J. Williams, T. Azim, A. -M. Piskopani, A. Chamberlain and S. Zhang, "Socio-Technical Trust For Multi-Modal Hearing Assistive Technology," 2023 IEEE International Conference on Acoustics, Speech, and Signal Processing Workshops (ICASSPW), Rhodes Island, Greece, 2023, doi: 10.1109/ICASSPW59220.2023.10193586.

SOCIO-TECHNICAL TRUST FOR MULTI-MODAL HEARING ASSISTIVE TECHNOLOGY

Jennifer Williams [1], *Tayyaba Azim*[1], *Anna-Maria Piskopani* [2], *Alan Chamberlain* [2], *Shuo Zhang* [3]
[1] University of Southampton, UK
[2] University of Nottingham, UK
[3] Bose Corporation, USA
j.williams@soton.ac.uk

ABSTRACT

The landscape of opportunity is rapidly changing for audio-visual (AV) hearing assistive technology. While hearing assistive devices, such as hearing aids, have traditionally been developed for populations of deaf and hard of hearing (DHH) communities, the ubiquitous use of in-ear technology and recent advances in edge computing are reformulating what drives research and development in this domain. With that comes new challenges to consider from the perspective of multiple different stakeholders. In this position paper, we elaborate on seven key socio-technical challenges that may impede the adoption of trustworthy multi-modal hearing assistive technologies. We also draw upon a recent survey being piloted in the UK to examine perceptions of trust for audio systems in the context of human rights. We strongly encourage the research community to consider *trust* as a factor in developing new AV assistive hearing technologies, as trust may ultimately drive adoption of this technology within broader society.

***Index Terms*—** multi-modal technology, hearing assistance, privacy, security, trust, survey

1. INTRODUCTION

According to the World Health Organization (WHO), as of 2023 more than 5% of the world's population is deaf or hard of hearing (DHH) and this is expected to increase to 1 in 10 people worldwide by 2050[1]. Likewise, it is important to note that *wearables* [1], and more specifically *earables* [2] are entering the industrial tech market at a rapid rate, in an effort to offer more services to the general public – these range from background noise cancellation [3] and speech enhancement [4], to higher quality phone calls and hands-free music listening experiences. Wearables are essentially wearable computers that can perform tasks or provide services in a discrete manner that does not interrupt daily life [5]. Wearables may also include devices such as earbuds and hearing aids, whose purpose is to enhance or change audio for the benefit of the user. For the DHH community, these wearables have traditionally been focused on unimodal processing such as audio-only hearing aids that mostly rely on digital signal processing (DSP) algorithms [6].

Recent advances in edge devices, including on-device neural network accelerators and reduced algorithmic complexity, now allow wearable assistive devices to include both audio and visual components, branching into the areas of *audio-visual* (AV) or *multi-modal* processing [7]. The multi-modal aspect of AV hearing assistive technology (HAT) may provide a range of benefits for users, including the capability to selectively enhance speech based on the user's eye gaze [8, 9] and lipreading-based technologies [10]. Given that speech enhancement in noisy environments is especially challenging, adding the visual aspect to hearing aid algorithms has been predicted to result in more reliable performance [11]. While the DHH community is a primary stakeholder in the development of multi-modal hearing assistive technology, there are many other stakeholders to consider, with a range of different needs and priorities.

In this paper, we first describe our survey that is currently being piloting in the United Kingdom, that explores trust toward audio systems in the context of individual rights. Next, we present and discuss issues that contribute to trust in relation to hearing assistive technologies in terms of socio-technical challenges. The seven challenges presented in this paper are paramount for the research community to consider as an additional perspective during algorithm development in order to achieve the maximum positive impact for the DHH community, which may ultimately impact upon the usability and uptake of the technology as well as its effectiveness when being used.

2. PILOT SURVEY: TRUSTWORTHY AUDIO SYSTEMS

We are currently developing a large-scale survey[2] that probes public perceptions of trust towards a variety of audio systems, including AV technologies meant to help blind (visually impaired) and DHH communities. In our first pilot of the larger survey, we collected responses using the Qualtrics[3] and Prolific[4] platforms from 45 individuals (balanced between male and female respondents) who are based in the United Kingdom. We collected background information such as income level, educational attainment, profession, and age range. Participants were provided with a series of statements alongside a 5-point Likert scale of agreeableness (strongly agree, somewhat agree, neutral, somewhat disagree, and strongly disagree). For clarity in this paper, we have combined the 'strong' and 'somewhat' categories. Participants were asked to respond to the questions as honestly as possible.

In Figure 1 we show some example statements and responses with regard to individual rights in the UK. As seen in Figure 1, we found that the majority of participants believed that their permission is required in order for their voice to be captured by a device and that they would like to know if their voice has ever been used (and for what purpose). Next, we provided participants with a series of various scenarios to contextualize audio systems in use. In this paper, we focus on two particular scenarios for discussing AV assistive

This work was supported by the UK Engineering and Physical Sciences Research Council (EPSRC) through the Trustworthy Autonomous Systems Hub (EP/V00784X/1).

[1] https://www.who.int/news-room/fact-sheets/detail/deafness-and-hearing-loss

[2] University of Southampton Ethics ERGO Number: 78339

[3] https://www.qualtrics.com

[4] https://www.prolific.co

	Agree	Neutral	Disagree
When I speak, I reveal personal information.	70.45%	15.91%	13.64%
My voice is a personal characteristic. It is a part of my identity.	93.18%	4.55%	2.27%
Anyone is allowed to record my voice without my permission.	18.19%	18.18%	63.63%
I carefully read the privacy policy before agreeing to the terms of service.	34.09%	4.55%	61.36%
I have been harmed by using audio technologies (e.g. through identity theft).	0.00%	9.09%	90.91%
I am not sure if someone has used my voice.	75.00%	15.91%	9.09%
I would like to know if someone has used my voice and for what purpose.	95.45%	4.55%	0.00%

Fig. 1. Responses regarding awareness of individual human rights and technology.

technologies:

> **Scenario #1:** Nancy is blind. She uses a special type of AI-assistive device that speaks out loud and describes her surroundings.
>
> **Scenario #2:** Jane is hard of hearing (almost completely deaf) and uses a special hearing aid to help her throughout the day. This hearing aid can enhance specific voices that are within 5-10 metres from where she is standing. It can also generate transcripts of conversations, which she can access and read to herself later.

	Agree	Neutral	Disagree
I have a right to know that my presence is being observed and described by an AI technology.	63.63%	15.91%	20.45%
Nancy has the right to use this technology, including in public and private spaces.	86.36%	4.55%	9.09%
Nancy should wear earbuds or earphones so that no one has to listen to her device.	50.00%	20.45%	29.54%
There are better types of technology to help the blind that Nancy should be using instead.	15.91%	61.36%	22.73%
When I'm around Nancy, I worry if there is a database storing too much information about me.	27.27%	25.00%	47.73%
I would like the ability to control whether Nancy's AI device describes me out loud or not.	29.54%	18.18%	52.27%

Fig. 2. Responses regarding perceptions of visual assistive technology for communication scenario # 1.

	Agree	Neutral	Disagree
Jane's hearing aid should only enhance my voice if I am speaking with her.	72.72%	13.64%	13.63%
Jane might overhear a conversation that she was never meant to hear.	90.91%	0.00%	9.09%
I have a right to know if my voice is being enhanced or amplified by an AI device, even if it is meant as an assistive technology.	63.63%	13.64%	22.72%
I am not comfortable with my speech being transcribed without my permission.	45.45%	13.64%	40.91%
Jane has a right to use this technology, regardless of my opinions about my privacy.	65.91%	18.18%	15.91%
I worry that my words will be transcribed incorrectly.	65.91%	11.36%	22.73%

Fig. 3. Responses regarding perception of audio assistive technology for communication scenario # 2.

We show responses for Scenario #1 (Figure 2) and Scenario #2 (Figure 3). We found that most participants believe that they have the right to know if an assistive device is observing them and describing them (such as with visual assistance or scene analysis). With regard to hearing aids, most participants responded that the hearing aid should only enhance a voice if they are speaking directly with the hearing aid wearer, with some concerns that a hearing aid wearer might overhear a conversation unintentionally. At the same time, in both scenarios, participants tend to agree that the users of the assistive technology have the right to use these devices in the assistive context.

3. SOCIO-TECHNICAL CHALLENGES

This section highlights some of the socio-technical challenges faced by multiple stakeholders, ranging from the end users to technical developers and clinicians. We also consider people in the user's local environment to be a stakeholder in AV hearing assistance, as their presence (image and sound) may be captured with such devices. Here we present seven socio-technical challenges: (1) social acceptance, (2) complexity of integrating multiple technologies, (3) cost and battery life, (4) non-compliance, (5) variability in user preferences, (6) integrated explainability, and (7) privacy and security concerns.

3.1. Social Acceptance

Although the use of hearing aids has increased in the last few decades, due to people openly seeking help for hearing problems and more celebrities and public figures talking openly about the use of their hearing aids[5], researchers and technology developers still face the challenge of designing socially acceptable devices. The social acceptability of smart devices is dependent upon a given users' needs and values, that ultimately define how they want to present themselves to the world, and how they would like to be perceived in various social contexts [12]. Hearing aids could be perceived as a sign of aging, mental inadequacy, weakness and disability, thus affecting an individual's professional image and social life. With the advancement in hearing aid technology, wearables have become smaller, more discreet, and increasingly powerful – all of these help hearing aid users to be able to hide the assistive device. Additionally, society has become more educated about hearing loss and the technology supporting this community. These efforts have helped in minimising the stigma associated with hearing aids, however this problem still persists for people who are self conscious and who worry about being judged socially or stigmatised [13].

3.2. Complexity of Integrating Multiple Technologies

The design of hearing assistive devices involves the application and combination of a range of technologies from different domains, including speech enhancement, speaker identification, speech recognition, sound localization, and noise cancellation, among others [4, 11]. These capabilities rely on a variety of inputs, such as audio, visual, and haptic (touch) feedback, where each could potentially be developed by different organizations. Integrating them seamlessly can be a significant challenge to achieve a comprehensive and effective AV HAT technology for individuals with hearing loss. The new Audio-Visual Speech Enhancement (AVSE) Challenge takes the first step toward accomplishing this by setting benchmarks in this research area [9].

In a real-world deployment, some products that are currently on the market are being used in lieu of hearings aids as medical devices [14]. It has been shown that Apple Wireless Airpod Pro Earbuds, originally designed for non-DHH communities, are being adopted and used for hearing assistance by the DHH community because of a LiveListen feature that Apple incorporated into the design [15]. However, as [15] argues, the LiveListen functionality meant to help the DHH community has limited reach, for example in cases where Apple has underestimated the users needs with simple technical issues like software updates or failed to advertise this feature in marketing. At the same time, products like the Apple Airpod Pro have been exalted for having the potential to reduce overall stigmatization of hearing aids, as more people adopt this technology and consider it "hip" (i.e., socially acceptable) to use [16]. Such products not only contribute to the reduction of social stigma that

[5] `https://www.amplifon.com/au/blog/8-famous-people-wearing-hearing-aids`

hearing aid wearers experience, but they can also integrate easier with other "smart" technologies that people may already be using.

Another challenge relates to the synchronization of the different modalities (audio/visual/haptic) in a given system, so that they provide a consistent and unified experience for the user. Multimodal hearing technologies offer an opportunity to overcome the primary issue of traditional hearing aids, which is the problem of non-discrimination of audio sounds. Traditional hearing aids cannot localize or focus sound enhancement capabilities based on the user's immediate needs in their environment [2]. Technically, the developers need to ensure that various modalities do not interfere with each other, and that the user can selectively focus on the modality that is most relevant to them at any given time. Researchers could also use this opportunity to make AV HAT compatible with other existing gadgets and assistive devices in the environment, such as hearing aids, cochlear implants, smartphones, television, wireless handsets, headphones, etc. This will be a significant challenge as different devices use different technologies developed by different manufacturers, but it has the potential to provide a seamless user experience. Any delay in audio transmission to the hearing aid due to synchronisation or compatibility issues can further add to the non-compliance of the technology.

3.3. Cost and Battery Life

Hearing assistive technologies can be expensive, especially those that incorporate multiple modalities. High costs can make them inaccessible to some users who would stand to benefit from using them. Battery life is also an important issue in the design of multi modal hearing aids as different components of these devices needs to be charged when used for an extended period of service. Though recent work from [17, 18] has focused on developing energy efficient machine learning models, the issue of cost is very important for deploying future AV HAT technologies.

3.4. Non-Compliance

As hearing assistive technology is considered as a medical device, compliance among users is the key to treating hearing loss and improving quality of life. A study by [19] reports that the majority of adults aged 55-74 years old refuse to wear their hearing aids. Reasons for non-compliance span many socio-technical issues from poor speech quality, difficulty with battery life, difficulty being fitted with an audiologist, and even the perception that the hearing aids are not useful for everyday life situations [20]. Non-compliance is a large issue still because as work from [21] posit, untreated hearing loss in midlife can contribute to dementia due to disrupted brain activity in difficult or noisy listening environments. These issues will become more challenging when HATs are multimodal.

3.5. Variability in User Preferences

Since people have different hearing and visual capabilities, their preferences towards the use of different modes of communication may vary. For example, in case of television programs, some viewers with hearing disability may prefer to turn up the volume, whereas others feel more inclined to read the captions or follow the program with a sign language interpreter overlay. ProtoSound [22] is one step towards personalization as it allows DHH users to experience a customized sound experience and the algorithm requires few training examples to scale across many different types of sounds. Because of these individual differences, technology designers should strive to accommodate personal needs and preferences of individual users making their experience more user friendly and positive [23]. Not only should this effort involve tackling additional barriers to communication with the wearable devices but also it should aim for convenience in wearing the devices along with handling users cultural preferences [24, 25].

There is also a dire need to make these devices accessible for everyone, including those with disabilities. This can require special considerations, such as providing alternative input and output methods for users with mobility impairments. Training should also be arranged for people using the multi modal hearing assistive technology so that they could learn to use the technology effectively at their own pace and according to their personalised needs [26].

3.6. Integrated Explainability

In order to improve the power and understanding of AI algorithms that are integrated with hearing aids, deep learning based models are being used to amplify the performance and experience of the technology [4, 10, 23]. However, these deep models are black boxes and do not offer explanations for the decisions made by the device. The lack of explanations pose a direct threat to the end users' rights and community's trust towards the use of the technology and can negatively impact how people formulate their attitudes towards the use of AI for beneficial uses. In order to protect rights and mitigate any algorithmic risks, AI research communities and human rights organisations propose AI guiding principles to assist developers to design devices in a publicly accountable ways. Among them are: human rights' protection, explainability, responsibility, audibility, accuracy, fairness, transparency, user control. [6,7,8]. To comply to explainability principle, algorithmic decisions (such as predictions, decisions, actions, and recommendations), as well as any data driving those decisions must be explained to the end-users and other stakeholders in non-technical terms. Adoption of the technology, and building trust, will require users to understand how voices and noises are amplified, especially when the users have some control over their preferences (described above). It is therefore required that the future research focus more on transparency, interpretability, and understandability in the design of AI technology used for hearing assistance.

3.7. Privacy and Security Concerns

Privacy concerns are a major issue for multi-modal wearables, including non-medical devices such as Google Glass [7]. Though often viewed as a feature (rather than a security concern), sensing algorithms such as EarID can perform user authentication and identification using a built-in microphone inside of the earbud itself [27]. With multi-modal hearing technology, the privacy concerns compound as non-users in the ambient environment may object to being "watched" by a device [28]. These concerns are not without merit. Very recent work from [29] shows that it is possible to use built-in motion sensors of a device alongside powerful speakers to passively detect word boundaries, speaker gender, and and even recognize some of the spoken words using only the minute vibrations – all without a person's knowledge or permission. In our pilot study (Section 2), we also identified some mismatches in how the general

[6] `https://www.fatml.org/resources/principles-for-accountable-algorithms`

[7] `https://rm.coe.int/cai-2023-01-revised-zero-draft-framework-convention-public/1680aa193f`

[8] `https://rm.coe.int/ethical-charter-en-for-publication-4-december-2018/16808f699c`

public view their privacy versus their understanding of the rights that others have for using assistive AV devices.

While there are no specific guidelines for the preservation of privacy for people around hearing aid users, the European General Data Protection Regulation (GDPR) provides general principles[9] that apply to the collection, processing, and storage of personal data, including the data related to hearing aids. Under the GDPR, personal data must be collected and processed lawfully, fairly, and transparently. This means that individuals must be informed about what data is being collected, how it is being used, and who it is being shared with – ultimately this poses a special challenge for AV assistive devices where people's data may be collected based on their mere presence in the local environment of technology user.

AV hearing assistive devices can potentially collect many types of information such as user characteristics, biological information, audio information, spatial and location information, and user interaction. They may also occasionally collect special category data like health information. Particularly concerning is the capability to capture information about non-users, i.e., people who are in the users' surrounding environment without authorization [30]. The unauthorised incorporation of voice recognition systems, accumulation of localisation data, and the collection and storage of users' metadata, are all examples of how these devices may affect the data protection and privacy rights of individuals. In addition, like any other internet-connected device, these devices may also suffer from security loopholes than can be actively exploited to steal data or run unauthorised software [31]. By using these devices, users could lose control of their data or risk that their behaviour is analysed and used for profiling purposes similar to the IoT devices [32].

To mitigate these risks, special security and privacy safeguards are required. For example, in order to comply with GPDR, the different stakeholders of smart glasses (service providers, designers, users) should consider the following recommendations [31]:

- a) apply data minimization by not collecting the data unless really needed (art.5);
- b) perform a data protection impact assessment (art.35);
- c) embed *data protection by design and by default* in the development process (art.25);
- d) provide appropriate information to the users and non-users by developing new and creative ways to inform and enquire the consent from non-users (art.7 and 13);
- e) safeguard users' rights and provide user control (art.14-21) that allows them to request for the removal of personal data, have it transferred to another organisation or object to the processing of their personal data for certain reasons;
- f) show security and vulnerabilities notifications and security updates (art.32).

Informing non-users while keeping AV hearing devices discreet is a particular difficult challenge in this context [33]. Data protection authorities such as the United Kingdom Information Commissioner's Office (ICO) propose that devices like body-worn cameras should have clear signage, verbal announcements or lights/indicators on the device [34]. These indicators insufficiently inform non-users in public spaces. According to the ICO's recent report [30], novel solutions for AV devices may include: location-based notifications prompting users to minimise or cease audio capture in sensitive locations such as hospitals. Embedding redaction technology within devices that will blur or mask parts of the audio or video footage by default is another alternative and has recently been suggested for safely incorporating audio into smart building design, where there are also privacy concerns [35, 36]. In sum, AV hearing aid devices could help people participate in all life activities, but it should not be developed and used at the expense of their rights and other people' rights. Researchers and developers should consider this to create more efficient ways to safeguard security and privacy and ultimately more trustworthy products.

[9] https://gdpr-info.eu/

4. DISCUSSION

We have presented seven key socio-technical issues for the research community to consider while innovating new AV hearing assistive technologies. These technologies serve the greater good and are a demonstration of how AI can be used to serve the society. Still, the breadth of social, technical, and legal issues that remain may slow or stymie the adoption of AV hearing assistance. We urge the scientific community to undertake this research with these issues in mind, as some of them may be mitigated with careful design and planning.

Many of the issues echo what we have observed in our pilot survey in the UK, which is currently underway to recruit more responses from the general population. It is important to note that some of the issues we have discussed in this paper are not unique to AV hearing assistive technologies, though it should be considered that multi-modal technologies can amplify existing socio-technical gaps (e.g., explainability and privacy).

Further, we encourage the scientific community to proactively engage with the relevant stakeholders to begin to address some of the socio-technical challenges that we have discussed. Early engagement means that researchers and developers can make forward progress to reaching the ideal technology that serves that DHH community, and which will ultimately increase uptake and compliance, while mitigating stigma. AV hearing assistive technologies are exciting, and the current state of low-power edge devices offers a timely opportunity to innovate this special use of AI for social good.

5. REFERENCES

[1] Tom Page, "A forecast of the adoption of wearable technology," *International Journal of Technology Diffusion (IJTD)*, vol. 6, no. 2, pp. 12–29, 2015.

[2] Romit Roy Choudhury, "Earable computing: A new area to think about," in *Proceedings of the 22nd International Workshop on Mobile Computing Systems and Applications*, 2021, pp. 147–153.

[3] Karina C De Sousa, David R Moore, Lina Motlagh-Zadeh, Hermanus C Myburgh, and De Wet Swanepoel, "Do smartphone hearing aid apps work?," *The Hearing Journal*, vol. 72, no. 11, pp. 34–35, 2019.

[4] Peter Udo Diehl, Yosef Singer, Hannes Zilly, Uwe Schönfeld, Paul Meyer-Rachner, Mark Berry, Henning Sprekeler, Elias Sprengel, Annett Pudszuhn, and Veit M Hofmann, "Restoring speech intelligibility for hearing aid users with deep learning," *Scientific Reports*, vol. 13, no. 1, pp. 2719, 2023.

[5] Oliver Amft and Paul Lukowicz, "From backpacks to smartphones: Past, present, and future of wearable computers," *IEEE Pervasive Computing*, vol. 8, no. 3, pp. 8–13, 2009.

[6] Brent Edwards, "The future of hearing aid technology," *Trends in Amplification*, vol. 11, no. 1, pp. 31–45, 2007.

[7] Jason Hong, "Considering privacy issues in the context of google glass," *Communications of the ACM*, vol. 56, no. 11, pp. 10–11, 2013.

[8] Astrid Yi, Willy Wong, and Moshe Eizenman, "Gaze patterns and audiovisual speech enhancement," *Journal of Speech, Language, and Hearing Research: JSLHR*, vol. 56, no. 2, pp. 471–480, 2013.

[9] Andrea Lorena Aldana Blanco, Cassia Valentini-Botinhao, Ondrej Klejch, Mandar Gogate, Kia Dashtipour, Amir Hussain, and Peter Bell, "AVSE Challenge: Audio-Visual Speech Enhancement Challenge," in *2022 IEEE Spoken Language Technology Workshop (SLT)*, 2023, pp. 465–471.

[10] Ahsan Adeel, Mandar Gogate, Amir Hussain, and William M. Whitmer, "Lip-reading driven deep learning approach for speech enhancement," *IEEE Transactions on Emerging Topics in Computational Intelligence*, vol. 5, no. 3, pp. 481–490, 2021.

[11] Amir Hussain, Jon Barker, Ricard Marxer, Ahsan Adeel, William Whitmer, Roger Watt, and Peter Derleth, "Towards multi-modal hearing aid design and evaluation in realistic audio-visual settings: Challenges and opportunities," in *First International Conference on Challenges in Hearing Assistive Technology (CHAT-17) Stockholm, Sweden*, 2017.

[12] Marion Koelle, "What makes wearable technologies socially acceptable?," *XRDS: Crossroads, The ACM Magazine for Students*, vol. 29, no. 2, pp. 30–35, 2023.

[13] Lukas Riedel and Thure Waller, "We All Need a HearO-Fighting Hearing Aid Stigma," *Masters Thesis, Chalmers University of Technology, Sweden*, 2018.

[14] Joe Dysart, "Smart earbuds: a looming threat to the hearing aid market?," *The Hearing Journal*, vol. 70, no. 3, pp. 30–31, 2017.

[15] James N Gilmore, "Design for everyone: Apple airpods and the mediation of accessibility," *Critical Studies in Media Communication*, vol. 36, no. 5, pp. 482–494, 2019.

[16] Shelley D Hutchins, "Stylish In-Ear Devices Might Reduce Stigma of Wearing hearing Aids," *Leader Live*, 2017.

[17] Leandro A Passos, João Paulo Papa, Javier Del Ser, Amir Hussain, and Ahsan Adeel, "Multimodal audio-visual information fusion using canonical-correlated graph neural network for energy-efficient speech enhancement," *Information Fusion*, vol. 90, pp. 1–11, 2023.

[18] Leandro A. Passos, João Paulo Papa, Amir Hussain, and Ahsan Adeel, "Canonical Cortical Graph Neural Networks and Its Application for Speech Enhancement in Audio-Visual Hearing Aids," *Neurocomput.*, vol. 527, no. C, pp. 196–203, mar 2023.

[19] Abby McCormack and Heather Fortnum, "Why do people fitted with hearing aids not wear them?," *International Journal of Audiology*, vol. 52, no. 5, pp. 360–368, 2013.

[20] Eleftheria Iliadou, Qiqi Su, Dimitrios Kikidis, Thanos Bibas, and Christos Kloukinas, "Profiling hearing aid users through big data explainable artificial intelligence techniques," *Frontiers in Neurology*, vol. 13, 2022.

[21] Timothy D Griffiths, Meher Lad, Sukhbinder Kumar, Emma Holmes, Bob McMurray, Eleanor A Maguire, Alexander J Billig, and William Sedley, "How can hearing loss cause dementia?," *Neuron*, vol. 108, no. 3, pp. 401–412, 2020.

[22] Dhruv Jain, Khoa Huynh Anh Nguyen, Steven M. Goodman, Rachel Grossman-Kahn, Hung Ngo, Aditya Kusupati, Ruofei Du, Alex Olwal, Leah Findlater, and Jon E. Froehlich, "ProtoSound: A Personalized and Scalable Sound Recognition System for Deaf and Hard-of-Hearing Users," in *Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems*, 2022, pp. 1–16.

[23] Krish Suresh, Kevin Franck, Julie G Arenberg, Yohan Song, Daniel J Lee, and Matthew G Crowson, "Development of a predictive model for individualized hearing aid benefit," *Otology & Neurotology*, vol. 44, no. 1, pp. e1–e7, 2023.

[24] Raja Kushalnagar, "Deafness and hearing loss," *Web Accessibility: A Foundation for Research*, pp. 35–47, 2019.

[25] Oussama El Ghoul and Achraf Othman, "Virtual reality for educating sign language using signing avatar: The future of creative learning for deaf students," in *2022 IEEE Global Engineering Education Conference (EDUCON)*. IEEE, 2022, pp. 1269–1274.

[26] Jill E Preminger, Maria Oxenbøll, Margaret B Barnett, Lisbeth D Jensen, and Ariane Laplante-Lévesque, "Perceptions of adults with hearing impairment regarding the promotion of trust in hearing healthcare service delivery," *International Journal of Audiology*, vol. 54, no. 1, pp. 20–28, 2015.

[27] Yongpan Zou, Haibo Lei, and Kaishun Wu, "Beyond legitimacy, also with identity: Your smart earphones know who you are quietly," *IEEE Transactions on Mobile Computing*, 2021.

[28] Batya Friedman, Peter H Kahn Jr, Jennifer Hagman, Rachel L Severson, and Brian Gill, "The watcher and the watched: Social judgments about privacy in a public place," *Human-Computer Interaction*, vol. 21, no. 2, pp. 235–272, 2006.

[29] Ahmed Tanvir Mahdad, Cong Shi, Zhengkun Ye, Tianming Zhao, Yan Wang, Yingying Chen, and Nitesh Saxena, "Earspy: Spying caller speech and identity through tiny vibrations of smartphone ear speakers," *arXiv e-prints*, pp. arXiv–2212, 2022.

[30] Information Commissioner's Office, "ICO Future Tech Report: Tech Horizons," 2022.

[31] European Data Protection Supervisor, "Smart glasses and data protection," Mar. 2023.

[32] Data Protection Working Party, "Opinion 8/2014 on the on Recent Developments on the Internet of Things," 2014.

[33] Zhangbing Li, Baichuan Wang, Jinsheng Li, Yi Hua, and Shaobo Zhang, "Local differential privacy protection for wearable device data," *Plos One*, vol. 17, no. 8, pp. e0272766, 2022.

[34] Information Commissioner's Office, "Additional considerations for technologies other than CCTV," Accessed: 2023-03-25.

[35] Jennifer Williams, Vahid Yazdanpanah, and Sebastian Stein, "Safe audio ai services in smart buildings," in *Proceedings of the 9th ACM International Conference on Systems for Energy-Efficient Buildings, Cities, and Transportation*, 2022, BuildSys '22, p. 266–269.

[36] Jennifer Williams, Karla Pizzi, Shuvayanti Das, and Paul-Gauthier Noé, "New challenges for content privacy in speech and audio," in *Proc. 2nd ISCA Symposium on Security and Privacy in Speech Communication*, 2022, pp. 1–6.