"It Didn't Sound Good with My Cochlear Implants": Understanding the Challenges of Using Smart Assistants for Deaf and Hard of Hearing Users

JOHNNA BLAIR, Penn State University
SAEED ABDULLAH, Penn State University

How do deaf and hard of hearing (DHH) individuals use smart assistants (SAs)? Does the prominent use of voice interfaces in most SAs pose unique challenges for DHH users? In this work, we aim to answer these questions by conducting 4 in-depth interviews, as well as collecting survey data from 73 DHH individuals. Our findings show that individuals, even with profound deafness, can leverage SAs to accomplish complex daily tasks. However, we also identified a number of common challenges DHH individuals face when interacting with SAs (e.g., high pitch used in the default SA voice interfaces can be incompatible with hearing aids, difficulty using mobile SAs in public places with loud background noise). Based on these insights, we provide a set of suggestions for designing SAs that can better accommodate a wide range of hearing abilities. Specifically, SAs should provide more customization options to allow the user to tailor their SA to meet their hearing needs over time. For example, using a pitch-frequency test feature, much like audiograms conducted by audiologists, could allow users to calibrate their SA's voice to fit within their optimal range. We also see a need to provide more clear and actionable error messages conveyed beyond audio notifications, such as more meaningful light notifications. These recommendations and findings provide the first step forward toward a more inclusive SA by addressing accessibility needs unique to this group.

CCS Concepts: • **Human-centered computing → Human computer interaction**; *Accessibility*; Empirical studies in accessibility.

Additional Key Words and Phrases: Smart Assistants, Conversational Agents, Voice Interfaces, Accessibility, Deaf, Hearing Loss

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1 INTRODUCTION

Smart assistants (SAs) with voice interfaces are becoming increasingly ubiquitous in our daily activities and interactions. They enable users to interact with devices using speech commands. Most mobile devices now contain embedded SAs with voice interfaces (e.g., Alexa, Siri, Google Assistant). Furthermore, recent standalone devices (e.g., smart-speakers including Amazon Echo and Google Home) also include similar SAs. This has resulted in significant growth in devices with smart assistants. Recently published figure by Amazon notes that there are

Authors' addresses: Johnna Blair, jlb883@psu.edu, Penn State University, University Park, PA, USA; Saeed Abdullah, saeed@psu.edu, Penn State University, University Park, PA, USA.

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"hundreds of millions of Alexa-enabled devices out there" [2]. Similarly, Google Assistant is now available on more than one billion devices [15].

As these numbers indicate, a significant fraction of the population now has access to SAs with voice interfaces. Voice as an interaction modality has the potential to significantly improve accessibility for a wide range of users. For example, individuals with visual impairments or mobility issues can use voice interfaces in SAs to perform complex tasks [34]. Using speech to interact with devices can be more naturalistic as well. As a result, SAs can lower the barriers of technology use for those who may have difficulty interacting with current interfaces because of small screens and manual interactions. This can be particularly useful for "digital non-natives" including older adults as well as individuals with manual dexterity or vision issues. Indeed, older adults have been some of the earliest adopters of smart-speakers. A national study in the US conducted by NPR reported that older adults (age > 55) are the largest group of "first adopters"—they account for 33% of all users who have owned smart-speakers for a year or more [26]. Given that older adults are often reluctant to use new technologies [19], their surprisingly high adoption of smart speakers clearly conveys the potential usefulness of voice based SAs for this population. Smart assistants, thus, can provide unique opportunities for supporting communities who are not mainstream users of current digital technologies.

However, voice interfaces used by SAs might also pose unique challenges for individuals with different accessibility needs—specifically, for deaf and hard of hearing (DHH) community. The World Health Organization estimates around 466 million people worldwide have disabling hearing loss [29]. According to the Hearing Loss Association of America, 20% of individuals (or 48 million) report some degree of hearing loss [28]. Hearing loss also disproportionately affects older adults, especially regarding degenerative conditions. In the US, approximately one in three people between the ages of 65 and 74 has hearing loss, and almost half of those older than 75 have difficulty hearing [27]. Moreover, age is the strongest predictor of hearing loss among adults [28]. As SAs are becoming a ubiquitous gateway to interact with different devices, it is important to ensure that SAs can support the needs of different communities including the DHH users. Indeed, given the high adoption rate of SAs among older users and the prevalence of hearing issues with aging, we argue that it is critical for smart assistants to understand and design for the unique requirements of deaf and hard of hearing users. However, little work has looked specifically into how individuals who are deaf or hard of hearing might use smart assistants in their daily lives. That is, we do not yet know the use cases and motivations DHH users have for adopting SA devices, as well as the limitations they face while interacting with SAs. We consider this to be an significant gap in current knowledge.

In this study, we aim to address this gap. We first conducted in-depth qualitative interviews with four deaf older adults who have used smart assistants. Given the increasing adoption of smart assistants and the extent of hearing loss in this population, these interviews helped us to explore their usage contexts as well as identify key challenges and design ideas. Leveraging these findings, we then designed a survey to collect data from 73 SA users with hearing loss who are more age-diverse. This helped us to confirm that the use patterns and challenges uncovered through initial interviews persist across a more diverse group of DHH users. Furthermore, broadening the data collection scope enabled us to gather additional insights and design ideas. Our specific contributions in this work are:

- This is the first study that investigates how deaf individuals use SAs in their daily activities. We found that our participants regularly engage with SAs to complete a wide range of tasks including informational searches, calendar reminders, and news updates. This highlights that individuals even with profound deafness can and want to leverage the ubiquity and wide availability of SAs. Our findings confirm that there is a need for better designed SA that can address the unique accessibility requirements of the DHH community.

- Toward this goal, we have identified a number of common challenges DHH users face while using SAs. For instance, the high pitch of default voices used in most SAs can be difficult to follow for individuals wearing hearing aids. We have also identified some of the current limitations associated with trying to embed the use of SAs within their daily routines and more complex tasks. For instance, many users relied on visual feedback to supplement voice responses. This led to disruptions in the naturalistic flow the expected of their SAs and restraints on the locations in which they wanted to use them.
- Based on these findings, we have proposed design opportunities to improve accessibility for various hearing capabilities. For example, we discovered how new interaction modalities (e.g., leveraging light in SAs to convey system status) can significantly improve the usability of SAs for DHH users. We have also identified how customization opportunities (e.g., using audiogram-like tests to determine optimal voice characteristics for individual users) can better match their unique and ever-changing needs.

2 RELATED WORK

The term "smart assistants" (SA) can be classified into several variants, as illustrated in the work by Knote et al.[18]. In this work, we refer to SAs as systems that use *"the user's voice [...] to provide assistance by answering questions in natural language, making recommendations and performing actions"* [3], p.223. Research on SA use has looked into the common tasks for which general users choose to engage with their SAs and how these use cases help embed SAs into their daily lives. Despite their popularity, SA use comes with its own set of challenges for general users. These challenges can be amplified when voice technologies are used by specific user groups, such as those who with speech impairments. However, for other groups of users, such as those with mobility or vision issues, SAs can have a positive impact on accessibility.

2.1 Smart Assistants

Recent studies have provided a better understanding of how people use SAs within the context of their daily lives[6, 9, 17] and the type of roles they assume [21, 22, 35]. Users typically show a high-use period of excitement when first introduced to the device, which typically levels out as users learn the device's limits and they become part of daily routines [37]. However, the way SAs are used can also be influenced by users' mental models and expectations for the device[9, 35, 37].

When people use technologies that have more human-like social cues, such as SAs, they often adopt more human-like scripts to interact with them. The ability to "speak" to systems as they would to other people often leads users to attribute human-like properties to smart assistants [35]. Those who personify their devices, or attribute human pronouns, show increased levels of satisfaction with their devices. However, it is undetermined whether that personification leads to better experiences or that successful SA experiences lead to users viewing them as more human-like. Other work has shown that using SAs for more sociable actions also led to increased personification behaviors [22] and poses questions of whether those personifying SAs are more emotionally attached and those who show no personification are more skeptical of the device's relative intelligence [22].

SA use can present some challenges related to the user effectively communicating with the device and understanding the device's responses and programmed expectations [23, 30]. For users, a lack of device cues to facilitate turn taking can lead to interruptions and asynchronous conversations [31, 32]. When faced with an unfamiliar voice user interface (VUI), Myers et al. [25] found that user characteristics like programming experience has no impact on users' VUI performance metrics, but those with more technical confidence engaged with more trial and error attempts to use the VUI. However, users with more "cautious" performance indicators, such taking more time to initiate VUI interactions, had a higher desire for visual feedback. These findings suggest a need for VUI design that can be more tailored to different user approaches.

Although users expect to use SAs hands-free, they occasionally provide screen-based feedback depending on the task initiated, requiring users to physically interact with their devices (e.g., showing results of a web search on screen instead of a verbal response) [24]. Additionally, there is often a disconnect between how people talk naturally and the way smart assistants have been trained to expect users to talk, which can lead to inaccurate speech recognition [24, 40]. This poses a challenge for effective SA use, especially for those with speech impairments [5].

2.2 Agents for Older Adults

Despite assumptions that older adults may be unlikely or more reluctant to adopt newer technologies, studies have shown this has not been the case for voice technologies like smart assistants and smart home speakers[16, 17, 26]. These smart assistant devices have shown a unique popularity within this age group, as compared to wearable devices [16]. Compared to young adults (those under 30), adults 60 years or older are much more likely to be daily users of smart assistants[17].

Given this growing popularity, recent research has aimed to leverage SAs for older adults given the potential opportunities these devices provide to improve accessibility. This is largely because their speech-based interaction methods can feel more naturalistic for those who are not digital natives. Speaking to a device, rather than using other modalities, closely mimics that of speaking to another person. This familiar action has been viewed as more approachable for older adults who may be otherwise reluctant to adopt different technologies due to other perceived barriers [4, 19, 33].

At the same time, this verbal interaction can help bypass the accessibility issues for other technology interactions. For example, the small screens and text as well as the fine motor movements and manual dexterity required to carry out common tasks smartphones can be challenging in an aging population [10, 19]. SAs, however, can still be operated despite mobility issues [10]. Initial studies exploring the use of SAs with older populations has highlighted a growing interest in adopting new technologies, not only to keep in communication with their younger, more tech-savvy, family members, but also because of the potential they have for maintaining their independence, as they can be used to manage daily tasks through physical and cognitive conditions that can develop in late adulthood [4, 33].

2.3 Accessible Voice Technologies

Recent studies have explored the use of SAs to address a number of different accessibility needs, such as visual impairments, mobility concerns, and speech conditions [5, 10, 34, 36, 38]. In the case of visually impaired users and those with mobility issues, accessibility and increased independence can be seen as an unintentional outcomes for verbal interactions central to smart assistant use [10, 34, 36, 38]. Conversely, people with speech impairments can face additional difficulties interacting with SAs. When commonly used SAs, Siri, Google Assistant, and Amazon Alexa, were tested against common speech impairments, all three devices accurately recognized commands 50-60% of the time [5].

Those in the DHH community who do not primarily use a sign-based language often use some form of technology on a daily basis to aid in their hearing. Among those, voice to text programs on mobile phones have become a popular method for live captioning [13]. These technologies are often used in conversations to provide supplementary information and are especially helpful for managing larger conversations with multiple members [13, 14]. The visual feedback from speech-to-text programs allow DHH users to more easily follow conversations that bounce between multiple people, such as workplace meetings, and feel more actively engaged in conversations, rather than excluded [13, 14].

Some work has been done regarding DHH use of voice interfaces and other devices. Bigham et al. [7] explored the ways in which DHH individuals may face difficulties using speech to control various home devices. As voice

interaction has become more common in new products that do not provide screens for visual feedback, such as smart appliances, this can be challenging for some users. Using voice recordings of DHH individuals, they assessed the degree to which current SAs struggled to recognize unaided deaf voices (those using neither cochlear implants nor hearing aids). When listening to unaided deaf voices, Amazon Alexa produced an error rate of 40%, as compared to Amazon Alexa's 5% error rate for detecting all voices [7]. Their proposed pathways to DHH accessibility in speech-controlled devices was to leverage the use of text to speech programs as an intermediary for voice-controlled devices [7]. However, little work has been done with the specific goal of understanding how current users of SAs who are deaf or hard of hearing interact with their devices in the context of their everyday lives, as well as their expectations and challenges, from first-hand experiences.

Findlater et al. [11] explored user preferences for sound awareness technologies that can provide haptic or visual feedback to inform DHH users of sounds in a given environment. Their work focused on smartphone, smartwatches, and head-mounted displays. Our study, on the other hand, focuses on different types of devices (e.g., commands directed to a smart speaker). Furthermore, the interactions supported by smart assistants can be more nuanced and complex than just the presence of sound notifications. For example, a successful task completion might require multiple dialogue steps between a user and a SA. As such, the accessibility needs and constraints for DHH individuals can be considerably different for SAs compared to the devices and interactions considered in Findlater et al. [11]. Our study, thus, provides unique insights into the usage patterns and accessibility concerns for novel interactions supported by an increasing number of devices.

3 METHODS

To address these gaps, we first conducted exploratory interviews with four individuals who were self-described as profoundly deaf and members of the Deaf community. Throughout these in-depth interviews, we specifically focused on gathering first-hand account of users' experiences with SAs, as well as understanding their expectations of these devices. Our goal with these interviews was to uncover the lived-experiences and challenges felt by those with the more profound cases of hearing loss, or those who stand to face the most challenges while using SA, and examine which of these initial concerns are persistent across the wider DHH population. To address this, we then collected survey data from 73 hard of hearing respondents, across a range of ages and degrees of hearing loss.

In other words, we first focused on community members who face most difficulties in interacting with voice assistants. We then leveraged the findings to develop a survey to explore the accessibility needs and concerns of the wider DHH community, including even those with mild to moderate hearing loss. Given there has not been much work on the accessibility issues of using voice assistants for this community, the order of these two studies helped us to develop a more informed survey for the larger population. Furthermore, by focusing on the most severe cases and unmet needs first, we were able to identify fundamental accessibility issues in this context. The subsequent study helped us to validate these concerns in the broader community

3.1 Interviews

For recruitment, we reached out to hearing loss support organizations and Deaf advocacy groups, both locally and online. Our inclusion criteria included individuals who were considered profoundly deaf, currently using either a cochlear implant or hearing aids, and did not use a signing language (American Sign Language or Sign-Exact English) as their preferred method of communication. All participants had used SAs in the past and were familiar with different functionalities and features of their respective devices.

Four in-depth interviews were conducted with participants living in the US and Canada. Three interview participants were female, and one male. These individuals ranged between 53 and 63 years of age at the time of their interviews. As mentioned above, older adults are one of the largest user groups of smart speakers and hearing issues significantly impact this population. As such, these interviewees provide a unique opportunity

to explore their motivations for adopting SAs, their expectations, and any challenges they had encountered. All interview participants described themselves as profoundly deaf, reporting approximately an average of 85% hearing with the use of their assistive hearing devices. Two participants used hearing aids to support their hearing on a daily basis. The other two participants had gotten cochlear implants within the last decade, after previously using hearing aids. Three participants had begun to lose their hearing in childhood, becoming profoundly deaf later in adulthood. One participant had become deaf within the year prior to her interview with no prior hearing loss.

All participants owned a mobile device with a built-in smart assistant program (i.e. Siri, Google Assistant, and Amazon Alexa for Kindle). Only one participant owned smart speakers, having both an Amazon Echo and Amazon Echo Show which features a screen display. The other participants still reported using an Amazon Echo by way of family or friends and were familiar with its basic functions. Two participants were daily users of their SAs. Another reported using his a few times a week and the fourth participant had stopped using her phone-based SA after using it for a while, preferring to complete tasks through the other web-based means she had used prior to using SAs.

We conducted these interviews using a variety of methods including in-person interviews, phone-based interviews, and text-based chats. We adopted this flexible method to better accommodate different hearing needs of our participants, especially for those who did not live locally and completed their interviews remotely. We gave participants the opportunity to choose their preferred means of communication and level of comfort (i.e.,most compatible with their hearing needs and devices used). For example, one participant completed a phone interview using Bluetooth enabled hearing aids that paired directly with their phone. Two participants chose to use text based chat, as it was their main form of online communication. These differences in data collection methods may have some impact on the insights gathered. For example, there is a conversational delay when interacting via text chat versus an in-person interview, which could lead participants interviewed in this manner to provide less candid or shorter responses due to typing instead of speaking more fluidly. However, we believe that being inclusive to different abilities, promoting greater accessibility and comfort, and building a sense of rapport with participants was also crucial to gathering insightful and genuine responses.

Our key research goal is to understand how an increasingly ubiquitous technology — smart assistants — impact a significant number of individuals with hearing issues. That is, we aimed to understand their unique usage patterns as well as the accessibility issues when they interact with these devices. The researchers developed interview and survey questions to address these research goals. For example, we wanted to understand how different hearing issues might impact the usage patterns. As such, we asked questions to get a sense of their hearing loss severity. To understand their SA use, we asked questions about the devices they owned or had used, their common use case and use frequencies, as well as positive attributes they saw with SAs. To understand their challenges with SA use, we asked them to walk through notable past interactions, discuss new features or changes they would make to improve their experiences. We also leveraged recent work on accessibility (e.g., [7, 11–13, 34]) to design the interview script and surveys.

This list of questions first asked about the participant's background (e.g. level of hearing, hearing devices used, and their current age and age at the time of hearing loss). Then, we asked about their general use of SA, such as what devices they own or have used in the past, how often they use their SAs, and for what tasks they commonly use their SAs. Following this, we asked them to rate their past experiences and describe some notable SA experiences they have had in more detail — including both positive and negative interactions. We also asked which types of tasks they believed their SAs were most suited for. After this, we had in-depth discussions about the specific challenges they face when using SAs. We asked them to walk us through issues arising from their difficulty in understanding SA responses as well as misinterpretation of their voice commands by SAs. We also asked what they would change or new features they would add to make SAs easier to use and better meet their needs, including different types of feedback. We were also interested in the positive aspects they associated with

interactions from SAs and new capabilities they wanted to have in SAs. We closed our interviews asking what they wanted designers and developers to understand about their experience being deaf or hard of hearing and keep in consideration for future SAs.

A full list of the questions included in our interview guide can be found in the appendix. This list of interview questions was used as a guide for conducting interviews. All interviews included these questions in this order. However, some additional follow-up questions were asked based on individual response to provide more clarity or to ask participants to provide more detail or context to their previous response. After their interviews, two participants also followed up with us via email to provide additional thoughts and suggestions that they had regarding smart assistants. Each interview was between 40 to 75 minutes in length. All participants were electronically compensated with a $20 gift card for their time at the conclusion of their interview.

Following each interview, the first author compiled transcripts of each participant's responses. Verbal interviews — those taking place via phone or in-person — were audio recorded. These recordings were transcribed by the first author. For text-based interviews, all chat logs were saved verbatim as a transcript document. A bottom-up thematic analysis was performed by both researchers to identify consistent themes in the data set, using a qualitative interpretivist approach described by Braun and Clarke [8]. This data analysis was done in two phases. In the first phase, each researcher reviewed all transcripts separately and individually identified categories and themes within participant responses. In the second phase, both researchers iterated on this process together — merging common themes and identifying consistent sub-themes across categories. This process continued until a consensus was reached on the final themes as reported in the following sections of the paper.

3.2 Survey

Leveraging the wide range of issues identified in these interviews, we aimed to broaden the scope of our data collection to understand whether these trends persisted across the wider DHH community — including individuals from different age groups and different hearing abilities. Throughout the recruitment process, we used a professional service — Qualtrics panel — to collect data from individuals who met the inclusion criteria (i.e. considered deaf or hard of hearing and use phone or home-based smart assistants). Using a professional service like Qualtrics helped us to ensure diversity in our population sample. Given the use of a Qualtrics panel, we do not have access to response rate data (e.g., individuals who met the criteria but declined to take the survey). Additionally, we used "attention-check" questions to ensure data quality. That is, we embedded these questions within the survey to eliminate participants who might not have read the questions carefully or did not provide genuine responses. Qualtrics also use "speed-checks" — eliminating responses from those who finish the survey too quickly given the number of questions — as another measure to ensure data quality. Any respondents who failed to meet these criteria were excluded from the survey sample. A total of 73 respondents met these inclusion criteria and completed the survey.

These 73 respondents had an average age of 37.7 years (SD 13.5 years) with a range of 19-77 years at the time of the survey. The gender distribution of our sample was 43 females to 29 males, and 1 respondent who listed their gender as other. Regarding the level of hearing loss, 16% had mild hearing loss, 66% had moderate loss, and 18% had severe hearing loss. Respondents were an average age of 24.6 years of age when their hearing loss began (SD 15.1 years). Age at hearing loss onset ranged from 1- 70 years. Hearing aids were used by 55% of survey respondents, all of which were in the moderate to severe hearing loss groups. Respondents reported using both mobile and home smart assistants, however 69% considered a mobile SA (Siri, Google Assistant, or Amazon Alexa on Kindle) to be their primary SA. Survey respondents had been using their SAs between 2 months and 2 years, with an average 15 months (SD 11). None of the survey respondents reported that they had since discontinued their use of smart assistants entirely.

Based on initial insights from our interview sessions, this survey included both closed and open-ended questions allowing users to rate their own experiences, as well as providing opportunities for in-depth discussions of the problems they encounter, usage patterns in different contexts, and their own suggestions for future design. We developed questions related to the range of SA use challenges reported by our interview participants to help determine which of these key issues faced by those with very severe hearing conditions were experienced even by those with milder forms of hearing loss. This is an exploratory study to understand what use and challenge patterns exist across the larger DHH population. As such, we did not have specific hypotheses to test in the study. We analyzed closed ended responses using descriptive statistics to understand the existing trends in use across respondents. For open-ended responses, we used the same bottom-up thematic coding process applied to the interview transcripts [8]. A complete list of the questions included in this survey can be found in the appendix.

4 RESULTS

In the following sections, we present the major themes and broad list of challenges uncovered during our interview sessions with profoundly deaf SA users—themes which then helped guide the development of our survey for the wider DHH population. These themes included their common use cases, SA expectations, and the existing challenges they face while using SAs within the context of their daily lives. For each of these themes, we discuss the responses from our profoundly deaf interview participants, followed by the ways in which these initial themes align with our survey data and persist across the surveyed users of more varied hearing loss. We also address the points where the challenges experienced by our profoundly deaf interview participants diverged from survey respondents of varied levels of hearing loss. In conclusion, we discuss the role that diversity within the DHH population plays in the use of smart assistants.

We report on these findings using both qualitative and quantitative measures. In the case of qualitative information, we include key quotes provided during sessions with interview participants and included in the open-ended responses of our survey respondents. To report these items, insight provided from interview participants will be labeled *"I"* followed by their study number (e.g. "I3"). Likewise, quotes from survey respondents will be labeled *S* followed by their survey id (e.g. "S9").

4.1 Use Cases and Experiences

The participants in this study, from both the interviews and the survey samples, use SAs for a wide range of tasks and activities. Specifically, interview participants initially mentioned using phone-based assistants for information lookup while travelling, such as locating businesses or initiating GPS directions. They also used SAs in their homes for informational searches, checking the weather, sports updates, playing trivia games as well as setting reminders and calendar appointments. Furthermore, they reported putting each device to the test with difficult questions, riddles, and jokes as soon as they had got them.

Our survey respondents reported using their SAs for a range of these same tasks. In particular, the most frequent tasks for survey respondents were: alarms and timers (n=47), weather (n=47), calendars and schedules (n=44), and informational searches (n=42).

Overall, these tasks and activities are similar to the general use cases as mentioned in a number of recent prior studies [9, 26]. However, there is a notable exception involving music playback. Bentley et al. [6] found that music play dominates daily interactions with SAs (40% of all commands were related to music in their data set). For interview participants, who were all profoundly deaf, music playback through SA was not a priority. Interview participant (I3) mentioned using an Amazon Echo Show for music. However, he wanted it to display real-time lyrics to help him piece together the different layers of sounds so he could follow along. Despite frequently enjoying live music experiences, I2 explained why she did not use SAs for music playback: *"music sounds very different through [hearing] aids. I don't think it's something most deaf people are seeking because we have trouble*

with background sounds. It can reach a level of physical pain in your ear [...] The music is always too loud versus speaking voices. So I'd think any kind of device that creates extra background noise wouldn't be purchased frequently by deaf people". This particular use case, thus, shows a subtle but important distinction between general users and DHH users when it comes to the perceptions of SAs, especially smart speakers. While 27 survey respondents—all with mild or moderate hearing loss—mentioned using SAs for entertainment, only six respondents specifically mentioned music as common use for their SAs. There were no significant differences in entertainment or music use across age.

Throughout the interviews, participants reflected on having to learn their SAs' way of interacting with them and adapting to the device over time. One interviewee recalled a bit of a learning curve involved with using her SA, in that *"it may not work well [at first] but you have to just keep trying"* (I4). One participant (I2) likened learning to use SA commands to learning how to use a search engine when it first became available. *"I think a lot of it comes down to experience rather than disability. It's not necessarily intuitive for people off the bat. I just had a lot of practice [...] how to play with keywords to get the most useful responses. If you don't have that experience, then the disability makes it more difficult"*. This same idea reflected in the survey data with 62% of respondents felt that it took some degree of practice to feel comfortable using their SA. This sentiment showed a significant relationship in terms of age, with older users more likely to agree with this statement ($\chi^2(1, N = 73) = 6.16, p < .0131.$).

Interview participant 2 (I2) provided a unique perspective on SA use with hearing loss. Unlike the others who had experienced hearing loss from childhood, she had become deaf within the last year from a medical complication with no prior hearing loss. Because of this, she had used her SAs both before and after her hearing loss. I2 reported far less difficulty understanding the device's responses as well as carrying out SA interactions with fewer errors. This further highlights that users' experiences can vary significantly in terms of the onset of their hearing loss as well as their familiarity to SAs. We think that these two aspects of user diversity are important points to consider for future design.

4.2 User Expectations

Interview participants had varied expectations regarding the roles of SAs in their daily lives. Most individuals from both the survey and interview had either purchased SAs for themselves or took advantage of SAs embedded in devices that they already owned (e.g., Siri) out of their own curiosity. Sixty-three percent of survey respondents first used SAs on devices they had purchased for themselves, as compared to using another person's device (20%) or a device gifted to them (16%). Prior to use, all interview participants assumed that they would face some hearing related challenges, but not to the degree that will render SAs completely unusable for them.

Seventy-three percent of survey respondents felt a degree of reluctance prior to adopting SAs within their daily routines, due to perceived hearing-related challenges — either the device would not understand them clearly or they would have difficulty hearing the device consistently. Survey respondents with less severe hearing conditions had higher expectations and generally assumed fewer hearing-related challenges with use, however these relationships were not statistically significant.

After using for a while, one interview participant (I4) was underwhelmed by the current capabilities of SAs and stopped using them in her day to day activities: *"it's not that I can't understand Siri [...] but you have to learn new habits. I just haven't switched into doing more verbally, because I just rather search and read texts out of habit"* (I4). Sixty-eight percent of survey respondents and 3 out of 4 interviewees reported maintaining or increasing their SA use over the course of ownership, regardless of their age or degree of hearing loss.

Despite this, much of our survey data also points to overall positive perceptions of smart assistants by DHH users. For example, prior to using SAs, 42% expected them to be extremely useful; only 3% believed they would be "not at all useful" prior to using SAs. After using and getting used to their SAs, 42% of respondents believed their opinions about SAs had become "much better" over the course of use. Those with more severe hearing loss were significantly

more likely to report a positive change in their opinions of SAs over time ($\chi^2(6, N = 73) = 13.4, p < .0369$). Ninety-five percent of respondents reported being either extremely or somewhat satisfied with their overall experience with SAs across age and hearing loss severity.

Both sets of participants expected SAs to be more capable in the near future to support a wide range of daily tasks. Interview participant I1 expected SAs to *"help me—[given me] being handicapped—to be more independent and more capable of things"*. She also hoped for digital companionship from SAs that will provide *"motivational speaking when I am alone"*. In their open-ended responses, survey respondents mentioned tasks they would like to use their SAs for in the future, including language translation services, health tracking features, and as a sleep and meditation guide.

4.3 SA Challenges

Despite these initially positive responses about SAs, interview participants also identified a number of issues when asked to describe their experiences using SAs in more detail. The voice characteristics of SAs, communication expectations, and usage disruptions were among the challenges faced in smoothly embedding SAs within their daily routines. When addressing which of these challenges were persistent across the survey respondents, it became apparent that some of these challenges are faced by users to varying degrees, depending on the specific nature of their hearing loss or age.

4.3.1 Default Voice Characteristics Used in SAs. For all interview participants, the default voice of the various SAs was a leading issue in terms of both the pitch and the speed of SAs responses. I4 noted that *"depending on a male or female voice, and the pitch, determines how much I hear"*. All major SAs (i.e., Siri, Google Assistant, and Alexa) use a higher pitched female voice. This was problematic depending on the type of hearing devices used by a DHH individual. Higher pitch sounds caused difficulties for individuals using traditional hearing aids. On the other hand, those using cochlear implants noted difficulty hearing some lower tones.

Furthermore, the comfortable pitch range for those with hearing aids can evolve over the course of time requiring several adjustments by their audiologists. This can make use of SAs particularly challenging for individuals with hearing issues. I2, who was most recently deaf, recalled Google Assistant's voice being somewhat difficult to understand when she first got her hearing aids. However, after several months of adjusting, the hearing aids could more easily accommodate the default voice tone of her SA. In the past, she had switched the voice of her standalone GPS device to a lower tone *"because it was less irritating than the higher pitched female tones"* (I2), but wished she could find an easy away to do the same with her SA devices.

Half of our survey respondents found SA responses difficult to understand in their entirety and had mixed views regarding the voice characteristics of their SAs. When asked if they found issues with the voice of the SA, 36% did not see it as a challenge. There was a significant relationship with age, as older users were more likely to report difficulties due to the pitch or tone of the SA's voice ($\chi^2(1, N = 73) = 10.10, p < .0015$). Difficulty with pitch and tone was also shown as significant for those with higher degrees of hearing loss ($\chi^2(8, N = 73) = 15.5, p < .0496$). However, when asked if having the option to change the SAs voice would improve their ability to use the device, 86% of respondents agreed with this statement, regardless of age or hearing factors. In open-ended responses, some reported their main solution to combat SA voice challenges was to simply turn up the volume of the device, as it worked *"well enough to get by"* [S23]. Others did not see this as a reasonable enough solution. As one respondent [S58] stated in an open-ended response, *"I can turn up the volume to hear her, but then I start bothering the neighbors, which is a problem."* Survey respondents also noted issues that could not be addressed just by changing volume, as some pitches just do not register with their hearing aids, regardless of the device's volume. As one respondent [S17] pointed out, *"at least adding emphasis to the keywords"* within the response would go a long way in mitigating some challenges with long verbal responses and allow users to quickly get the gist of the device's response despite missed words.

Both interview participants and survey respondents reported the speed of voice responses from SAs to be challenging at times. Even if they could follow responses from SAs at their default speed, our interview participants preferred the SA to speak slower. As participant I1 described in her interview, her hearing aids let her hear layers of sounds, which she then had to process and piece back together in order to get the full meaning. Due to the speed of responses from SAs, she often had to ask her devices to repeat responses in order to gather enough information. However, given the delay in interpretation due to piecing together layers of sounds relayed from her hearing aid, she would often understand the message midway through the SA's repeated response. She would then have to wait until the SA finished speaking to start her next task, reducing overall efficiency.

This particular issue also caused challenges for the majority of our survey respondents—70% of the respondents mentioned frequently asking their SAs to repeat responses and 40% reported wanting their device to speak more slowly. There was a significant relationship between age and the likelihood of reporting that their SA spoke too fast ($\chi^2(1, N = 73) = 7.5, p < .0062$), but there was no significant difference regarding their degree of hearing loss. In their open-ended responses, one survey respondent recalled asking Alexa to repeat so many times that *"[her] husband just started relaying whatever she said so [she'd] stop asking her over and over"* [S66]. Popular smart assistants, such as Amazon Echo, do provide accessibility options to request Alexa to slow down the speed of her responses. However, interview participants in particular, were not aware that they could make such a request verbally in the middle of a task and instead opted to asked for the repeated responses.

Because of these challenges in default voices used by SAs, interview participants reported relying on dual feedback — using both voice and screen display to complete tasks. While prior studies found screen-based responses unfavorable as compared to voice responses [24], participants in this study preferred to have screen-based responses or have voice responses paired with supplemental information on their device screens. This finding mirrors the interface preferences of "cautious" user types reported by Myers et al [25]. A SA without any screen (e.g., Google Home, Amazon Echo) was thus perceived less useful by interview participants as it could not provide visual feedback. Interview participant I3 — whose family previously owned an Amazon Echo — recently purchased an Amazon Echo *Show* for the specific purpose of having a screen display. For the survey sample, 96% of respondents preferred to have a screen for additional feedback on their SAs, regardless of their age or degree of hearing loss. As noted earlier, a majority of the survey respondents considered phone-based SAs, which include some screen-based information, to be their primary SA.

4.3.2 Communicating with the Device. Participants also noted a number of other issues communicating with their SA. All interview participants recalled experiencing "a bit of a learning curve" when they first started using their smart assistants, regarding how the device expected them to interact with it, understanding error messages, and how to correct those errors. Many SAs — especially smart-speakers — use lights to provide visual feedback and convey system status, nut interview participants recalled some difficulty interpreting this visual feedback. When explaining about how to better convey errors, I2 suggested to *"expand [the lights] further, rather than the lights just going away when it gets stuck, because that gives me nothing."* They wanted to know not only that an error occurred, but what type of error, and what they could do to address it for future interactions. *"It would be nice to know where it stopped understanding or what exactly went wrong. Should I repeat that or say it differently?"* (I2). By comparison, 79% of survey respondents believed these visuals to be helpful, however 86% believed that this light feedback could be improved and more intuitive, regardless of their age or degree of hearing loss.

Interview participants using Google Assistant on phones also expressed similar frustrations when it came to understanding errors. *"We need to be told more explicitly what commands to use. The problem is, that's not really self-explanatory...There's no way to ask Google what it wants from me"* (I2).To avoid error messages or receiving incorrect responses, some participants had developed different adaptation strategies. One participant mentioned having difficulties to use Google Assistant to successfully call her pharmacist from her contacts. She was not sure

about the root cause of the error (e.g., her pronunciation of the business name). To address this error, she instead renamed the contact so that SA can perform the intended task successfully.

Interview participants also mentioned the inability of SAs to understand their voice commands to be a significant barrier to use. Some participants had difficulty with the device understanding their voice at the beginning, but they believed this to be just as true for any new SA user. As stated by I2, *"It's so trainable to your voice...just trial and error"*. Some participants paid particular attention to enunciate well when communicating with their SAs to avoid errors. As noted by I3 of his initial experiences: *"some words I didn't say clear enough for [the SA] to understand."* As I4 stated, *"most people hearing me wouldn't know I am deaf, but I still feel the need to be more precise when talking to Siri."*

The interview participants who used hearing aids reported that they often removed their hearing aids while at home to be more comfortable and get away from overpowering sounds. They expressed an interest in using their SAs unassisted. One participant (I2) mentioned *"even when I have my aids turned off, it works just as well for what I need to do, as long as there is the screen,"* regarding her use of voice to initiate tasks for screen-based responses, such as web searches. However, I4 recalled *"It's difficult sometimes, but if I enunciate more, it doesn't have too much trouble understanding me,"* when her cochlear implant is disconnected.

4.3.3 Problematic Use Cases. Voice quality and visual feedback aside, participants' hearing concerns affected the degree to which their SAs could be seamlessly embedded in their daily tasks. These challenges disrupted the "naturalistic interaction" characteristic of SAs, such as talking hands-free with the device while completing extraneous tasks with little effort. Many needed to be near the device either to see visual feedback or hear the device's verbal responses more clearly. For some, this meant only being able to use their SA in specific locations, rather than using devices across rooms. This requirement of being close to the device was seen as a disruption for tasks, such as prepping food in their kitchen. Users would have to pause their current task, move to their SA to ask a question, and resume their task only after they were finished using their SA, rather than completing the tasks in tandem like they expected to do.

Interviewees and survey respondents both referred to different ways in which their hearing needs limited how they could use their SAs. This was especially the case for mobile SAs when used outside the quiet confines of their own homes. Even when participants wanted to use SAs in public places, it was difficult due to background noise interference. Not only did they have to focus on following voice responses from SAs, but also needed to filter out other distracting ambient sounds. Others felt uncomfortable using SAs where others could hear them. For some, this stemmed from a feeling of being judged—*"I don't want people to think I don't understand how to use it. I do. I just can't always hear it"* [S59].

Survey respondents also noted that they wanted to use mobile SAs in their cars—25 of 73 respondents reported that they currently use SAs while driving. In theory, they liked the idea of using voice for directions or other hands-free tasks while driving. However, in practice, some respondents noted in their open-ended responses that the amount of attention they had to devote to understanding the verbal responses without relying on screen-based responses could be difficult and problematic within this context.

4.4 Opportunities for Increased Accessibility

Despite these challenges for using SAs, both sets of participants were very optimistic about the potential for SAs to address some accessibility challenges they faced. When SAs performed well for participants, participants perceived them to be extremely helpful within their daily lives. Many individuals felt a greater sense of accomplishment, efficiency, and like they could take better control of daily routines, despite their hearing loss. Eighty-four percent of survey respondents noted the potential of SAs to increase their independence and 86% noted SAs impact on how efficiently they complete daily tasks, regardless of age or degree of hearing loss. Some saw SAs as a learning

opportunity, such as one respondent who claimed SAs *"helped me recognize words that I still have problems with [enunciating] when it doesn't understand, so then I know what things to work on"* [S27].

Based on open-ended responses, respondents and interviewees alike felt that SAs had the potential to make certain workplace tasks easier, more specifically, those that involved communicating with multiple people at once. They wanted to deploy SAs in work meetings or school settings to help facilitate conversations, via real-time captions or to act as a note taker for any missed information. Using the SA in this way would allow them to be more actively engaged in conversation, rather than *"feel left out or constantly trying to play catch-up"* [S9].

For some participants (both in interviews and the survey), talking to strangers in public, such as asking for directions or for help in a store, was sometimes seen as a stressful experience. They did not always feel comfortable, often anticipating difficulties understanding the other person. Some participants used SAs to avoid this, opting to ask Siri or Google Assistant to help answer questions, instead of asking someone they did not know. However, other participants saw this common situation as an opportunity to use SAs to facilitate conversations in public. A few participants reported actively using SAs to help translate people's voices or particular words that did not register well with their hearing devices. Others voiced interest in a SA task that would aid in this common situation more specifically.

4.5 Diversity of DHH Users

Throughout this work, we have addressed SA use across varying degrees of hearing loss, from interview participants who were profoundly deaf, to 73 survey respondents whose hearing loss ranged from mild to severe. Despite these differences, some challenges persist across users to varying degrees. Not only does this fluctuation in hearing needs exist across DHH users, but also within individuals, as their hearing conditions change or hearing aids are adjusted over time. Such fluctuations across and within individuals can greatly affect the perceived accessibility of existing SAs. Interview participants pointed out how other members of the DHH community with varying hearing ranges may encounter different experiences and challenges. For example, they noted that individuals who are deaf from early childhood and those who mostly use sign-based language would likely face significant challenges in using SAs, more so than themselves. Additionally, interviewees discussed how individuals who mostly use sign language (e.g., ASL) often take on different speech patterns ("speaking in signs") compared to "sign-exact English" (SEE) which maintains the grammatical structure of written English. This could result in communication difficulties with voice interfaces, as SAs have been trained to anticipate specific sentence and grammar structures.

As described by our interview participants, some DHH users can have more monotonous voices lacking inflections, which they believed could be another challenge to using SAs. Furthermore, the gradual degenerative hearing loss that can occur over time in older adults may also affect voice characteristics. This could create difficulty for successful interactions if SA voice models are only trained using data from the general population. As such, a SA that can shift its voice recognition and speech generation models dynamically will be particularly useful to meet accessibility needs of those across variable hearing conditions. This further reiterates the points made by Bigham et al. addressing the inaccuracies of speech recognition for deaf individuals[7]. Overall, the diversity within the DHH community means there is a wide range of needs and constraints across individuals. These constraints might also change dramatically over time. Future iterations of SAs should take such variability in consideration to address accessibility needs of this community as a whole.

5 DISCUSSION

Through this work we aimed to understand the use and challenges of SAs for this specific population of users. To do so, we collected survey and interview data from 77 individuals who were either deaf or hard of hearing. As a result, we found that our DHH participants use SAs to accomplish numerous tasks, but this use is not without

its unique challenges. For instance, participants found the higher pitched default voices used in most SAs to be particularly difficult to hear even when using hearing aids. Also, participants' hearing needs often restricted the way in which they could use their SAs, such as having to be positioned close to their device or needing to be in a quiet room rather than out in public places. From these findings, we have identified directions for future design to better accommodate users' needs. To make SAs more accessible we suggest increasing opportunities for customization, providing more meaningful feedback, and cultivating a better understanding of the DHH community's lived experiences more broadly.

5.1 Design Recommendations

While our findings suggest that deaf and hard of hearing individuals can and do engage with SAs—some on a daily basis—their interactions with SAs are not without roadblocks or disruptions. Improved voice qualities, as well as clear and intuitive visual feedback can allow individuals even with extreme hearing conditions (i.e., profound deafness) to seamlessly integrate SAs in their daily routines with far fewer task interruptions. Making these design changes to address the accessibility needs of those with the most severe hearing loss can still accommodate those with lesser degrees of hearing loss, as well as other users, such as older adults who may face degenerative hearing loss over time. By incorporating both improved voice qualities and more clear and intuitive visual feedback, users with varying hearing conditions could more easily embed the use of SAs into their daily lives, regardless of task, context, or location.

5.1.1 Device Introduction. To make SAs more accessible, we suggest including customization features in the initial device setup procedures and call more attention to existing accessibility features from the beginning of use. Rather than having the user to adapt to the standard higher-pitched female voice, designers should include options for users to change gender, pitch, and speed of the voice used in SAs to their ideal. These findings reinforce the importance of pitch pattern for oral communicating individuals when using wearable technologies to provide environmental sound information, as noted in Findlater et al.[11]. This type of early customization can be particularly useful for individuals wearing cochlear implants or hearing aids as these devices can have difficulties capturing the pitch frequencies used in most SAs. Age related hearing loss often more severely impacts the ability to hear high-frequency sounds[39]. As such, a SA should provide customization options that allow the device to adapt to these changes in hearing abilities over time. Furthermore, customization can be beneficial for all user groups, beyond just those who may be deaf or hard of hearing. The increased ability to customize the SAs can increase their perceived sense of ownership, which could in turn, improve their overall experience with their SAs.

5.1.2 New Modalities. Based on participants' responses, we suggest incorporating different interaction modalities in the design of future SAs, such as Bluetooth and audiogram-like features. For instance, I2, who was interviewed by phone with the assistance of Bluetooth-enabled hearing aids, expressed interest in SAs that could connect directly to her hearing aids. That is, when listening to audio *without* the Bluetooth device, her hearing aids would pick up all available sound including any background noise. Then, all sounds get amplified to the same volume making it much more difficult for her to decipher a specific audio stream. However, when her hearing aids are connected directly to a device via Bluetooth, the distracting background noise is removed. This can significantly improve auditory experiences. A SA can provide similar functionality for DHH individuals — providing an option to directly connect to hearing aids through Bluetooth devices — to make communications more efficient and effort-free. Although some smart assistants currently offer Bluetooth connectivity, hearing aids that are Bluetooth-compatible are often very cost-prohibitive and inaccessible to many individuals.

5.1.3 Recalibrating Pitch. For DHH individuals, the comfortable pitch range can vary over time depending on hearing aid adjustments. This can create considerable difficulties in understanding responses from SA. To address

this issue, I3 suggested the ability to calibrate the voice response from SA over time by using an audiogram-like test, which is used commonly by audiologists. In this case, users would be given example pitches or words by the SA to which the user would respond if and when they could hear the device. In doing so, SAs can have objective and concise information about comfortable hearing ranges for an individual. This information then can be used for adapting voice responses from SAs.

This recalibration via audiogram feature could be initiated by the user when their hearing or aid devices have changed substantially. In other instances, the device could initiate this process by periodically checking in with the user, asking "how am I doing?" or "Would you like to adjust my voice to better hear me?". Additionally, this option could be prompted when the device recognizes a significant amount of communication errors with the user, such as several repeat response commands. In the case that the SA addresses the user about these options, this action should be paired with an appropriate visual component, such as a unique light pattern to communicate with the user unprompted.

5.2 Discoverability and Visual Cues

Participants also described difficulties in exploring and knowing about features and functionalities provided by a SA. Discoverability is critical for good usability, but is amplified when other usability needs associated with hearing are also not adequately met. In other words, not only do users often face difficulties hearing their device, but some also they find the design of current SAs and the type of feedback provided (e.g., simplistic light patterns) as too ambiguous at times to help overcome these hearing-related challenges. As such, being able to clearly convey what a SA can do and how to use it to complete certain complex tasks is an important research challenge.

Additionally, users found it difficult to anticipate errors or understand the device's expectations for each interaction. Interviewees and survey respondents alike expressed an interest in having more thorough instructions at the beginning of use to help inform their behaviors. For instance, some wished they had been given concrete examples of commands they could use and a better idea of what to expect when conversing with their SAs. This falls in line with the suggestions previously made by Myers et al. [25] of a "training wheels" introduction for more "cautious" VUI user types within the general population (e.g. those without hearing loss).

Because of these common communication errors, we suggest system design address these issues more proactively, such as recognizing a user's common problem points and providing tailored solutions. Following high demand, users can now verbally request Amazon Alexa to speak faster or slower.[1]. This concept could be leveraged to further improve accessibility for DHH users by asking the user for their in-situ feedback about its response speed. For instance, if a SA was to repeat a response to the user three times in a row, the device could give the response to the user, but follow up with *"would you like me to speak slower next time?"* at a slower pace of speaking. By providing an option like this, errors can be addressed more seamlessly and in the moment. It can also help users discover existing accessibility options and lead users to apply them when needed in the future without prompting.

Participants liked that smart speakers, like Amazon Echo, provided some form of visual cues, despite not having a screen. However, they wanted the lights to convey more informative messages, beyond the mere indication from devices about on-going processing or communication errors. Participants were receptive to the idea of using different patterns or colors to add more specificity, such as communicating the specific type of error that occurred and how to fix the error for future interactions. Because of this, we suggest future work to explore options for more expressive light-based communication for error messages, but also as a way to inform users of successful interactions. This type of visual feedback could be used to clarify the device's expectations for the user, but also do so in a way that is educational and mitigates the negative experiences of users [20].

Interview participants, as well as many survey respondents, wanted information about common commands, error codes, and visual feedback to be more tangible, such as a small card that comes with their device or visual

examples with written directions. One interview participant noted that there were often video tutorials online to teach her how to use her SA, but she found videos more difficult to follow because of insufficient captioning or no captions provided at all.

While screen-based information may not be a priority for other users, whose use is motivated by SAs' hands-free capabilities, simplifying devices to interact through voice alone only hinders accessibility on the larger scale. Therefore, we suggest considering the implications of providing multiple feedback modalities and the opportunities it can provide for use within a diverse and broadening user population.

5.3 DHH Users and the Wider User Population

While some of the findings of our work support previous findings applied to the general population, we show that they can be significantly heightened for those experiencing hearing loss. Previous work has shown that SA use is not without its challenges, even for those without hearing-related barriers, for both communicating with the device and anticipated SA responses [23, 30]. For users, a lack of device cues to facilitate turn taking can lead to interruptions and asynchronous conversations [31, 32]. Conversational cues, which SAs currently present verbally or try to convey through often ambiguous light behaviors, are especially important for DHH users for contextual information and to help fill in any conversational gaps between them and their SA.

When Myers et al. [25] looked into user preferences for voice user interfaces (VUI) factors such as assimilation bias influenced user performance metrics and those who had more technical confidence often adopted a trial and error approach to using an unfamiliar VUI. Those who were classified as "cautious users"—those who performance indicators show more time take to consider and complete VUI tasks—wanted more visual information to use or a "training wheels" mode to help orient themselves to the device. These same preferences were voiced by both interview and survey responses. Participants, especially those interviewed, talked about the learning curve they faced when they first tried out their SAs, which involved trial and error to understand, not only how the device worked, but how the device worked given their specific hearing needs and any adjustments they needed to make in their voice commands for more successful interactions. Interview participants suggested improving user tutorials, including options similar to the "training wheels" mode discussed by Myers, but specifically called for more visual-based tutorial information to help them get used to their devices. In other words, while SAs giving more verbal feedback during this introduction period was perceived as useful by our DHH users, having supplementary visual resources, such as video tutorials with full captions or written example scripts, would be more helpful for their specific needs.

Although users expect to use SAs hands-free, they occasionally provide screen-based feedback depending on the task initiated, requiring users to physically interact with their devices (e.g., showing results of a web search on screen instead of a verbal response) [24]. Although SA users without hearing conditions have shown some frustration when phone-based SAs choose to relay information visually, through screen-based messages, rather than the expected verbal response [24], presenting this information in two formats (visual and verbal) or allowing the user to customize this response format could help meet user needs on a wider scale.

Additionally, there is often a disconnect between how people talk naturally and the way smart assistants have been trained to expect users to talk, which can lead to inaccurate speech recognition [24, 40]. Work to further expand the type of voices and patterns SAs are trained to anticipate could help address some of the speech differences present for those with more severe hearing loss. This could also improve how well SAs interpret users verbal commands on a much wider scale, from general users to those with more specific concerns, such as those with speech impairments [5].

This shows that there is an overlap in the challenges faced by DHH users and those noted for users without additional hearing barriers, with those of more profound hearing loss experiencing them to a greater degree. Because of this, our findings and design recommendations, although originally meant to increase accessibility

for DHH users, could potentially improve SAs' overall ease of use for the population as a whole and could have larger implications beyond this original context.

6 CONCLUSION

Smart assistants have become increasingly common in our daily activities. However, little work has looked into how deaf and hard of hearing users engage with SAs. Determining accessibility issues that might uniquely impact this user group is critical for addressing their needs, as well as developing better technology for a diverse population. This study aimed to address this important research gap by conducting an in-depth qualitative study with four profoundly deaf individuals, followed by a survey of the broader DHH community.

While the small number of participants in the interview portion of this study is a limitation, they showed some degree of variation in the way they viewed and used SAs. These interviews also provided a rich background and useful pointers to explore through our larger survey sample, as well as address whether their concerns are echoed throughout the wider DHH community. Despite age and hearing loss, we found a high level of consistency regarding their use cases and expectations for SAs, as well as the types of challenges and experiences they faced while using SAs. These key challenges were felt by users to varying degrees of severity. This highlights that there is not necessarily one solution to make SAs more accessible to this user group, but rather there is a need for a holistic approach that provides flexibility and customization in the way users can interact with their devices. This work provides an initial look into how voice-based devices are currently used and received by those whose needs may not have been set as a priority during the initial stages of SA development.

To fully understand the range of accessibility concerns for DHH users, future work should include those newly introduced to SAs, those who have discontinued their use of SAs over time, and those with more severe hearing conditions unaided by hearing devices. Moving forward, it will be critical to conduct a more longitudinal look at how DHH users interact with their SAs in real life contexts. This can be achieved by analyzing real-time SA use and the content of their existing usage and data logs from SA devices. Such quantitative data can provide a complementary perspective on their use and uncover other potential accessibility roadblocks, beyond those reported by participants in this study.

Echoed by the words of one respondent [I4], SA designers should *"put themselves in our shoes, see what it is really like, and try to imagine that they are hard of hearing."* Given this common sentiment, we strongly believe that future iterations of SAs should take a participatory design approach and involve members of DHH community directly in the design and evaluation processes. As I4 noted: *"They need to involve us ahead of time to keep ahead of things, rather than asking us how to fix something once they find it doesn't work well for us."* This study sheds light on the ways in which SAs can better accommodate a range of hearing abilities and provides a step forward toward a truly inclusive SA.

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7 APPENDIX

7.1 Interview Questions

7.1.1 Background.

- Describe your general level of hearing
- Any aid devices you currently use.
- For how long?
- Age

7.1.2 General Use.

- Which smart assistants have you used before (Siri, Alexa, Google Home, Google Assistant, Cortana, etc.)?
- *If multiple.* Which do you use most often?
- Are these all devices that you own or have you also tried out other people's SAs?
- How often would they say you use your smart assistant? e.g.- never, a few times ever, one a week, everyday...
- How long have you used your smart assistant?
- How did you first hear about smart assistants? –or- how were you first introduced to SAs?

7.1.3 Experiences with SAs.

- How would you rate your past experiences using SAs?
- Can you describe some of your experiences (e.g. when you first started using them vs. currently)?
- Can you guide me through thoughts you commonly have while using your SA?
- Any interactions that stick out to you?
- What do you most commonly use them for?
- For what tasks do you find them most useful?
- For what tasks do you feel they fall short?

7.1.4 Challenges faced.

- What are some of the major challenges you have faced while using the SAs?
- What do you find most frustrating about some of your interactions with the SA?
- Is the main concern understanding the device response or the device understanding your response?
- What about the current design isn't working or do you not like?
- Ideally, what elements would you change about Alexa, Siri, Google?

7.1.5 Expectations of SAs abilities.

- Before using your SA, what did you expect them to be able to do?
- *If multiple* Did you have differing opinions or expectations of your two different devices?
- *If only one* What led you to choose the SA that you have over others?
- If phone based, did the idea that your phone included Siri/Google Assistant factor into you decision to purchase the phone?
- What type of user do you imagine different SAs being developed for? –E.g. who do you think was Apple/Google/Amazon's target user when they created their devices?
- Who do you think would find them most useful?
- Now that you have used your SA for some time, how do your initial expectations hold up to how you feel about your SA now? E.g. Was it better, worse, or exactly as expected?
- What led you to form those expectations?
- *For those who had low expectations*, did that make you reluctant to use SAs? What eventually changed your mind?

7.1.6 Positive attributes and new opportunities for use.

- What do you like about SAs, based on your experience?
- How do you feel about the type of responses it provides?
- Are they useful or what you were looking for?
- Are they given in a way that is easily understood?
- In what new ways do you think SAs could help you out in your daily life?
- If you could add any new skills or features to your current SAs, what would they be?
- What other types of feedback would be make the device more useful?
- If the challenges (as previously mentioned) were eliminated or made more accessible, how could you see yourself using Alexa, Siri, Google?
- What new opportunities can you see for future use (for others, not necessarily themselves)?
- If you could design your own smart assistant, what types of features or capabilities would you want it to have?

7.1.7 Home-based SAs.

- Have you ever tried out a home-based agent, like Amazon Echo with Alexa or Google Home?
- If not, have you wanted to...why/why not? (Are they reluctant to use a device without screen feedback?)
- What additional features or types of feedback would improve their ease of use?
- Would you be interested in using a home-based device, like Amazon Echo or Google Home, just to test out what they are capable of doing?
- In what cases in your own daily life could a home-based device be useful (or more useful than your phone-based device)?

7.1.8 Privacy/security concerns.

- Do you have any concerns of privacy or security in interacting with SAs?
- If so, what are they?

- What types of information would you feel uncomfortable sharing with Alexa, Siri, Google?

7.1.9 *Concluding Thoughts.*

- Based on your own experience you have any additional design suggestions to make these types of technology more accessible to the DHH community?
- What would you like designers or developers to think about or better understand when designing voice technologies in the future?

7.2 Survey Questions

(1) What is your current age?
(2) Would you describe yourself as either deaf or hard of hearing?
(3) Have you used a smart assistant before? This can include those on mobile devices (e.g. Siri, Google Assistant, Amazon Alexa) or home-based smart assistants, such as Amazon Echo, Google Home.
(4) What is your gender?
Male
Female
Otherwise specified
(5) At what age did you first become hard of hearing or deaf?
(6) How would you describe your current level of hearing loss?
Mild
Moderate
Severe
Profound
(7) Do you currently use any devices to aid your hearing (e.g. cochlear implant, hearing aids, etc.)?
(8) What hearing devices do you currently use (if any)?
(9) Which smart assistants have you used before? (Choose all that apply.)
Amazon Echo
Google Home
Siri on iPhone
Alexa on mobile device (Kindle, phone etc.)
Google Assistant on mobile device
Microsoft Cortana
Other
(10) Which smart assistant do you use most often?
Amazon Echo
Google Home
Siri on iPhone
Alexa on mobile device (Kindle, phone, etc.)
Google Assistant on mobile device
Microsoft Cortana
Other
(11) How often do you use your smart assistant?
Many times daily
Once a day
4-6 times a week
2-3 times a week

Once a week
Every few weeks

(12) How many months have you used a smart assistant?

(13) How did you first come to have a smart assistant?
Purchased it myself
Someone in my household purchased it
Given as a gift
Used a friend or family member's device
Used at my workplace
Other

(14) What do you commonly use smart assistants for? (Choose any that apply.)
Setting timers/alarms
Lists- groceries, to-do items
Scheduling- calendar, appointments, etc.
Weather
News updates
Information searches
Entertainment- games, trivia, jokes, etc.
Online shopping
Controlling other smart home devices- lights, temperature
Communication- checking messages, calling/texting others

(15) For what other tasks have you used your smart assistant?

(16) Where do you often use smart assistants? (Check all that apply.)
Living/Family Room
Kitchen
Bedroom
Bathroom
Office
Car
On the go (e.g. travelling, public spaces, etc.)
Other

(17) How would you rate your past experiences using smart assistants?
Extremely satisfied
Somewhat satisfied
Neither satisfied nor dissatisfied
Somewhat dissatisfied
Extremely dissatisfied

(18) Prior to using smart assistants, how would you describe your expectations for using them?
Extremely useful
Very useful
Moderately useful
Slightly useful
Not at all useful

(19) How do you feel your opinions about smart assistants have changed over time?
Much better
Somewhat better

About the same
Somewhat worse
Much worse

(20) What do you find most frustrating about some of your interactions with smart assistants? (Choose any that apply.)
Device not understanding my commands
Not understanding device responses
Low voice quality
Inaccurate responses
Too fast or too slow voice responses
Lack of visual feedback
Not applicable

(21) How satisfied are you with the accuracy of your smart assistant's responses?
Extremely satisfied
Somewhat satisfied
Neither satisfied nor dissatisfied
Somewhat dissatisfied
Extremely dissatisfied

(22) How useful do you find your smart assistant's responses?
Extremely useful
Very useful
Moderately useful
Slightly useful
Not at all useful

(23) How easy is it for you to understand responses from the smart assistant?
Extremely easy
Somewhat easy
Neither easy nor difficult
Somewhat difficult
Extremely difficult

(24) How accurately does your smart assistant understand your commands and questions?
Extremely accurate
Very accurate
Moderately accurate
Slightly accurate
Not accurate at all

—For the following questions, indicate how you agree with each statement about your experiences with smart assistants.—

(25) I was initially reluctant to use a smart assistant
Strongly agree
Somewhat agree
Neither agree nor disagree
Somewhat disagree
Strongly disagree

(26) I often have difficulty understanding responses from the smart assistants
Strongly agree

Somewhat agree
Neither agree not disagree
Somewhat disagree
Strongly disagree

(27) I often ask my smart assistant to repeat itself so that I can understand its responses
Strongly agree
Somewhat agree
Neither agree nor disagree
Somewhat disagree
Strongly disagree

(28) Using a smart assistant has been easier than I originally expected
Strongly agree
Somewhat agree
Neither agree nor disagree
Somewhat disagree
Strongly disagree

(29) The tone or pitch of my smart assistant's voice makes it difficult to understand
Strongly agree
Somewhat agree
Neither agree nor disagree
Somewhat disagree
Strongly disagree

(30) My smart assistant speaks too fast
Strongly agree
Somewhat agree
Neither agree nor disagree
Somewhat disagree
Strongly disagree

(31) The usefulness of my smart assistant depends on whether I am using a hearing device (e.g. cochlear implant, hearing aids)
Strongly agree
Somewhat agree
Neither agree nor disagree
Somewhat disagree
Strongly disagree
I do not currently use a device to aid my hearing

(32) I use my smart assistant less often now than when I first got it
Strongly agree
Somewhat agree
Neither agree nor disagree
Somewhat disagree
Strongly disagree

(33) It takes longer for me to ask my smart assistant a question than typing it into Google search
Strongly agree
Somewhat agree
Neither agree nor disagree

Somewhat disagree
Strongly disagree

(34) It has taken a lot of practice to learn how to successfully interact with my smart assistant
Strongly agree
Somewhat agree
Neither agree nor disagree
Somewhat disagree
Strongly disagree

(35) I feel like developers considered my needs when designing my smart assistant
Strongly agree
Somewhat agree
Neither agree nor disagree
Somewhat disagree
Strongly disagree

(36) I feel like my smart assistant has helped to increase my independence
Strongly agree
Somewhat agree
Neither agree nor disagree
Somewhat disagree
Strongly disagree

(37) I find my smart assistant is very intuitive to use
Strongly agree
Somewhat agree
Neither agree nor disagree
Somewhat disagree
Strongly disagree

(38) I feel like I can accomplish tasks more efficiently when using my smart assistant
Strongly agree
Somewhat agree
Neither agree nor disagree
Somewhat disagree
Strongly disagree

(39) I am often unsure whether my smart assistant has heard my command or question
Strongly agree
Somewhat agree
Neither agree nor disagree
Somewhat disagree
Strongly disagree

(40) I feel like my smart assistant responds better to other people's voices than my own
Strongly agree
Somewhat agree
Neither agree nor disagree
Somewhat disagree
Strongly disagree

(41) I find the visual feedback used by my smart assistant easy to understand (e.g. light notifications, screen-based messages)

Strongly agree
Somewhat agree
Neither agree nor disagree
Somewhat disagree
Strongly disagree
—For the following set of questions, please rate how useful you would find these feature if they were added to smart assistants (e.g. Google Home, Amazon Echo)—

(42) A smart assistant using different light patterns to provide feedback — for example, light patterns to indicate when it has understood your commands and when it needs you to repeat commands
Extremely useful
Very useful
Moderately useful
Slightly useful
Not at all useful

(43) A smart assistant with a screen that provides visual information to supplement verbal responses — for example, the screen showing the transcript of audio responses from the smart assistant
Extremely useful
Very useful
Moderately useful
Slightly useful
Not at all useful

(44) A smart assistant providing a written reference guide along with video tutorials. Such a guide will provide details about available commands as well as describing common error messages in the smart assistant
Extremely useful
Very useful
Moderately useful
Slightly useful
Not at all useful

(45) The ability to customize the smart assistant's voice to my liking (e.g., changing pitch, gender, speed)
Extremely useful
Very useful
Moderately useful
Slightly useful
Not at all useful

(46) (*conditional on their response of the question above.*) In what ways would you like to customize the voice of your smart assistant? Why?

(47) How concerned are you about your privacy when using smart assistants?
Extremely concerned
Very concerned
Moderately concerned
Slightly concerned

(48) How concerned are you about your security when using smart assistants?
Extremely concerned
Very concerned
Moderately concerned
Slightly concerned

Not concerned at all

(49) What types of tasks would you feel uncomfortable using your smart assistant for? (Choose any that apply.)
searching for personal health information
tasks using your banking information
controlling your home security system
making online purchases
recording daily diary entries
tracking daily diet and exercise information
guided meditation
as a motivational speaker or for daily affirmations

(50) What are your main security concerns for using your smart assistant? If any.
(51) For what tasks do you find your smart assistants to be most useful?
(52) What features in smart assistants do you find most challenging to use?
(53) In what ways have smart assistants improved accessibility for your daily tasks?
(54) In what ways have you found your smart assistant to be incompatible with your hearing needs?
(55) Based on your own use, what features would you add to your smart assistant to improve your overall experience?
(56) What tasks would you like to use your smart assistant for that it currently cannot do?
(57) In what ways could smart assistants help you complete workplace or school tasks? (e.g. facilitating conversations, group meetings, etc.)
(58) In what ways could you use smart assistants to connect with friends and family in or outside of your household? (e.g. entertainment, keeping in touch, etc.)
(59) In what ways would you use mobile smart assistants to help with tasks out in public places? (e.g. running errands, traveling, public transportation, etc.)
(60) Based on your own experience using smart assistants, what do you think is for designers and developers consider when creating smart assistants for other deaf or hard of hearing users?