"this is much better to have it in the back, this way"* further mentioning that setup 1 felt a bit distant. During this experience, the actuators' volume was manipulated by a researcher leading to the conclusion that it's best when all 3 actuators are perceivable, and that if feels "empty", when the seat is not actuated. After the live bass performance (same as for setup 1), P3 claimed that it's fun to use the setup, but still feels like he is *"missing something"* and that he *"just misses actually being able to enjoy music"*, a fact that was not changed by using the presented setup. Nevertheless, he could *"feel"* the voice more through the hand grip, just as with setup 1. When asked whether he preferred the live performance, or the recorded one, he said that the latter one is nicer because there's more instruments, "more different sounds". This led us to and impromptu drum and bass duo performance with two of the authors, briefly jamming over the bass line from *Fever*. The participant claimed that he always thought the bass sound is coming from the drums (in live shows), but now he understands how to separate the two.

His experience with Installation 3 reflected P1's comments on the gestural performance. He reported that he never experienced a music performance where music was played by the gestures and felt on the body.

6. DISCUSSION AND FUTURE DIRECTIONS

6.1 Process-oriented Assessment on CI and Music

Due to the variance in CI users' perception, experience, and understanding of everyday sounds, speech, and music, we believe that the experience designs should be personalized to the individual CI users and offer customization. Although CI users might share common difficulties in experiencing music such as pitch identification, source localization, and instrument segregation (auditory streaming), their priorities in addressing these challenges significantly vary from individual to individual. For example, P1 experienced hearing the nuances in pitch variances of singing however due to her music practice, she prioritize practicing onset detection and phrasing to support her singing in choir. Similarly, P2 preferred limiting his experience to the music styles he enjoys and enhancing these specific styles rather than practicing for the gaps in his music perception. Researchers and designers should consider such interpersonal differences not only in hearing profiles but also musical appreciation, engagement, and preferences. The factors such as age, hearing aid use, musical training among many others have significant influence in such design considerations when working with CI users.

Similarly, for many CI users, experiencing music is new and requires constant practice and learning. An ongoing musical engagement where users can practice where they experience difficulty in understanding music becomes crucial. Our assessment approach reflects this process of exploring and understanding CI users' hearing and engaging with technology in ways to both support their hearing development and music appreciation. Their participation in ideation and leading the design directions was crucial to the research process.

Because their reference of music is more subjective when they articulate their music perception and experience, we frequently referred to the current literature on assessing CI hearing and informed our experience design research. We believe that a more holistic approach to supporting CI users' music engagement offers more embodied approaches to listening and music-making. Developing new musical interaction experiences leads an integrated and a participatory research process rather than distinctly dividing design, assessment, and evaluation processes. Additionally, we observed that this process-oriented assessment facilitates designers to find more collaboration opportunities with CI users since finding participants in the CI community still remains one of the biggest challenges. We believe that creating a more formal organization around cochlear implant use and music can support their participation in design and research, enhancing their musical experiences.

6.2 Guidelines for Designing Multisensory AMTs

Designers who develop tactile displays for CI users can benefit from creating devices that are flexible and that can account for different musical tastes, hearing abilities, and musical engagement levels. While our sample size limits us from generalizing overall CI users' experience in the broader community, the very different requirements from each participant only underlines the need for flexibility and customization in design. Furthermore, special attention should be taken towards not creating unpleasant experiences, as it was briefly the case for P1 (tactile stimulation too powerful) and P2 (unpleasant music choice). Prior knowledge of target groups can help with the preparation, but a certain step towards this pre-study is ensuring that displays have basic controls for tactile and auditory stimuli levels and in the case of multi-actuator devices, setups have independent control for each transducer in paramount. Another helpful approach is to consider flexible or modular hardware that can be easily reconfigured according to user's needs. Through participatory action, research can explore individual requirements. Lastly, whenever possible, we suggest the integration of visual feedback in forms of gestural or movement-based performance or visualization that can support the gaps in perception from either the tactile or the auditory channel.

7. CONCLUSIONS

In this paper, we study cochlear implant (CI) users' engagement in music and ways to support their musical experiences both in listening and participating. We conduct exploratory workshops with three participants who all use cochlear implants with different hearing profiles. Based on our discussions, we addressed their individual musical needs and tested their experience in listening music through three different installation setups. Each installation investigated a different musical aspect that CI users experience difficulty perceiving. The motivation behind the installations extends beyond informing CI users about musical content but also to enrich their listening experience and musical appreciation. We discuss key findings, results, our observations on their interaction with these three listening modalities. We detail our process-oriented assessment and provide guidelines for designing multisensory integration to creating musical interaction and experiences, with specific focus on CI users. Our efforts address the lack of available resources for CI users' music perception, understanding, and enjoyment.

Music listening needs to be approached as a multifaceted experience which can be challenging and effortful for the hearing impaired individuals. Moving forward, we hope to utilize our interaction tools and listening experiences for CI users in offering them new rehabilitation and practice frameworks while supporting their musical enjoyment. We further plan to address one of the prominent research challenge and limitation we faced during our workshop series: accessing the cochlear implant users and Deaf communities. We hope to continue our work on music for hearing impairments through building communities and meaningful collaborations between CI users, musicians, designers, and researchers, as there seems to be genuine enthusiasm and interest in using hearing assistive devices s for music, from CI users.

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