Audio engineering by people who are deaf and hard of hearing: balancing confidence and limitations

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ABSTRACT

With technological advancements, audio engineering has evolved from a domain exclusive to professionals to one open to amateurs. However, research is limited on the accessibility of audio engineering, particularly for deaf, Deaf, and hard of hearing (DHH) individuals. To bridge this gap, we interviewed eight deaf and hard of hearing (dHH) audio engineers in music to understand accessibility in audio engineering. We found that their hearing magnified challenges in audio engineering: insecurities in sound perception undermined their confidence, and the required extra "hearing work" added complexity. As workarounds, participants employed various technologies and techniques, relied on the support of hearing peers, and developed strategies for learning and growth. Through these practices, they navigate audio engineering while balancing confidence and limitations. For future directions, we recommend exploring technologies that reduce insecurities and "hearing work" to empower DHH audio engineers and working toward a DHH-community-driven approach to accessible audio engineering.

CCS CONCEPTS

• **Human-centered computing → Empirical studies in accessibility**.

KEYWORDS

accessibility, deaf, Deaf, hard of hearing, audio engineering, music

ACM Reference Format:
Keita Ohshiro and Mark Cartwright. 2024. Audio engineering by people who are deaf and hard of hearing: balancing confidence and limitations. In *Proceedings of the CHI Conference on Human Factors in Computing Systems (CHI '24), May 11–16, 2024, Honolulu, HI, USA.* ACM, New York, NY, USA, 13 pages. https://doi.org/10.1145/3613904.3642454

1 INTRODUCTION

Audio engineering involves the practice of recording, manipulating, and reproducing sound in various settings, including music, podcasts, film, television, and radio. Today, it is regarded more as an expressive activity akin to an art form than an objective activity without aesthetic considerations [76]. Historically, this discipline was accessible primarily to professionals who had access to studios with high-end hardware and software equipment. However, thanks to technological advancements, audio engineering has become more affordable to a broader population [45, 62]. In particular, Digital Audio Workstations (DAWs) have significantly contributed to this shift by digitizing many audio engineering tasks [3]. Nowadays, DAWs are available at low cost or even for free, with plugins that extend their functionality. Consequently, audio engineering has become more accessible, allowing individuals with DAWs to engage in creative sound activities.

However, there has been limited research on the accessibility of audio engineering for people with disabilities, particularly deaf, Deaf, and hard of hearing (DHH) people[1] [13, 55]. We have seen the growing attention to accessibility in a broader HCI field [66] and more specific audio and sound technology field [31]. For people who are blind and have low vision, a few studies have emerged to address the current state of accessibility in audio engineering [92, 102]. For DHH people, a recent survey study provided preliminary insight into the accessibility of creative sound activities, which partially encompassed audio engineering [87]. Yet, research on how DHH people engage in audio engineering is still underexplored.

However, the DHH global population continues to grow. According to the World Health Organization, more than 1.5 billion people (1 in 5 individuals) worldwide are affected by some degree of hearing loss as of 2021, with an expected increase to nearly 2.5 billion people (1 in 4 individuals) by 2050 [88]. Additionally, noise-induced hearing loss is an occupational hazard for audio engineers, as their work often involves exposure to harmful noise levels [38, 71, 106, 115], but a stigma within the industry prevents open discussion about this issue [2, 19]. Considering this context and the predominantly auditory nature of audio engineering, it is crucial to develop a comprehensive understanding of the current state of accessibility in audio engineering for DHH individuals.

Our paper seeks to address this gap by understanding the current state of accessibility in audio engineering through an interview study with eight audio engineers in music who are deaf and hard of hearing (dHH). We present our findings on how they balance confidence and limitations in audio engineering through technologies and techniques, hearing peers' support, and their learning and growth strategies. We then discuss future research directions to empower DHH audio engineers with potential technologies and to achieve DHH community-driven accessible audio engineering. To our knowledge, this is the first interview study focusing on audio

CHI '24, May 11–16, 2024, Honolulu, HI, USA

ACM ISBN 979-8-4007-0330-0/24/05.
https://doi.org/10.1145/3613904.3642454

[1] People identify themselves as Deaf with a capital D when they share a cultural bond within the Deaf community, whereas the identification of hard of hearing and deaf with a lowercase d refer to audiological hearing levels.

engineering by DHH people. Our work contributes to paving the way for accessible audio engineering by DHH individuals.

2 BACKGROUND AND RELATED WORK

2.1 Hearing experience by DHH people

DHH people often encounter difficulties perceiving sound characteristics such as pitch, loudness, timbre, and spatial information [26, 28, 78]. Some rely on medical devices like hearing aids (HAs) or cochlear implants (CIs) to enhance auditory perception. While these devices are often helpful for speech perception [7, 108], they can complicate music perception, which involves a wider frequency range and elements such as melody and harmony. For example, HA users deal with issues like distortion, acoustic feedback, unbalanced frequency gain, and compression [14, 24, 67]. Similarly, CI users face difficulties in perceiving pitch and timbre [58, 64, 70]. Additionally, tinnitus, listening fatigue, and hearing fluctuation can negatively affect their hearing quality [42, 118].

To experience sound, DHH people often depend more on non-auditory senses, such as vision and touch [110]. Researchers have investigated ways to improve DHH people's perception of sound and music through visualization [27, 30, 41, 83], haptic feedback [44, 60, 69, 82], or a combination of both [50, 51]. Text descriptions, including transcripts and captions, serve as crucial visual aids for DHH individuals to access speech (e.g., conversation) and non-speech sounds (e.g., sound effects, environmental sounds, and background music) in videos [6, 56, 120] and podcasts [15, 25, 39].

Building upon these studies, our work explores how DHH people navigate these complex hearing experiences in audio engineering.

2.2 Audio engineering and accessibility

Without the context of accessibility and disability, there are numerous studies on audio engineering and its technologies and tools. Studies have examined the impact of digital production with DAWs on the creative production process [5, 112], as well as various interfaces for audio engineering, such as visual-based [22, 23], gesture-based [97], language-based [10], and multi-modal interfaces [81]. AI-powered mixing and auto-mastering solutions have also emerged [21, 59, 109].

In contrast, research on audio engineering concerning accessibility and disability is limited. There are studies on specific aspects of audio engineering for blind and low-vision individuals [37, 52, 72, 111]. More comprehensive approaches have only recently been explored, with researchers conducting studies on the current state of accessibility in audio engineering for blind and low-vision individuals [92, 102], and designing digital tools to make the process more accessible [90, 101]. For DHH populations, a survey study [87] provided preliminary insight into the use of technology in broader creative sound activities, including music playing, by DHH individuals. This study highlighted the use of hearing devices and technologies for sound manipulation and visualization, aimed at enhancing sound perception both auditorily and visually, as well as reducing hearing fatigue. However, its focus was largely on the technological aspects, with only a limited exploration of audio engineering.

Our work aims to expand upon the past research by seeking a comprehensive understanding of the current state of accessibility in audio engineering focusing on dHH individuals.

2.3 DHH people's self-development and social practice in creative sound activities

Previous studies have revealed the diverse approaches DHH individuals use for self-development in creative sound activities. Fulford et al. found that knowledge of music theory enhances self-efficacy among DHH musicians [32]. Evelyn Glennie, a professional percussionist who is deaf, emphasizes the importance of feeling sound throughout the body [34]. Churchill explores how DHH musicians experience music-making from cultural, discursive, and contextual perspectives [18]. In the realm of podcasting, DHH podcasters weave their experiences into their work, often highlighting DHH perspectives and advocating for DHH representation in the field [9, 54]. Furthermore, personal stories from DHH individuals illustrate their unique practices and experiences in creative sound activities [2, 16, 26, 36, 119].

On a broader interpersonal and social level, various organizations support DHH people's creative sound activities [1, 78–80, 84, 86]. For example, the Association of Adult Musicians with Hearing Loss [86] supports DHH musicians and fosters community growth. The Frequalise Project [77] by Music and the Deaf [78] conducted a series of 26 workshops to provide enriching music learning experiences to 63 young DHH individuals. Additionally, research on Accessible Digital Musical Instruments (ADMI) [31] involves collaborative design efforts [122], working with DHH individuals to design instruments that provide multi-modal feedback through visual and haptic means [11, 12, 107].

Building upon this foundation, we aim to gain a deeper understanding of how dHH individuals engage in learning and development, both intrapersonally and interpersonally, in audio engineering.

3 METHODS

3.1 Procedure

To understand the current state of accessibility in audio engineering, we conducted remote semi-structured interviews with eight dHH audio engineers. We recruited our participants by reaching out to online communities focused on DHH, audio engineering, and music on platforms such as Facebook and Reddit; organizations supporting DHH people; DHH audio engineers or equivalent identified from public information; and through referrals.

Each interview lasted approximately one hour through Zoom or Google Meet. We asked participants about their preferred way of communication, including the option of sign language interpreters. The interviews were primarily in spoken English, with occasional use of the chat function. We recorded all interviews after obtaining the participants' consent. We compensated participants with a $20 Amazon gift card (or an equivalent for participants in other countries). All participants were fluent in English and over 18 years old.

During interviews, we first asked participants about their demographic and hearing-related information. Then, we inquired about

Table 1: Study participants

ID	DHH identity[1]	Hearing description[2]	Hearing device[3]	Experience	DAW
P1	SS-HoH	severe loss	HA, BAHA	professional	Reaper
P2	deaf	profound loss	HA, CI	professional	Cubase
P3	SS-deaf	no hearing due to microtia	none	professional	Reaper
P4	SS-deaf	very little hearing (about 50%)	none	professional	Ableton
P5	SS-deaf	profound loss	none	amateur	SunVox
P6	HoH	high frequency hearing loss	HA	amateur	Reaper, Ableton
P7	HoH	moderate to severe loss	HA	professional	Ardour, Audacity
P8	HoH	moderate to severe loss	HA	professional	Digital Performer

[1] SS = Single-Sided, HoH = Hard of Hearing

[2] We asked participants open-ended questions about their hearing and briefly interpreted their answers.

[3] HA = Hearing Aid, BAHA = Bone-Anchored HA, CI = Cochlear Implant

their audio engineering experiences, including how they started audio engineering, how it aligned with their hearing, the technologies they used, the challenges they faced, and the practices and strategies they employed to make audio engineering more accessible. We also asked participants to show their past work and guide us through the process by sharing their screens, if possible. The study received the New Jersey Institute of Technology IRB approval.

3.2 Overview of Participants

We recruited eight participants (Table 1): six from the United States and two from the United Kingdom. They all identified themselves as male. Their ages ranged as follows: one between 18-24 years old, two between 25-34, three between 35-44, and two between 65-74. To protect their privacy, we have not linked age and country details to individual participants.

All participants were well experienced as professionals or advanced amateurs. Six held degrees in audio engineering or related music fields from higher education institutions (P2, P3, P4, P6, P7, P8), while two developed their music knowledge from childhood due to their musically proficient families (P1, P5).

Participants' hearing identities included deaf, Hard of Hearing (HoH), Single-Sided deaf (SS-deaf), and Single-Sided HoH (SS-HoH). Three were born DHH or became DHH early in life (P3, P5, P6). Five became DHH later in life, after gaining knowledge in audio engineering or related musical fields (P1, P2, P4, P7, P8). Their degree of hearing loss ranges from moderate to profound. The frequencies they struggle with span from low to high, encompassing the entire frequency range. They also reported difficulty hearing in specific situations, such as noisy environments, and health issues related to hearing, such as tinnitus and migraines.

3.3 Analysis

The goal of this analysis is not just to understand how DHH audio engineers perform specific tasks within their practice. Rather, it is to understand how they approach the audio engineering activity as a whole given their hearing, from technological and technical, social, and self-development perspectives, to better support this population in their audio engineering practice.

To do so, we employed Braun and Clarke's Reflexive Thematic Analysis approach [8], valuing its flexibility and the emphasis on researchers' subjectivity and reflexivity. First, we transcribed the video recordings and conducted initial coding, aiming to identify the current state of accessibility in audio engineering. We then discussed the codes and their relationships to gain a better understanding. Next, we categorized the codes, examined their connections, generated initial themes, and examined them. We iterated refinement until we developed themes and conceptualized their relationships, as presented in this work.

4 FINDINGS

We present our findings on how participants balance confidence and limitations while navigating audio engineering. First, we describe their hearing challenges highlighted in audio engineering. Then, we identify their strategies to address these challenges, as well as the persisting issues and newly arisen obstacles, through three sub-themes: leveraging technologies and techniques (section 4.2); incorporating hearing peers' support (section 4.3); and learning and growing audio engineering skills (section 4.4).

To provide context, we first outline the processes and tasks in audio engineering for music. Our division aligns with the one from [102] and is also consistent with the descriptions provided by our participants. These processes are detailed as follows:

- `Recording`: Capturing sounds using microphones and DAWs into audio recordings. Recording setups can vary from simple to complex; for instance, vocal recording setups can range from using one microphone for one vocalist to several microphones for many vocalists simultaneously.
- `Editing`: Selecting recordings for use in audio "tracks" and editing them in DAWs, such as trimming and aligning. Tracks are containers for organizing and grouping recordings for processing. Each track typically represents a single source, such as a vocal, guitar, or drum.
- `Mixing`: Applying equalization (EQ) and effects — e.g., noise reduction, stereo field, reverb, etc. — to individual source tracks and the master track (the sum of all source tracks), to make them sound good as a whole. This process concludes in rendering all tracks into the master mix, which typically consists of two channels (left and right).
- `Mastering`: Making final adjustments to the master mix, including precise EQ, to ensure it sounds good with various

sound systems, and to sonically unify a sequence of master mixes to be released as an album.

We also would like to emphasize that these processes and tasks are not merely procedural, but audio engineering is a form of art. Our participants directly or indirectly characterized audio engineering as an art form and a means of expression; participants conveyed their artistic expressions through audio engineering. Broadly, the goal of audio engineering can be described as creating the "*best sounding final artistic product*" as P4 said, involving constant decision-making based on understanding sound and subjective choices to achieve artistic goals. Participants typically attempted to make the best decisions for their artistic goals in each process. For example, P4 discussed various approaches in the recording process, such as obtaining the cleanest recording or discovering interesting sounds, considering the final output, "*I always try to defer to whatever has the best sound. Sometimes that isn't a thing that's going to make the mixing easier in the end. I will take a more difficult time doing the mix, if I think that it will end up with a better product in the end.*" Similarly, P2 adopted different mixing approaches depending on the songs, "*It's all dependent upon what you're working on.*"

4.1 Hearing challenges in audio engineering

Our participants' hearing status influenced their perception of specific sound characteristics, including pitch, loudness, timbre, and stereo image. These auditory nuances introduced unique challenges within their audio engineering practices.

Participants expressed underlying insecurities regarding their auditory perceptions in audio engineering. P7 remarked, "*My ears are a little deceptive.*" Those who were born DHH expressed the lack of the innate understanding of sound that hearing individuals have. P3, who was born SS-deaf, stated, "*I can't ever really experience it [stereo sound] the same way that the people with two ears can.*" Such insecurities often translated to extra time and effort to achieve audio engineering tasks. P2 said, "*If I did not have the hearing loss, it would have taken half the time at least because I could trust what I was hearing. The whole thing was having to knowing that I was going to have to second guess.*"

Our interviews further underscored the extra hearing energy required in audio engineering as DHH audio engineers. Although hearing fatigue is a concern in this field regardless of hearing status, they tend to experience it more easily. As P8 explained, "*[Hearing fatigue] probably would come on quicker than if I didn't have the hearing loss.*" Complicating this were issues tied to their hearing health, such as fluctuating hearing, tinnitus, hyperacusis, and migraines. P4 elaborated, "*I always have a baseline of fifty percent hearing loss... But then, depending on the day, or sometimes even the hour, I have fluctuating hearing loss on top of that, along with the tinnitus.*"

In addition, the use of HAs presented additional challenges. All five participants who used HAs (P1, P2, P6, P7, P8) reported limitations when using HAs for audio engineering tasks. While acknowledging the utility of HAs for speech, they noted that HAs hindered their ability to perceive music, which encompasses a broader range of frequencies and loudness than speech. For example, the automatic application of various effects such as compression, filtering, and EQ in HAs was not optimal for music. P1 remarked, "*It [HA] helps with some things but... hearing aids in general aren't brilliant for music. There's lots and lots of issues... You get feedback with them, you got a horrible pulse distortions and pulse interference... It sounds awful sometimes.*" Additionally, the unsatisfactory quality of HAs' settings specialized for music led to further frustration. P7 recounted his struggles hearing a man play the guitar, "*If I switch the hearing aid to my music mode, it's supposed to turn some of the effects off, so that you can hear everything... But I was having a hard time figuring out what chords he was playing. It was because the strumming was so bright, I could hear his strumming in his fingers moving on the frets more than I could hear the actual tone... without the hearing aid, the guitar is a lot quieter, but I can hear the chords.*" [edited for clarity]

To navigate these challenges, our participants employed various workarounds, which we elaborate on in the subsequent sections.

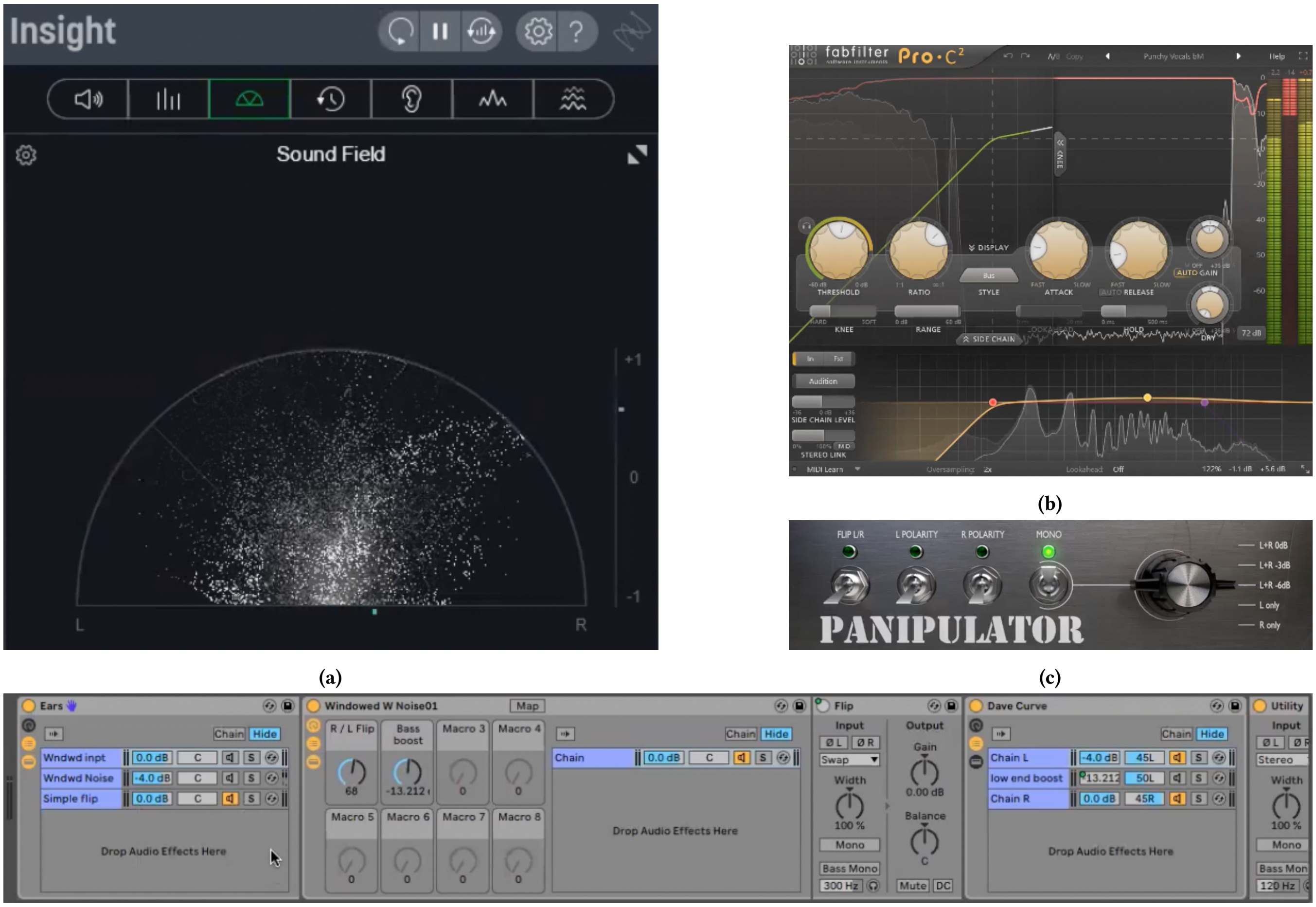
4.2 Technological workarounds and techniques: successes and limitations

In this section, we describe the various technologies and techniques employed by our participants. Additionally, we describe the constraints of HAs as a hearing technology for audio engineering.

4.2.1 Successes and remaining challenges in utilizing technologies and techniques. We found participants employed a combination of sound visualization, sound manipulation, and other techniques to accomplish audio engineering tasks. These workarounds helped them perceive sound, achieve the desired sound through audio engineering tasks, and alleviate the listening workload.

Participants reported using visualization and sound manipulation for the stereo image tasks, such as panning, phase interference, and balancing the harmony and sound levels between the left and right channels. In particular, SS-deaf and SS-HoH participants emphasized the difficulties with stereo image tasks. For example, P3 said, "*Because I can only hear out of one ear, I don't actually know [what's happening in stereo] when I'm listening.*" They utilized various visualizations (Figures 1a and 1b) and sound manipulation tools (Figure 1c) to tackle stereo imaging tasks. For example, P5 said, "*I use all of the visual tools in existence to try and get a good grasp on what's happening with the sound... Stereo editing just isn't possible without these visualizations.*" To make the process even more efficient, P4 employed a chain of sound manipulation in Ableton (Figure 1d), "*[Ableton] has the ability to essentially create chains of its built-in plugins. So I use those a lot to create devices to allow me to do the things like flipping the channels back and forth or the collapsing into Mono.*"

Participants also reported the use of visualization when applying EQ. Visualization of EQ helped their audio engineering process, enabling them to shape the sound as they wanted. P7 remarked, "*I'm looking at the EQ just to see to make sure there's not any spikes and then bring the spikes down [if any]. I'm not really listening as much as I am looking at the EQ... Having a visual equalizer is super helpful because I can see what the sound is doing.*" In addition, adjusting EQ with numeric values along with visualization helped more accurate audio engineering. For example, P8 applied EQ automation (i.e., applying and controlling EQ over time) by specifying the numeric values of EQ parameters such as filter frequency in hertz and the filter gain in decibels with visual information (Figure 2a). Moreover,



(a) (b) (c) (d)

Figure 1: Screenshots of technologies participants used for stereo imaging tasks. (a) P3 checked the phase interference of the overhead mics through visualization in drum mixing. (b) P1 checked the phase interference of a vocal track recorded in stereo. (c) P3 checked the stereo image through sound manipulation, such as stereo flipping, polarity flipping, and stereo/mono conversion. (d) P4 created chains of plugins, including stereo flipping and EQ, to make the mixing process efficient for their hearing.

EQ was not just for designing the outcome sound but also facilitated the intermediate editing process, making the sound easier to perceive. P7 adjusted EQ to emphasize the mid-frequencies, compensating for his hearing challenges in that range during editing (Figure 2b), saying, "*You can see I bring down the highs and the lows so I can focus just on the mids... Then, at the end... I try to make it sound pretty even.*"

While the workarounds reduced the listening workload, enhanced their confidence in sound perception, and improved task efficiency, our participants still faced challenges due to the limitations of technological solutions. P2 pointed out that visualization could not fully convey the sound, stating, "*I can depend on my eyes and the graphic readout only so much.*" Similarly, P1 echoed, "*Visualizing stuff is only so useful.*" Due to the limitation, participants felt a lack of confidence in audio engineering. P6, who had high-frequency hearing loss, expressed his lack of confidence when editing cymbal sounds, even with visual cues: "*I didn't really have a lot of confidence... because I can't hear a big chunk of the symbols*" To navigate these challenges, participants often sought assistance from hearing peers, which we will discuss further in Section 4.3. When this was not an option, they had to rely on guessing, as P5 stated, "*You do end up with complicated guessing game when you're mixing songs.*"

Notably, all technologies and tools mentioned by our participants were not specifically designed for DHH individuals; rather, they were commonly used by audio engineers in general. However, these tools were particularly crucial for our participants, enabling them to work better with sounds in audio engineering.

Finally, it is worth mentioning in the case of P8 that their artistic goal led to the choice not to use certain techniques that would lead to easy answers. When P8 worked on sound level adjustment and noise reduction for a vocal track, P8 precisely adjusted the

(a) (b)

Figure 2: Screenshots of technologies participants used for applying EQ and effects. (a) P8 clearly described the numeric values for EQ automation, saying, "*A little bit of a boost at about 55 hertz, pretty wide, to give it a little bit of extra fullness on the bottom. And a little bit of a shelving boost in the high frequencies, so that's set for 1,600 hertz. And then it's shelving, so it continues all the way out.*" (b) P7 used EQ to compensate for their hearing during the mixing process by boosting mid-range frequencies.

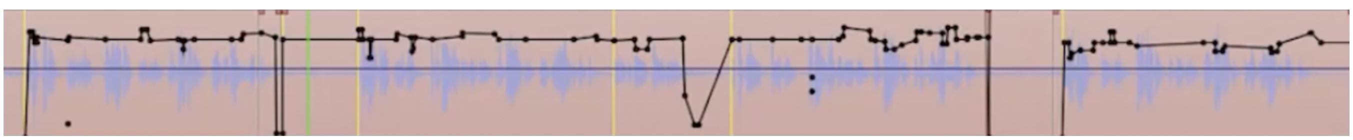


Figure 3: A screenshot from the interview with P8. To achieve a natural sound, P8 manually adjusted the volume control of a vocal track, represented by black dots and lines, instead of applying compression, which could result in the track sounding overly processed.

sound level of a vocal track (Figure 3) with visualization. This required manual adjustment and iteration of listening, with a lot of tedious work. Yet, he chose to do so instead of applying compression which was a common and easier choice but could result in the track sounding overly processed. He explained his artistic choice, "*Most often, nowadays, vocal tracks use... compression... and invariably they changed the sound. The vocal wouldn't sound as natural with compression, but that sound is very well accepted nowadays. In fact, many artists would not accept hearing their voice without [the compression]. But this particular song... I didn't want it to sound compressed.*"

4.2.2 Demand for HAs for music and audio engineering. As outlined in section 4.1, participants using HAs faced challenges for audio engineering tasks, particularly in perceiving music. In this section, we describe a deeper understanding of their experiences with HAs, highlighting the need for enhancements in HAs for music and their interactions with audiologists.

Our participants called for improvements in HAs to better perceive music. For example, P6 expressed a desire to know how HAs processed sound and to adjust it, stating, "*It would be nice to be able to have more control and transparency about what my hearing aid [is] actually doing to sound.*" Similarly, P7 demanded a more inclusive design for HA, "*The researchers need to expand their idea of who is affected by hearing loss. It's not just seniors who want to hear their grandchildren better... There are musicians out there with hearing loss and the devices that we have don't do the job... We need people who have hearing loss either working with or working for those hearing aid companies because otherwise they're making a product for a user group that they don't understand.*"

Alongside the need for HAs and HA companies, we identified a demand for audiologists with greater knowledge in adjusting HAs for music. Typically, HA users consult audiologists for programming their devices. However, our participants expressed dissatisfaction with the adjustment. For example, P2 described that audiologists lack an understanding in adjusting HAs for music, "*Unfortunately, they [audiologists] are all trained in the basis of all hearing aids is speech recognition. So when you start discussing going into music, they all say 'Well, it's very complex and we can't really do that.' But it is totally possible... The problem is they have to think out of the box that they were trained in.*" Similarly, P1 highlighted the importance of working closely with an audiologist, saying, "*To get music sounding good, you need an audiologist who is prepared to work with you on that.*" Nevertheless, P8 shared the difficulties in finding such skilled audiologists, remarking, "*I hate to say it. But* *even some of the best audiologists in my area do a poor job... I tried relying on one of the better known audiologists in the area, and it was a terrible experience.*"

Moreover, inadequate equipment and testing procedures hinder the proper adjustment of HAs for music. P2 shared that the quality and sound level rating of speakers and the sound samples used were insufficient, "*[Audiologists] don't have any speakers that can reproduce 95 decibels in the room... In the case [of] my audiologist, we can't even get above 70 decibels in the room... They're using pre-program[med] material, which is compressed... So there's no dynamic range.*" P8 also mentioned the limited frequency resolution in testing, "*If the analysis is only one-third octave bands, you can have terrible peaks and dip within the band that don't show up.*" These issues make it difficult to adjust HAs for music, as music has a wider dynamic range, wider frequency range, and important fine detail.

To our surprise, two participants (P2, P8) programmed their HAs by themselves to overcome these limitations. This self-programming approach allowed them to adjust their HAs to better suit their hearing needs and the sounds they wanted to hear. It should be noted that this approach is unique; it requires technical software, which is sometimes available on HA company websites, and the knowledge to use the software to adjust HA based on individual hearing needs. P2 shared his experience of self-programming HAs and promoting this knowledge:

> "*I've been self-programming my hearing aids for 20 years and giving advice for musicians who have hearing aids in order to get the best out of their hearing aids for the audiologist... Every other week I hear from some other musicians [saying] 'I can't hear with my hearing aids.' It's always the same problem and it's always the same solution... I get to communicating with them, talk with them. I discovered the audiologist didn't set them [HAs] up properly. Then I tell them, 'this is what you need to do, write this all down, go show it to the audiologist.'... They come back from the audiologist [saying] 'I hear a great.'*"

This highlights the significance of addressing communication issues between HA users and audiologists. Proper training for audiologists in adjusting HAs for music is crucial, as is the skills of HA users to accurately describe what they hear through HAs. P1 elaborated on the importance of clear communication and mutual understanding:

> "*You need to know how to describe the problems you're hearing [with] the hearing aid. A lot of people don't have the vocabulary that audiologists need them to have... I can describe because of my audio production knowledge and my physics knowledge to an extent... But if you go into an audiologist and say 'it sounds squawking when I play this thing', they can't use that information in any meaningful way. It's like 'Okay, squawking. What does that mean?'... So it's a problem on both sides. We need to be able to better describe the things we're hearing and audiologists need to be able to better understand how to help musicians.*"

4.3 Social-based workarounds: working with hearing peers

Participants emphasized the importance of hearing people's support during audio engineering. They leveraged hearing individuals' assistance to accomplish tasks that may be challenging to complete independently due to their hearing and technology constraints. However, this reliance on hearing people's support introduced additional nuances they struggled to navigate, such as mental barriers when seeking feedback and obtaining high-quality input. These complexities highlighted the delicate balance that DHH audio engineers must maintain when engaging with hearing collaborators to overcome limitations and advance their skills.

4.3.1 Leveraging support from hearing peers. All participants reported that they sought support from hearing individuals to address their lack of confidence and validate the quality of their work. By obtaining feedback, they ensured that their work met their desired standards. For example, P4 explained, "*[Feedback] give[s] me an extra set of normal ears*[2] *to make sure that I haven't done anything that sounds off balance or anything that's probably a result of my hearing... because I'm afraid that there will be something that I will mix that will sound bad and I won't notice.*" Feedback contexts ranged from specific tasks to overall quality assessments. In any situation, DHH audio engineers commonly relied on feedback from hearing individuals.

The importance of feedback extends beyond its conventional role in audio engineering for DHH audio engineers. Even for hearing audio engineers, getting others' feedback is common. P2 said, "*I don't know of any musician or engineer that trust[s] their own judgment enough... Even the guys I used to work with that were turning out platinum hits [asked for feedback]... Self-criticism goes a long way and it's always worth it.*" However, DHH audio engineers often experience a heightened reliance on feedback to fill the lack of confidence and to ensure the quality of their work. P4 said, "*[Before becoming DHH] I would sometimes send stuff out to get feedback on it. But I feel like now I am more reliant on that feedback, whereas in the past I would be confident enough to put something out or give clients like a final mix, without necessarily having somebody else check it. I wouldn't do that anymore.*"

This support sometimes extended to more collaborative work to accomplish tasks. For example, P2 described the iteration of getting feedback and revision until achieving the desired goal, "*I have a friend of mine who is a very good mastering engineer... I would finish one [a mix] and send it off to [my friend] and he'd send it back and he [would say] 'You don't have the bass up loud enough.' So, I would push the bass up and then he [would say] 'Well, that's great. But you have too much 80 Hz, so pull that down.'... So I pull it down and send it back to him and he [would say] 'perfect okay'.*

4.3.2 Considerations when seeking hearing peers' support. While hearing individuals' support was beneficial for our participants, its reliance introduced additional layers of considerations to navigate.

One prominent barrier was the mental burden of constantly seeking assistance. Participants typically turned to close friends,

[2]We acknowledge the implication of the term "normal" in the context of accessibility and disability. Its use here, as quoted from the participant, aims to preserve the original expression.

colleagues, or partners for help. Yet, with this assistance often rooted in kindness and friendship, they were reluctant to overburden others and felt uncomfortable asking for help too frequently. For example, P2 asked for support from his friend only after he tried everything he could, saying, "*I don't want to impose on him because he's doing this for free... I make a point of getting it as far along as I can before I send it to him... I need to make sure everything is as best as I could get.*"

Another challenge arose in securing high-quality feedback. Feedback might not require extensive expertise for relatively simple tasks, such as checking for strange noises and timing differences. However, for more complex tasks, finding reliable individuals capable of providing valuable feedback could be challenging. Considering audio engineering as an art, not only expertise but also personal taste mattered. For example, P2 said, "*I can trust his [my mastering engineer friend's] ears, because he hears it [music] the same way I do... A mastering engineer can take a recording and make it sound three or four different ways. It's just a matter of like 'are you hearing it from the same approach?', and he does. So, I could trust it.*" In contrast, individuals lacking audio engineering expertise may only provide superficial advice, limiting the utility of their feedback. For example, P6 said, "*People listen to it and they said they liked it, but it wasn't like in-depth feedback.*"

Lastly, participants grappled with their desire for independence. While they recognized the value of hearing individuals' support, they also sought to assert their capabilities as DHH audio engineers and artists. For example, P6, who positively relied on hearing people's feedback for their professional work in digital signal processing, expressed reluctance to seek support for private audio engineering projects, "*Probably a stubborn desire to be an independent producer... I just wanted to be able to make something and put it out there without having to ask too many people if it's good or not.*" Similarly, P7 described their willingness to be independent as an artist, "*I think a lot of artists, myself included, have this temptation to be like, 'this is a beautiful little creation and I'm not going to show you anything until it's exactly absolutely perfect. So, no one's going to get to see it. And then I'm going to release it. And once I release it, it's set in stone and no matter what you say I'm not going to change it.' Just kind of like a bad habit, but I think that's certainly where I come from.*" Balancing this need for autonomy with the benefits of hearing people's support adds another layer of complexity for our participants.

4.4 Cultivating resilience and perseverance: the journey of learning and growth

Participants described the significance of recognizing their limitations in audio engineering and shared their approaches to learning and progressing as DHH audio engineers.

4.4.1 Understanding and accepting the limitations. For participants to engage in audio engineering efficiently and confidently, understanding their hearing limitations played a crucial role. To accomplish tasks in audio engineering, participants needed to assess which tasks they could do based on their hearing and audio engineering skills and determine appropriate workarounds. As previously mentioned, seeking support from hearing individuals was a common workaround. For example, P2 explained, "*The challenge that I had to face is to understand what my limitations were and stop. Don't go any further than that... I make a point of getting it as far along as I can.*"

An alternative approach was to accept their limitations and work with them. For example, P6, who had difficulty hearing high frequencies, described his experience of deliberately not addressing his issue, "*[Sometimes I should] just work with that limitation, instead of trying to make a sound in that upper region that we think would sound good to you or somebody who can hear those frequencies, because I'd rather not guess.*"

4.4.2 Leveraging skills and knowledge gained in the past. Participants who became DHH after gaining familiarity with audio engineering reported leveraging their previously acquired skills and knowledge. For instance, P8 mentioned that their tools and equipment remained unchanged after becoming DHH, "*Rather than using different equipment, I rely on my experience and the skills that I developed before hearing loss. That's an important point.*" P4, who is SS-deaf, utilized their experience to employ a stereo flipping tool he hadn't used before becoming DHH, "*Before I had the hearing loss, I had a lot of experience with where to pan things. So I pretty much, as opposed to listening to it, would just pan things to where I knew from experience they should be. And then [I] would flip the left and the right back and forth to check.*"

Specifically, two participants (P2 and P8, who self-programmed their HAs) shared their unique strategies for iterations of relearning how to hear with HAs. With the use of HAs, they could not hear as they used to hear. But, they used the songs they remembered by heart as their point of reference to relearn hearing. For example, P2 said, "*I have pieces of music that I've played for 30 years that I've absolutely memorized, so I know what they're supposed to sound like... I had to basically relearn how to hear. 'Okay, I can't hear this, but I can hear that. So if that sounds like this...' and that would recenter my brain as to what I should be hearing... It was tedious. I had to say that.* Additionally, they applied the same technique for audio engineering. P8 explained, "*For the sounds that I'm working with, it's very important that I compare what I do to other sounds that I'm familiar with that are well known to be excellent in their sound processing... And I go back to one of my old recordings and compare... My relative hearing is still pretty good. If I hear one thing and another thing, I can hear if there's a difference.*" They also applied this strategy when receiving hearing peers' support, as P2 said, "*We would go back and forth with this [feedback process]... I would listen to what he did to my mix and then I would understand when I do the next one. That would be my point of reference. So I would listen back and forth, back and forth, back and forth, until mine sounded like his. So next time I send it to him, he didn't have to do so much work.*"

While the skills and knowledge obtained through formal education and training proved beneficial, P3, who learned audio engineering in college after becoming DHH, emphasized the extra effort he had to make compared to their hearing peers:

> "*Every kid learns the same foundational principles. But in my specific use case, it was important that I went back and did additional research to make sure I understood what was happening. It was more important for me to understand what's happening acoustically and physically than the other students. Because the other*

> *students can use their natural sense of hearing... But I had to do additional research to make sure I really knew what was happening.*"

4.4.3 Community involvement. We observed that participants predominantly engaged with audio-related communities that were not specifically for DHH people. These communities encompassed areas such as audio engineering, musicianship, specific music genres, and DAWs. However, two participants (P1 and P2) reported their active involvement in a music community specifically for DHH individuals. They both mentioned the same online community (the community's name withheld to avoid identifying the participants). While audio engineering was not a primary topic in this community, members shared information on broader topics related to sound, music, and DHH individuals. P1 said, "*I keep in touch with a few people through there [the online community]... It's a nice supportive group... They have meetups and things. And then, they talk about various challenges that are really specific to musicians, particularly issues with hearing aids and getting them tuned. It's a huge problem for musicians.*" Also, P2 took a role in empowering other members, giving advice on adjusting HAs with an audiologist for music, with his experience of self-programming of HAs. P2 said, "*Every other week I hear from some other musician [saying] 'I can't hear with my hearing aids.' It's always the same problem and it's always the same solution... I try to stay active in the game because it's sad to hear so many musicians [saying] 'I can't hear.'*"

In contrast, four participants (P3, P5, P6, P7) felt disconnected from DHH communities to interact with other DHH audio engineers or musicians. Given that the field is predominantly dominated by hearing individuals, they found it challenging to connect with their DHH peers. Notably, P6 and P7 expressed that they did not even think about looking for DHH people in the field. For example, P6 said, "*I haven't really met any [DHH people in the field]. In my entire life. I don't think I've ever met a single other person [at] my age with hearing loss... I've never sought out that Community... Now that you mentioned, it would be kind of cool.*"

While P3 generally preferred to be in touch with individuals close to him, the others (P5, P6, P7) expressed an interest in interacting with other DHH individuals in the field as the interview progressed. P7 said, "*I've never thought of it. Sure, it would be cool. I always thought that it's a very niche thing to be the age I am with the disability I have in the field that I'm in. But if there's other people, then sure... I'd certainly be open to it.*" Similarly, P5 said, "*I'd be interested to hear what how the other people suffer with their hearing loss. Perhaps some people have a kind of frequency degradation, or perhaps... they're on the very edge of what a hearing aid could help on both sides.*"

5 DISCUSSION

We have presented the current state of accessibility in audio engineering by dHH individuals. Their hearing status introduces complexities in audio engineering, leading to insecurities in sound perception and undermining their confidence. In addition, they must also navigate the intricacies of "hearing work" required in audio engineering. To maneuver through these challenges, our participants leverage technologies and techniques, seek support from hearing peers, and cultivate resilience and perseverance. Nevertheless, they still struggle with the limitations of these strategies and confidence issues stemming from their hearing.

In this section, we discuss recommendations to advance the accessibility of audio engineering by DHH people. Specifically, we see opportunities in designing various solutions to empower DHH individuals to confidently and efficiently conduct audio engineering while managing their hearing energy. We also discuss directions toward an approach to accessible audio engineering driven by the DHH community.

5.1 Technologies to empower DHH audio engineers

5.1.1 Automated audio engineering tools. Automated, AI-powered audio engineering tools have progressed remarkably in the past 15 years. Within the family of "intelligent audio production" tools, these tools analyze audio signals and adaptively process them to achieve some goal, e.g., making a "good-sounding mix" [21]. Some tools automate the entire mixing or mastering process [20, 40, 59, 74, 103, 109, 114], while others only automate a particular subtask such as sound-level adjustment [94], stereo-imaging [35], equalization [73, 93], compression [65], reverberation [17], and noise reduction [116]. While once relegated to research prototypes, there are now many commercial automated audio engineering tools, e.g., LANDR [57], RoEX [98], and Izotope's Ozone [48]. However, as previously mentioned, many people consider audio engineering as an art and therefore believe that there is not one objectively perfect mix as many automated mixing tools assume. Therefore, while there are opportunities to apply and evaluate these advancements for DHH audio engineers, investigating how they can reduce listening work, we must do so while examining their impact on users' creativity.

5.1.2 Perceptually-informed audio engineering tools. Other intelligent audio production tools and interfaces only semi-automate the process, yielding some control to the user to guide the process. Perceptually-informed audio engineering tools fall into this subcategory. These tools leverage computational models of auditory perception [33] to provide more perceptually-relevant information for the user to act upon [29, 47, 63, 113]. For example, MixViz presents visual information about complex inter-channel perceptual auditory masking to users in real-time to help them reduce the loss of salient audio content during the mixing process [29]. MaskerAid expanded this idea to the DAW timeline and found it meaningfully improved user performance toward the goal of producing mixes in which each track was clearly audible [63]. Similar ideas have since made their way into commercial products such as Izotope's Neutron [47]. All of these tools are more aligned with auditory perception than traditional audio visualizations and thus can potentially reduce the listening work of an audio engineer while still giving them control over the creative process.

5.1.3 Semantic audio engineering tools. While many professional audio engineers are capable of describing sound through language specifying the physical properties of sound, e.g., frequency and energy, this approach requires expertise and training. In contrast, novices tend to communicate sound ideas using other methods such as descriptive language (e.g., "Can you make it *warmer*?") [89, 95]. While a limited form of this style of interaction is now available in some commercial products [117], studies have shown that the language used to describe audio is not always universal and requires a more nuanced, adaptive approach [10, 104]. We see opportunities in building on previous research of such semantic audio production tools that leverage language-based control [10, 100, 104] and investigating how these approaches support DHH audio engineers, for instance, in selecting sound samples during the sound design process or applying audio processing adjustments. These tools could also facilitate effective communication for DHH audio engineers such as providing or receiving feedback, as well as communication between HA users and audiologists when adjusting HAs for music.

5.1.4 Exploring tactile interaction in audio engineering. Contrary to previous studies on tactile interaction in the sound domain, none of our participants mentioned using tactile solutions during their audio engineering processes. Past research has explored the use of tactile feedback to convey sound characteristics such as rhythm, loudness, pitch, timbre, spatial information, and emotion [46, 49, 75, 99, 105]. Moreover, tactile feedback has been utilized in creative sound activities, including composing and performing [11, 12, 107]. Exploring the possible integration of tactile interaction in audio engineering, especially in combination with other modalities, continues to be a promising area of research.

5.2 Toward DHH-community-driven accessible audio engineering

To empower audio engineering by DHH people, addressing the lack of learning opportunities is crucial. We can apply approaches from previous research in the broader accessibility community. One approach involves developing learning materials and conducting workshops. For example, Kearney-Volpe et al. [53] conducted workshops to support screen reader users in learning web development by designing learning resources. Similarly, Race et al. [96] developed a curriculum for blind and low-vision people to learn non-visual soldering skills. Another approach is to design new tools to facilitate learning. For example, Saha et al. [101] designed an extension for GarageBand that offers tutorials on audio production for blind users to conduct audio production. Additionally, Payne et al. [90, 91] conducted a study for blind and visually impaired musicians to compose music using a web browser-based music notation system co-designed with them. By incorporating these approaches into audio engineering for DHH individuals, we see opportunities for enhancing their learning experience in various ways, including developing fundamental audio engineering skills with DAWs, increasing awareness and utilization of tools and technologies, as well as learning theoretical knowledge about the human auditory system, acoustics, and signal processing.

We advocate for developing accessible audio engineering driven by the DHH community, i.e., designed by DHH people. We emphasize its importance, aligned with the shift in the accessibility field "*from designing for people, to designing with people, to designing by people*" highlighted by Lewis [61]. For one reason, audio engineering for DHH individuals encompasses a broad spectrum of factors, including DHH identity, degree of hearing, audio engineering tasks, technologies, and skills and knowledge. Designing by DHH individuals will help address complex individual needs. Furthermore, audio engineering as an art should not be dominated solely by hearing individuals' perspectives. As we see tensions between DHH and hearing people in creative sound activities [18, 121], it is crucial to strengthen the availability of choices for non-hearing-centric audio engineering in the whole sound community, regardless of DHH or non-DHH. To achieve DHH-community-driven accessible audio engineering, researchers and designers should work inclusively [43] and foster long-term partnerships by practicing "being with" the community [4]. This collaborative approach will drive progress from designing research prototypes to realizing research products [85].

6 LIMITATIONS AND FUTURE WORK

Our participants were well-experienced audio engineers and none identified as beginners. This could affect their responses, making them less focused on the workarounds and challenges they experienced during the early stages of engagement. Moreover, the limited participant pool may not offer a comprehensive understanding due to its size and gender imbalance, as all participants were male, which is a recognized issue in this field [68]. Finally, no Deaf individuals and bilateral CI users participated in this study. To better understand the current state of accessibility in audio engineering by DHH people, future research should expand its focus to those we could not reach out to.

Additionally, none of our research team members identify as DHH. While we both have some degree of musical and audio engineering background (the first author is an amateur musician, and the second author has formal training and professional experience as a musician and audio engineer), our perspectives on audio engineering and music are inevitably biased as hearing individuals. We attempt to be aware of and expand our perspectives by interacting with DHH people and learning American Sign Language. Still, we cannot fully empathize with DHH audio engineers' experiences.

To advance this research, we aim to collaborate with DHH audio engineers, further investigate their practices and challenges, and collaboratively design solutions. We strive to establish, maintain, and develop an accessible and inclusive community for DHH audio engineers, encompassing novices and those considering embarking on a career in audio engineering. This approach will facilitate interaction and support among DHH audio engineers and promote community-driven design and solutions for enhanced accessibility in audio engineering.

7 CONCLUSION

In this paper, we presented an interview study with eight dHH audio engineers to examine the current state of accessibility in audio engineering in music. We observed their hearing intensified difficulties in audio engineering: their insecurities in sound perception affected their confidence, and the extra "hearing work" introduced complexity. To navigate these complexities while balancing confidence and limitations, participants employed various technologies and techniques, sought the support of hearing peers, and developed strategies for learning and growth. As future directions, we discussed potential technologies that reduce insecurities and "hearing work" to empower DHH audio engineers and working toward a DHH-community-driven approach to accessible audio engineering.

ACKNOWLEDGMENTS

We thank all participants, organizations, and communities that contributed to this study.

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