Usability of smartphone listening devices

Applying the COM-B model to assess the usability of smartphone-connected listening devices in adults with hearing loss.

David W. Maidment[1,2], Yasmin H.K. Ali[1,2], Melanie A. Ferguson[1,2,3]

[1] National Institute for Health Research (NIHR) Nottingham Biomedical Research Centre, Nottingham, UK

[2] Hearing Sciences Section, Division of Clinical Neuroscience, School of Medicine, University of Nottingham, Nottingham, UK

[3] Nottingham University Hospitals NHS Trust, Queens Medical Centre, Nottingham, UK

Corresponding author

David Maidment, PhD
NIHR Nottingham Biomedical Research Centre
113 The Ropewalk
Nottingham, UK
NG1 5DU
E. david.maidment@nottingham.ac.uk
T. +44(0) 115 8232641
F. +44(0) 115 8232615

Running head

Usability of smartphone listening devices

Usability of smartphone listening devices

Abstract

Background: Unlike conventional hearing aids, smartphone-connected listening devices may require limited or no input from a trained audiologist in terms of device programming and adjustment. However, there is a lack of peer-reviewed evidence assessing the real-world perspectives of people living with hearing loss toward such technological innovations.

Purpose: This study assessed the everyday experiences of adults living with hearing loss toward a range of smartphone-connected listening devices using the COM-B model as a theoretical framework.

Research Design: A qualitative study whereby participants trialled one of the following smartphone-connected listening devices for two-weeks in their everyday lives: made-for-smartphone hearing aids, personal sound amplification product, smartphone 'hearing aid' app with wired earphones or wireless hearable. Individual semi-structured interviews were conducted.

Study Sample: Twenty adults (13 male, 7 female; mean age = 62.25 years, SD = 11.59) with mild-moderate hearing loss (mean better ear pure-tone average = 30.49 dB HL, SD = 17.51) were recruited using a convenience sampling strategy. All participants owned conventional hearing aids.

Results: The data were analysed using an established deductive thematic analysis procedure within the context of the COM-B model. The model stipulates that for individuals to engage in a particular behaviour (B), they must have sufficient capability (C), opportunity (O), and

motivation (M). *Capability*: One of the key advantages facilitating use and adherence of smartphone-connected listening devices was the ability for participants to make fine-tune adjustments in any listening situation. *Opportunity*: Participants commented that these devices could address issues surrounding stigma, as smartphones are ubiquitous in everyday life. *Motivation*: Participants consistently reported that the ability to make adjustments via a smartphone provided them with a greater sense of autonomy and empowerment. As a result, they felt more in control of their hearing loss.

Conclusions: This study lays the foundation for further high-quality research to explore whether smartphone-connected technologies have the potential to yield optimum benefits for people living with hearing loss.

Keywords: Hearing loss, hearing aids, smartphone-connected listening devices, COM-B model, Theoretical Domains Framework

Abbreviations: App = Application**,** BCW = Behaviour Change Wheel**,** COM-B = Capability, Opportunity, Motivation, Behaviour**,** HHIE = Hearing Handicap Inventory for the Elderly**,** PSAP = Personal sound amplification product**,** TDF = Theoretical Domains Framework

INTRODUCTION

Conventional hearing aids are effective, improving hearing-specific health-related quality of life, listening abilities, and general health-related quality of life in adults living with mild to moderate hearing loss (Ferguson et al. 2017). Consequently, the evidence is consistent with the assertion that hearing aids should be routinely offered to individuals who experience hearing and communication difficulties. Nevertheless, the majority of adults who would benefit from using hearing aids fail to access them (Chien and Lin 2012; Davis et al. 2007; Gopinath et al. 2011). For individuals who do obtain hearing aids, estimates of non-use vary from 3% to 24% (Ferguson et al. 2017). Non-use and suboptimal use of hearing aids is problematic, not least because untreated hearing loss can result in continued communication difficulties, social isolation, and reduced quality of life for both the individual and their frequent communication partners (Barker, Leighton, and Ferguson 2017; Vas, Akeroyd, and Hall 2017; Kamil and Lin 2015).

Limited access to and affordability of hearing healthcare have been cited as key reasons why adults do not seek help for their hearing loss (The National Academies of Sciences Engineering & Medicine 2016). In addition to high costs associated with hearing healthcare to the individual, another identified barrier to accessibility includes a lack of awareness or uncertainty in terms of how to access hearing healthcare, which may be compounded by clinic-based service delivery models that do not meet the needs and/or preferences of everyone living with hearing loss (Lin, Hazzard, and Blazer 2016). On this basis, there is a clear need to identify alternative service delivery models that could reduce these barriers.

Globally, the use of smartphone technologies in older adults is increasing year-on-year. In the UK, smartphone ownership has risen exponentially in 55+ year olds, from 19% in 2012, to 71% in 2017 (Deloitte 2017). A similar rise in smartphone ownership of 50-64 year olds has also be found in the US, rising from 34% in 2012 to 73% in 2018 (Pew Research Center 2018). Furthermore, over the last decade, there has been a proliferation of alternative devices to conventional hearing aids, which can connect wirelessly via Bluetooth to smartphones. Smartphone-connected listening devices include made-for-smartphone hearing aids, personal sound amplification products (PSAPs), as well as smartphone 'hearing aid' applications (or apps). Unlike conventional hearing aids, smartphone-connected listening devices may require limited or no input from a trained audiologist in terms of device programming and adjustment. These devices allow the user to adjust and personalise their hearing programmes (e.g. gain and frequency response) via an accompanying smartphone app. As such, smartphone-connected listening devices could address barriers surrounding accessibility and affordability that prevent people from successfully managing their hearing loss. PSAPs and smartphone 'hearing aid' apps, for instance, can be purchased at a relatively low cost directly by the user. In comparison to conventional hearing aids, PSAPs also provide comparable electroacoustic characteristics (Callaway and Punch 2008; Reed, Betz, Lin, et al. 2017) and speech-in-noise performance (Reed, Betz, Kendig, et al. 2017). Similar findings have also been shown for smartphone 'hearing aid' apps (Amlani et al. 2013). However, a recent systematic review and meta-analysis revealed that there is no high-quality evidence assessing the clinical effectiveness of smartphone-connected listening devices (Maidment et al. In press).

An insight into user experiences of made-for-smartphone hearing aids has been provided in a qualitative study by Ng et al (2017). They found that, while adults living with hearing loss

experienced problems related to Bluetooth connectivity, participants reported that made-for-Smartphone hearing aids increased opportunities for social participation in their everyday lives. However, in comparison to PSAPs and smartphone 'hearing aid' apps, made-for-smartphone hearing aids are initially programmed to an individual's prescriptive target by a trained audiologist. Further investigation is warranted to determine whether a similar pattern of findings would be found for other smartphone-connected devices that can be purchased and programmed directly by the user.

On this basis, the current study aimed to qualitatively examine the everyday experiences of people living with hearing loss toward a range of smartphone-connected listening devices, using the COM-B model (Michie, van Stralen, and West 2011) as an underpinning theoretical framework (see Figure 1). The application of theories and models from health psychology has become increasingly prevalent in a hearing health context (e.g. Laplante-Lévesque, Hickson, and Worrall 2013; Saunders et al. 2013; Meister 2014; Barker, Atkins, and de Lusignan 2016; Heffernan et al. 2016; Ferguson et al. 2016). Nevertheless, Coulson et al (2016) argue that popular models used in the field of audiology, such as the Health Belief Model (Rosenstock 1966), Theory of Planned Behaviour (Fishbein and Ajzen 1977), and Transtheoretical Model (Prochaska and DiClemente 1983), have been widely criticised because they are inadequate at reliably explaining variations in complex human behaviour. By comparison, the COM-B model is a contemporary, supra-theory of behaviour change, which can enable researchers to understand and describe patient behaviour to improve clinical practices within audiology (Coulson et al. 2016).The model has been successfully applied to development of an intervention to improve hearing aid use in adult auditory rehabilitation (Barker, Atkins, and de Lusignan 2016; Ferguson, Maidment, and Henshaw In press).

The COM-B model stipulates that for individuals to engage in a particular behaviour (B), they must have sufficient capability (C), opportunity (O), and motivation (M) (Michie, van Stralen, and West 2011). Capability is defined as an individual's ability to physically and psychologically engage in or perform the behaviour. Opportunity refers to external factors that make the behaviour possible or prompt it. Motivation is a broad construct that includes basic drives and automatic processes, as well as reflective processes. The COM-B model can also be incorporated into a larger system, the Behaviour Change Wheel (BCW) (Cane, O'Connor, and Michie 2012; Michie, Atkins, and West 2014; Michie, van Stralen, and West 2011), which includes the Theoretical Domains Framework (TDF). The TDF consists of a number of different constructs, such as knowledge, skills, and social influences (see Supplemental 1 for full list), that are necessary to bring about behaviour change. In combination, the TDF and the COM-B model can be used to explain why an individual does or does not engage in a particular health-related behaviour. In addition, they can facilitate the identification of specific components (e.g. knowledge, skills, etc.) that need to be addressed in order to bring about a change in that behaviour. Thus, in combination, the TDF and the COM-B model can be used to describe and understand the essential components (or active ingredients) of complex healthcare interventions (e.g. hearing aids, smartphone-connected listening devices).

In this study, the behaviour of interest was the use of a smartphone-connected listening device to manage hearing loss in the real-world. The main aim of this study was to identify the factors from the TDF that influence the use of smartphone-connected listening devices in general. The secondary aim was to determine how these factors differed between four different smartphone-connected listening devices (made-for-smartphone hearing aid, PSAP, smartphone 'hearing aid' app with wired earphones or wireless hearable).

METHODS

Participants

A convenience sampling strategy was used (Patton 1990). Twenty adults were recruited from the National Institute for Health Research (NIHR) Nottingham Biomedical Research Centre (BRC) participant database, which contains details of people living with hearing loss and/or hearing aid users who have consented to be approached for research. Demographic information of the sample is provided in Table 1. Overall, participants presented with mild-to-moderate hearing loss. All participants owned conventional hearing aids and were experiences users; mean duration of hearing aid ownership was 6.9 years (SD =8.9 years).

Procedure

All participants attended a one-hour session at the NIHR Nottingham BRC, where written informed consent was obtained. Pure-tone air conduction thresholds were measured at octave frequencies (0.25 to 8kHz) for each ear following the procedure recommended by the British Society of Audiology (2011). In addition, the Hearing Handicap Inventory for the Elderly (HHIE, Ventry and Weinstein 1982) was completed. HHIE questions were asked as though participants were not wearing their hearing aids. An equal number of participants (n=5) were then assigned to one of the four smartphone-connected listening device groups. Participants were then randomly assigned to one of four device groups. Common to all devices was that they could be controlled using a smartphone app (see also, Figure 2). Hearing aid fitting procedures recommended by the device manufacturer were followed for each device as follows:

Made-for-smartphone hearing aid. Behind-the-ear Starkey Halo i110 hearing aids (Figure 2A) were individually programmed using InspireX 2016.2 software as directed by the

manufacturer (http://www.starkeyhearingtechnologies.com/inspirehelp/aah) according to the NAL-NL2 algorithm. Hearing aids were fitted with either custom earmoulds or open-fit slim tubes depending on the participant's hearing thresholds.

PSAP. In-the-ear Starkey AMP Personal Amplifiers (Figure 2B) were programmed using the accompanying smartphone app. In accordance with manufacturer guidance, participants wore foam-padded over-ear headphones during fitting. The AMP was initially adjusted using dual-tone multi-frequency signals generated by the smartphone app. One of three pre-set starting points, corresponding to mild, mild-to-moderate or moderate sloping hearing loss, was first selected by DM based on the participant's audiogram. Participants then listened to the media available within the app (adult female speech, adult male speech, restaurant conversation, and music). Participants made adjustments to low-frequency gain, high-frequency gain, overall gain, and/or output as needed.

Smartphone 'hearing aid' app with wireless hearable. The Petralex smartphone app (http://petralex.pro/) required participants to first complete an in-app audiometric test. The test includes pure-tone octave frequencies (.125 to 8 kHz), which are presented to each ear individually, with the user signalling when the tone becomes audible. On completion of the test, the user can save the test settings as a listening "profile". Microphone selectivity, gain and frequency response can then be adjusted.

Participants were provided a wireless hearable to use with the Petralex app (Figure 2C). The wireless hearable (The Dash by Bragi, https://support.bragi.com/hc/en-us/categories/200470531-The-Dash) was paired with the user's smartphone via Bluetooth, and included additional functionalities, such as health monitoring (e.g. heart rate) and activity tracking (e.g. step count).

Smartphone 'hearing aid' app with wired earphones. Identical to the wireless hearable described above, with the exception that participants were instructed to use the Petralex smartphone 'hearing aid' app with wired earphones provided with their smartphone (Figure 2D).

All participants trialled the assigned smartphone-connected listening device in their everyday lives for a period of two-weeks. Participants then attended a second session at the NIHR Nottingham BRC, where they were interviewed by DM. The interview schedule was flexible due to the semi-structured design of the interviews, though the core content remained the same across each (see Supplemental 2). The interviews were conducted face-to-face in a quiet room and lasted approximately one-hour. Each interview was audio-recorded and subsequently transcribed verbatim. Participants were paid a nominal inconvenience fee and travel expenses to attend each study session. The research was approved by the Faculty of Medicine and Health Sciences Research Ethics Committee, University of Nottingham, UK.

Data analysis

QSR International's NVivo 10 Software was used to organise and support the analysis of the data. Anonymised identification codes were assigned to each participant (e.g. P1, P2, etc.). The semi-structured interview data was analysed using Braun and Clarke's (2006) thematic analysis procedure. The analysis was deductive (or theoretical), as themes were derived from the components of the TDF, which each link to a specific determinant of behaviour (capability, opportunity, motivation) (Atkins et al. 2017). Furthermore, this approach is suited to answering a specific research question (Braun and Clarke 2006). To enhance the rigor of the analysis, and to ensure that the interpretation of the data was not limited to perspective of

the first-author, a second trained researcher (YA) independently coded all transcripts

(Yardley 2008). Any discrepancies were discussed and an agreement was made regarding

which codes should be applied. Themes were derived across all smartphone-connected

listening devices. Themes were refined and defined through re-analysis of the data and

discussions amongst the co-authors (Braun and Clarke 2006). The extent to which these

themes enabled the target behaviour (i.e. use of a device to manage hearing loss) for each

individual listening device were also identified.

RESULTS

Themes across all devices

A summary of the key themes, classified according to the TDF, that were most salient across

all smartphone-connected listening devices is provided in Table 2. Each domain was mapped

to the relevant source of behaviour (capability, opportunity, motivation) on the COM-B

model.

Capability

Skills

Digital literacy. The majority of participants reported that they required necessary

skills in terms of computer and digital literacy to use a smartphone-connected listening

device. P1 (made-for-smartphone hearing aid), said: "*I use computers a lot; I always have

done with my job, so it's very easy for me*". Conversely, participants reported that a lack of

skills in this area would have a detrimental impact on use. P3 (made-for-smartphone hearing

aid) commented: "*I think that anyone who is not technically astute would have difficulty in*

connecting-up and understanding the settings and how to adjust them". Thus, the importance of existing digital literacy skills influenced the perceived usability of the listening device trialled.

Knowledge

Awareness. All participants reported that they had a general lack of awareness of smartphone-connected listening devices prior to taking part in the study. Some participants reported that they would have liked more information about smartphone-connected devices. P9 (made-for-smartphone hearing aid) said: "*Nobody's ever said to me, 'Do you know that there are other devices available?' That's the thing, unless you actually go searching for it, which implies that you need to know that there is something out there in the first place*". Other participants reported that they assumed that alternatives to conventional hearing aids weren't available for hearing loss. P10 (smartphone 'hearing aid' app with wired earphones) explained: "*It never crossed my mind that you could use apps to help with hearing loss. I know you can get health apps and stuff like that, but I've always seen it* [hearing loss] *as a niche thing*". Taken together then, participants in the study reported that they might have considered using a smartphone-connected listening device if they were made more aware that they are available as a management option for hearing loss.

Memory, attention and decision processes

Device simplicity (plug-and-play). Adherence to use the device was influenced by whether the smartphone-connected listening device was viewed as simple and intuitive to use. If the device was perceived as unnecessarily complex or overly-sophisticated, participants stated that they were less inclined to persevere using the device. P5 (smartphone 'hearing aid' app with wireless hearable) said: *"Are they more sophisticated than they need to*

be? I would say that if you were going to use them just for hearing loss then I suspect they have many more menu features than you really require". In addition, P7 (smartphone 'hearing aid' app with wireless hearable) commented: "*If it doesn't plug-and-play, then you've really got to sit down for half a day and start going in depth to the instruction manual and people are less tolerant to try and sort things out themselves*". Moreover, all participants expected the smartphone-connected listening device to be straightforward to set-up, and with minimal instruction. P6 said: (made-for-smartphone hearing aid), "*It has to be a good piece of hardware, you switch it on and it works*".

Satisfaction with existing hearing aids. All participants made comparisons between the smartphone-connected listening device trialled and their conventional hearing aids. Several participants who were already satisfied with their hearing aids reported that they were less likely to use the device. P8 (PSAP) said: "*I found it difficult, well, not difficult, just more involved putting them in to your ear. If it's not broke don't fix it. So my current hearing aids work pretty well for me and so I stuck with them*". The smartphone-connected listening device was viewed more favourably if participants were less satisfied with their hearing aids. P12 (smartphone 'hearing aid' app with wired earphones) stated: "*I was quite surprised how good it was initially. In comparison with my hearing aids, which I don't use because I couldn't get on with them, I found that I was quite surprised by the sound quality, I could pick out individual words which is, you know, obviously a big advantage.*" Therefore, the degree of satisfaction with existing hearing aids influenced take-up, use and adherence of the smartphone-connected listening device.

Behavioural regulation

Adjustability. In comparison to conventional hearing aids, one of the key advantages facilitating use of the smartphone-connected listening device was the ability to make fine-

tune adjustments to meet individual needs and preferences. P8 (smartphone 'hearing aid' app with wireless hearable) commented: *"If there's a way of making it more finely tuned to myself then I like that opportunity."* All participants felt that the ability to make adjustments was extremely beneficial. P6 (made-for-smartphone hearing aid) explained: *"The more you can adjust something and make it better for you, the better!"*

Opportunity

Social Influences

　　Perception of others and self (stigma). Participants were cognisant of the stigma attached to hearing loss and hearing aids. Some participants commented that smartphone-connected listening devices could address issues surrounding stigma because smartphones are a part of everyday life, which could encourage people to seek help for their hearing loss sooner. P4 (smartphone 'hearing aid' app with wired earphones) said: *"The perception of having a hearing aid is not very cool is it really? An app might persuade people who wouldn't look at a hearing aid to actually use something, because they're on their phones all the time, their wearing headphones all the time. It is part of their life isn't it?"* However, some older participants expressed concerns that other people would perceive them in a negative manner. This was because they felt that the smartphone-connected listening device trialled might be better suited to a younger demographic. For example, P11 (smartphone 'hearing aid' app with wireless hearable) said: *"I had issues with my perception of what people thought about me. I felt that I couldn't go outside wearing them because I thought that other people would think I was some sort of old man trying to be down with the kids."* Nevertheless, P10 (smartphone 'hearing aid' app with wired earphones) reported that the benefits of using a smartphone-connected listening device were more important than the

perception of others: *"The benefit you would gain from it would outweigh any looks you would get. I'm just going to do what I'm going to do because it helps me out. You have any issues with it, then it's your problem. It doesn't matter about anyone else."*

Environmental context and resources

Perceived sound quality. Participants were more likely to use the smartphone-connected listening device if they perceived the sound quality to be better than that provided by their conventional hearing aids. P14 (smartphone 'hearing aid' app with wireless hearable) remarked: *"It was very good. It made listening to the TV and radio much clearer. With normal hearing aids I can hear the loudness of it, but I can't hear the words. When I used the app, I could hear more of the words."* Similarly, P3 (made-for-smartphone hearing aid) said: *"There is a difference in quality of the sound. The fact that these hearing aids are quantitatively 3-4 times better than my previous hearing aids makes a massive difference. It has given me one end of the audio spectrum to the other. I'm 100% convinced they are much better."* However, if the sound quality was perceived to be poorer, some participants abandoned using the smartphone-connected listening device altogether, instead opting to use their conventional hearing aids. Over amplification of background sounds was highlighted by numerous participants as having a detrimental impact on perceived sound quality. For example, P8 (smartphone 'hearing aid' app with wired earphones) remarked: *"They amplified everything, yeah, but they amplified the stuff I didn't want to hear too much. The quality of sound wasn't that great to be fair. It did sound like you're sat in a big hall and the echoing and things like that."* Overall, perceived sound quality of the smartphone-connected listening device was one of the most important factors prioritised by participants.

Comfort. Several participants reported that they frequently used the smartphone-connected listening device because it was comfortable to wear. For example, P9 (made-for-

smartphone hearing aid) stated: *"They were very comfortable to wear. They went in in the morning and they came out at night."* In addition, P11 (smartphone 'hearing aid' app with wireless hearable) said: *"They were comfortable, I couldn't tell that they were there."* By comparison, some participants discontinued using the smartphone-connected listening device if it did not fit within their ears comfortably. P17 (PSAP) commented: *"I didn't use them due to the fact that they didn't fit properly. They weren't small enough for my ear canals. That was an obvious problem and the reason for stopping using them."* Similarly, P5 (smartphone 'hearing aid' app with wireless hearable) said: *"I personally found the ear buds a little bit uncomfortable. I almost felt there was a pressure build-up."*

 Portability. Some participants reported that the smartphone-connected listening device was constrictive or cumbersome when completing everyday tasks. P8 (smartphone 'hearing aid' app with wireless hearable) remarked: *"Obviously you've got to carry the tablet round with you if you're going out and about, and that's an issue."* The majority of participants became frustrated if they were required to transport other equipment, namely, the wired earphones connected to the smartphone. This was summarised by P13 (smartphone 'hearing aid' app with wired earphones) who said: *"It's mainly the transportation of it. The fact that you've got this large device here and wires running to your ears, that's a major problem with it."* Consequently, ease of portability was a further consideration affecting use and adherence of a smartphone-connected listening device.

 Affordability. All participants reported that the cost of a smartphone-connected listening device, as well as their current financial situation, would be a determining factor influencing future access and use. P13 (smartphone 'hearing aid' app with wired earphones) said: *"I'm retired and not earning any money. It depends on how much money you've got as to what you think you can afford. I really can't afford any great amount at the moment."* Nevertheless, P1 (made-for-smartphone hearing aid) reported that they would consider

purchasing a smartphone-connected listening device if this was the only option available to them: *"Some people would not consider it a problem at all because they'd have plenty of cash. I've not got that great a pension, but I suppose if I really had to buy one I would."*

Motivation

Social role & identity

Age. All participants reported that a smartphone-connected listening devices might be more accessible to a younger demographic. P10 (smartphone 'hearing aid' app with wired earphones) commented: *"I think it depends on how old you are personally, not to be ageist. I think, if you're a bit tech-savvy you know how to explore an app and find that quite fun. I think if you are a bit older, maybe you don't, you haven't had a smartphone your whole life, I think it would be quite difficult."* Similarly, P7 (smartphone 'hearing aid' app with wireless hearable) said: *"The younger generation tend to use tablets and texting more. I think my generation would find it* [the smartphone-connected listening device] *just a bit irritating."* On this basis, participants felt that smartphone-connected listening devices were better suited to younger individuals because they have greater experience interacting with and using smartphone technologies.

Beliefs about capabilities

Empowerment. All participants reported that the ability to make adjustments to the smartphone-connected listening device provided them with a greater sense of autonomy. P4 (smartphone 'hearing aid' app with wired earphones) said: *"It's the independence, it's that it gives you the control, doesn't it? So if it works for you that's really important because you can control it and adjust it yourself. I like to be able to manage things for myself, where I*

can." In addition, P9 (made-for-smartphone hearing aid) commented: *"It's great. It gives you control. I can actually control my work more because I can actually hear what people are saying to me. So, it gives me that bit of control, and it's not other people running my life, it's me. It's not quality of life, it's just having a life."* The ability to make adjustments empowered participants to feel more in control of their hearing loss, resulting in less frustration, greater participation and more device use.

Goals

Improved hearing. All participants were highly motivated to use the smartphone-connected listening devices in order to improve their hearing and listening abilities. Smartphone-connected listening devices that achieved this were regarded positively. For example, P9 (made-for-smartphone hearing aid) said: *"Suddenly I heard this noise, and I thought, 'What the hell is that?' and I realised my husband was using the hairdryer upstairs. I'd never heard the hairdryer from downstairs. So, it just, I can't even describe how much better it made things."* Similarly, P10 (smartphone 'hearing aid' app with wired earphones) remarked: *"I think, for me, the clarity it gave me. It was just so easy to kind of have a conversation with someone and not be like 'pardon, pardon what was that?' I think for me that, because I haven't had that, and it was quite a monumental."* In contrast, if the smartphone-connected listening device did not improve the participant's hearing abilities, they reported that were less likely to continue using it. P4 (smartphone 'hearing aid' app with wired earphones) said: *"I don't feel that it addressed my sort of hearing problem. I didn't feel that it helped me at all. I felt more encumbered with having to deal with it basically. But again, if it was offering me something in terms of hearing improvement, I am sure I would persist with those practical difficulties."*

Differences between devices

Of the themes identified, there were distinct differences between smartphone-connected listening devices. The made-for-smartphone hearing aid was viewed most favourably. The smartphone 'hearing aid' app with wired earphones and PSAP were also viewed positively, but to a lesser extent. The device that had the least positive reviews was the smartphone 'hearing aid' app with wireless hearable.

Made-for-smartphone hearing aids

All participants reported that they had the necessary skills to use the made-for-smartphone hearing aid, as well as the accompanying app, because they were both straightforward to use: *"These were very quick and easy to use"* (P3). In addition, participants commented that they could easily make adjustments using the app to improve their ability to hear, particularly in noisy environments. As a consequence, participants consistently stated that this gave them a greater sense of control, empowering them to manage their hearing loss in their everyday lives. This resulted in less frustration and greater self-reported device use: *"I think the device is absolutely fantastic. They've improved my quality of life no end. It's that stopping you from wanting to burst into tears of sheer frustration. I feel much more confident now surprisingly enough"* (P9). All participants also felt that the made-for-smartphone hearing aids were superior in terms of sound quality in comparison to their conventional hearing aids that they could not adjust themselves. Nevertheless, participants were mindful that made-for-smartphone hearings aids are not currently available free-of-charge from the publically-funded NHS. Therefore, they were uncertain whether they would be able to financially afford these devices: *"I feel that I can't be spending this amount of money"* (P9).

Smartphone 'hearing aid' app with wired earphones

The majority of participants commented that this device was simple and intuitive to use, and required very little instruction to set-up. In relation, participants felt that it was easy to make adjustments and personalise the sound settings to meet their individual needs and/or preferences: "*The fact that you could fine-tune it yourself, rather than having to keep going back, is really invaluable*" (P4). Moreover, some participants felt that this device was less noticeable and, therefore, reduced the stigma associated with hearing loss. In particular P10 commented that the use of smartphones and wired earphones are the norm: "*It helped a lot and obviously no one looked at me weird because I could just be listening to music.*" However, all participants commented that this device was impractical from a portability standpoint, and would impede movement: "*It was alright except, as I say, I had to keep picking the thing up and going somewhere with it, which I didn't really think was very good*" (P14). Participants also expressed ambivalent views concerning the sound quality. Although some participants reported that the device improved listening in quiet environments, such as watching the television, all participants remarked that the device performed poorly in noisy listening situations, as all sounds were amplified, including the background noise.

PSAP

All participants that trialled this device felt that the PSAP was difficult to use and adjust using the accompanying smartphone app. All participants expressed concerns regarding the physical fit of the device. For example, P15 commented that the device moved and often fell-out of their ear: "*The only problem was if you are talking a lot or eating then they came out your ear, so you were forever pushing them back in again.*" In relation, P18 was apprehensive about inserting the device into their ear for fear that it would get stuck, commenting: "*I did have difficulty putting them into my ear. I pushed the device too far into*

the ear canal so it was difficult to retrieve." Despite this, participants commented that they persisted with the device because it was "*smaller*" and "*more discreet*" (P19) in comparison to their conventional hearing aids. Similar to the smartphone 'hearing aid' app with wired earphones, participants also reported that the device improved listening abilities in quiet environments, but provided little benefit when there was background noise: "*In a conversation with two female friends I found it very difficult to hear what they were saying on occasions*" (P2).

Smartphone 'hearing aid' app with wireless hearable

The main issue that all participants reported was the difficulty they experienced pairing the hearable device via Bluetooth to their smartphone. They reported that the device was overly-sophisticated or too complex to use: "*It depends on how techy savvy you are…my kids generation that have grown up with smartphones, I think they wouldn't bat an eye lid, they would be quite happy and they wouldn't need support, so I think it's a generational thing*" (P20). In addition, participants commented that the device was uncomfortable or irritating to wear for a prolonged period of time: "*I personally found the ear buds a little bit uncomfortable…I felt, I almost felt there was a pressure build-up*" (P5). Furthermore, all users ceased using the device due to the sound delay experienced when using the smartphone 'hearing aid' app, due to the wireless transmission of the sound from the smartphone microphone to the hearable. Participants regularly reported that the delay was "*irritating*" (P8), which reduced confidence in the device: "*I was not sensing that I was getting amplification in a way that was tolerable because of that delay, and I just assumed that it wasn't going to do anything for me*" (P11).

DISCUSSION

While the last decade has seen a substantial rise in the availability of smartphone-connected listening devices, there is a sparsity of peer-reviewed evidence assessing the real-world perspectives of people living with hearing loss toward such technological innovations. To date, only one published study has aimed to understand how smartphone connectivity can influence patient experiences and clinician practices, focusing solely on made-for-smartphone hearing aids (Ng et al. 2017). The current study contributes further to this evidence base by qualitatively describing the everyday experiences of people living with hearing loss toward a range of smartphone-connected listening devices. Additionally, these experiences are explained within the context of the COM-B model and TDF (Cane, O'Connor, and Michie 2012; Michie, Atkins, and West 2014), which serve as a theoretical underpinning to gain an insight into the specific determinants of the target behaviour (i.e. use of a smartphone-connected listening device to manage hearing loss).

Capability

With regards to individuals' ability to physically and psychologically use a smartphone-connected listening device to manage their hearing loss, the following five sub-themes emerged: (i) the requirement to have necessary digital literacy skills; (ii) awareness that these devices are an available management option for hearing loss; (iii) the expectation that smartphone connected listening devices should be simple and intuitive to use with minimal instruction (i.e. plug-and-play); (iv) the extent to which participants were satisfied (or not) with their existing conventional hearing aids; and (v) the advantages of being able to make adjustments to meet individual listening and communication needs. In terms of each individual listening device, both the made-for-smartphone hearing aids and smartphone

'hearing aid' app with wired earphones were straightforward to set-up and adjust. In comparison, participants reported that they experienced difficulties when attempting to adjust the PSAP, as well as when pairing the wireless hearable via Bluetooth for use with the smartphone 'hearing aid' app.

Ng et al. (2017) similarly found that patients identified themselves as either competent or incompetent technology users. On this basis, the level of technological competence could be used by clinicians as a means to identify suitable candidates for smartphone-connected listening devices. Nevertheless, Ng et al. (2017) argue that this assumption may be misguided, since patients who identify as less technologically competent may be willing to learn how to successfully use smartphone-connected listening devices. Given that smartphone ownership continues to rise exponentially year-on-year in older adults (Deloitte 2017), the potential barrier of digital literacy may become less of a concern in the future. Furthermore, a number of studies suggest that digital technologies are accessible to older adults with hearing loss, given that they report higher levels of computer and internet competency relative to that in the general age-matched population (Thorén et al. 2013; Henshaw et al. 2012).

We also found that participants in this study reported that they lacked awareness that smartphone-connected technologies were an available management option for hearing loss. Likewise, the National Academies of Sciences Engineering & Medicine (2016) report suggests that one of the key barriers to accessibility of hearing healthcare in adults is limited knowledge of available treatment options. There is, therefore, a need to better educate people living with hearing loss, as well as the public more generally, on the consequences of hearing loss and how it can be managed. In addition, sufficient training is warranted for general healthcare professionals, so that they might screen, refer, and/or educate people living with

hearing loss (Lin, Hazzard, and Blazer 2016). Public awareness campaigns are one approach that could address this need, which could also be facilitated through the use of mobile-enabled (or mHealth) technologies. For example, smartphone based hearing tests delivered via an app have been deployed in South Africa (https://www.hearxgroup.com/hearscreen/) and, more recently, the US (https://www.hearscreenusa.com/), to improve hearing loss awareness and subsequent help-seeking.

Opportunity

The external factors that enabled (or prompted) the use of a smartphone-connected listening device were clustered into the following five sub-themes: (i) a reduction in stigma because smartphones are a part of everyday life; (ii) the perceived sound quality of the device; (iii) the extent to which the device fitted comfortably within the ear; (iv) portability of the device when undertaking everyday tasks; and (v) affordability of the device relative to the individual's current financial situation.

Participants reported that the perceived sound quality for made-for-smartphone hearing aids was superior in comparison to participant's existing conventional hearing aids. Although equivalent outcomes have been shown for 'basic' and 'advanced' hearing aids (Cox, Johnson, and Xu 2016; Johnson, Xu, and Cox 2016), this finding likely arose because the made-for-smartphone hearing aids trialled could have been a much higher-specification than participant's existing hearing aids. For the other smartphone-connected listening devices, participants expressed ambivalence concerning perceived sound quality. Specifically, some participants reported that, while the PSAP and smartphone 'hearing aid' app provided sufficient amplification in quiet conditions, they were inadequate in noisy listening situations. In contrast, laboratory-based studies, employing behavioural measures of speech

intelligibility, have shown similar levels of performance between conventional hearing aids and both PSAPs (Reed, Betz, Kendig, et al. 2017) and smartphone 'hearing aid' apps (Amlani et al. 2013). While the potential dissociation between this study and previous findings warrants further investigation, a potential explanation is that people with hearing loss may provide self-reported estimates of speech intelligibility that are significantly lower than performance attained via behavioural measures (Cox, Alexander, and Rivera 1991). On this basis, caution should be exercised when comparing qualitative reports of perceived sound quality with quantitative measures of speech intelligibility.

We consistently found that smartphone-connected listening devices were viewed as potentially less stigmatising in comparison to conventional hearing aids. This was primarily attributed to the perception that smartphone technologies are ubiquitous and, as a consequence, less noticeable to others. The stigma associated with hearing loss and the use of hearing aids has been identified as a key barrier to accessing hearing healthcare (Wallhagen 2010; Southall, Gagne, and Jennings 2010; Barker, Leighton, and Ferguson 2017; Vas, Akeroyd, and Hall 2017). For example, people living with hearing loss may be concerned that others will perceive them as socially incompetent and cognitively diminished (Southall, Gagne, and Jennings 2010). It has been argued that smartphone technologies have the potential to reduce the stigma associated with hearing loss, as well as encourage and empower adults living with hearing loss to seek earlier intervention (Amlani 2015). Our findings support this notion, with many participants stating that smartphone-connected listening devices would likely be accessed sooner by individuals who might not want to use a hearing aid to manage their hearing loss. However, while stigma can be reduced through the integration of listening devices with smartphone technologies, it has been suggested that this

accessibility barrier could be further reduced through the promotion of better societal awareness hearing loss and hearing aid use (Ng et al. 2017).

Motivation

Three sub-themes were identified under the construct of motivation: (i) the view that smartphone-connected listening devices might be better suited to a younger demographic; (ii) the ability to make adjustments empowered users to self-manage their hearing loss; and (iii) an expectation that using the device should improve hearing and listening abilities. We consistently found that, irrespective of the smartphone-connected listening device trialled, the ability to make adjustments, such as in terms of gain and/or frequency response, gave users a greater sense of autonomy. As such, participants felt more in control of their hearing loss, which made them feel that they participate more fully in social situations. These findings are comparable to those of Ng et al. (2017), who also found that made-for-smartphone hearing aids increased self-reported opportunities for social participation in everyday life.

A commonly cited reason why people fitted with hearing aids stop using them is because they continue to experience difficulties when listening to and understanding speech in noisy situations (McCormack and Fortnum 2013). Our findings suggest that the provision of smartphone-connected listening devices may alleviate these difficulties, providing an opportunity for people living with hearing loss to alter their device programming in any situation to address their individual listening and communication needs. It should be noted, however, that the concept of situation-specific personalisation of hearing aid programming predates the proliferation of smartphone technologies. For example, the hearing aid programming preferences of the individual have previously been shown to differ depending on the listening environment (Keidser et al. 2005). Furthermore, Dillon et al. (2006)

introduced the concept of trainable hearing aids that could be optimally adjusted in any situation by the user, and would be capable of learning the user's preferred settings. This study adds to this existent literature, highlighting that it is important for people living with hearing loss to discreetly and conveniently control their own listening devices, such as via a smartphone app. This provides users with a greater sense of control, resulting in less frustration, greater participation and optimal device use.

Study limitations and future research

We acknowledge that there are a number of caveats to the design of the current study that could be addressed in future research. For example, we made the pragmatic decision to include only existing hearing aid users, to allow for a comparison between existing conventional hearing aids and smartphone-connected listening device. Participants who experience hearing loss, but have no prior experience of amplification, would potentially be devoid of pre-existing bias. Consequently, naïve users could provide alternative advantages and disadvantages to device usage that were not reported in the present study. In addition, for logistical reasons, it was only possible for participants to trial the smartphone-connected listening device for two-weeks. Participant's experiences may have been different if they had more time to use and acclimatise to the device. In relation, it is likely that participants had varied listening experiences, which could have influenced the outcomes of the study. While our aim was to understand the everyday experiences of people living with hearing loss toward smartphone-connected listening devices, information regarding the listening situations encountered by participants could be measured in future studies, such as via hearing diaries, data logging, or ecological momentary assessment (for recent application, see Timmer, Hickson, and Launer 2018). Logistical reasons also necessitated the use of a convenience sampling strategy, which is potentially less rigorous than other qualitative sampling

techniques. Nevertheless, the sample was representative of the target population (i.e. adults living with hearing loss currently using conventional hearing aids).

The current study is the first to evaluate the perspectives of people living with hearing loss toward a range of smartphone-connected listening devices. Recently published guidelines for hearing loss assessment and management by the UK National Institute for Health and Care Excellence (2018) recommend that randomised controlled trials are needed in the area of assistive listening devices, including smartphone-connected technologies. To that end, the findings from this study could be used to inform further work assessing the clinical- and cost-effectiveness of smartphone-connected listening devices that require limited or no audiological input. In accordance with the UK Medical Research Council guidelines (Campbell et al. 2000; Medical Research Council 2006), developmental studies involving qualitative methodologies should be used to provide important insights into how healthcare interventions operate, which can then be used to refine the robust design of furture effectiveness trials. However, further research in this area should also investigate the extent to which adults living with hearing loss require further assistance from a hearing healthcare professional, even if audiological input is limited during device programming. Indeed, a randomized, double-blind, placebo-controlled clinical trial has evaluated audiologist programmed and pre-programmed hearing aids (i.e. over-the-counter service delivery model)(Humes et al. 2017). Humes et al. (2017) found that, while both types of hearing aid resulted in similar levels of self-reported speech recognition and hearing aid benefit, satisfaction with pre-programmed hearing aids was lower, possibly because of the absence of audiological interaction.

Conclusion

This study has demonstrated the utility of applying a contemporary model of behaviour change, to explain the everyday experiences of adults living with hearing loss toward a range of smartphone-connected listening devices. We have identified the key factors that influence use of a smartphone-connected listening device to manage hearing loss when used by adults in the real-world. Overall, we found that people living with hearing loss want to conveniently personalise and adjust their own listening devices via their smartphone in order to improve their ability to listen and communicate in any situation. Given that smartphone technologies are ubiquitous, they also have the potential to reduce the stigma associated with hearing loss and hearing aids, which could encourage individuals to seek help from an earlier time-point, as well as empower them to manage their hearing loss. While additional evidence is necessary in this area, this study lays the foundation for further research to explore the effectiveness of smartphone-connected listening devices. Such research is needed to determine whether smartphone-connected listening devices have the potential to revolutionise hearing healthcare service delivery, as well as provide opportunities for wider accessibility to yield optimum benefits for people living with hearing loss.

Declaration of interest

Acknowledgements

References

Amlani AM, Taylor B, Levy C, Robbins R. (2013) Utility of smartphone-based hearing aid applications as a substitute to traditional hearing aids. The Hearing Review 20: 16-18.

Amlani AM. (2015) Improving Patient Compliance to Hearing Healthcare Services and Treatment through Self-Efficacy and Smartphone Applications. The Hearing Review 22: 16-20.

Atkins L, Francis J, Islam R, O'Connor D, Patey A, Ivers N, Foy R, Duncan EM, Colquhoun H, Grimshaw JM. (2017) A guide to using the Theoretical Domains Framework of behaviour change to investigate implementation problems. Implementation Science 12: 77.

Barker A, Leighton P, Ferguson M. (2017) Coping together with hearing loss: a qualitative meta-synthesis of the psychosocial experiences of people with hearing loss and their communication partners. International Journal of Audiology 56: 297-305.

Barker F, Atkins L, de Lusignan S. (2016) Applying the COM-B behaviour model and Behaviour Change Wheel to develop an intervention to improve hearing aid use in adult auditory rehabilitation. International Journal of Audiology 55: S90-S98.

Braun V, Clarke V. (2006) Using thematic analysis in psychology. Qualitative Research in Psychology 3: 77-101.

British Society of Audiology. (2011) *Recommended procedure: pure-tone air-conduction and bone-conduction threshold audiometry with and without masking.* Reading, United Kingdom.

Callaway SL, Punch JL. (2008) An electroacoustic analysis of over-the-counter hearing aids. American Journal of Audiology 17: 14-24.

Campbell M, Fitzpatrick R, Haines A, Kinmonth AL, Sandercock P, Spiegelhalter D, Tyrer P. (2000) Framework for design and evaluation of complex interventions to improve health. BMJ 321.

Cane J, O'Connor D, Michie S. (2012) Validation of the theoretical domains framework for use in behaviour change and implementation research. Implementation Science 7: 37.

Chien W, Lin FR. (2012) Prevalence of Hearing Aid Use Among Older Adults in the United States. Archives of Internal Medicine 172: 292-293.

Coulson N, Ferguson MA, Henshaw H, Heffernan E. (2016) Applying theories of health behaviour and change to hearing health research: time for a new approach. International Journal of Audiology 55: S99-S104.

Cox RM, Alexander GC, Rivera IM. (1991) Comparison of objective and subjective measures of speech intelligibility in elderly hearing-impaired listeners. Journal of Speech, Language, and Hearing Research 34: 904-915.

Cox RM, Johnson JA, Xu J. (2016) Impact of hearing aid technology on outcomes in daily life I: the patients' perspective. Ear and Hearing 37: e224-e237.

Davis A, Smith P, Ferguson M, Stephens D, Gianopoulos I. (2007) Acceptability, benefit and costs of early screening for hearing disability: a study of potential screening tests and models. Health Technology Assessment 11: 1-294.

Deloitte. (2017) *State of the smart: seventh annual mobile consumer survey*. London, United Kingdom

Dillon H, Zakis JA, McDermott H, Keidser G, Dreschler W, Convery E. (2006) The trainable hearing aid: What will it do for clients and clinicians? The Hearing Journal 59: 30.

Ferguson MA, Coulson NS, Henshaw H, Heffernan E. (2016) Application of health behaviour theory to hearing healthcare research: the state of play and beyond. International Journal of Audiology 55: S1-S2.

Ferguson MA, Kitterick P, Chong L, Edmondson-Jones M, Barker F, Hoare D. (2017) Hearing aids for mild and moderate hearing loss in adults. Cochrane Database of Systematic Reviews CD012023: 1-46.

Ferguson MA, Maidment DW, Henshaw H. (In press) Knowledge is power: improving outcomes for patients, partner and professionals in the digital age. Perspectives of the ASHA Special Interest Groups.

Fishbein M, Ajzen I. (1977) *Belief, attitude, intention, and behavior: an introduction to theory and research*. Addison-Wesley, Reading, MA.

Gopinath B, Schneider J, Hartley D, Teber E, McMahon CM, Leeder SR, Mitchell P. (2011) Incidence and predictors of hearing aid use and ownership among older adults with hearing loss. Annals of Epidemiology 21: 497-506.

Heffernan E, Coulson N, Henshaw H, Barry JG, Ferguson MA. (2016) Understanding the psychosocial experiences of adults with mild-moderate hearing loss: a qualitative study applying Leventhal's self-regulatory model. International Journal of Audiology 55: S3-S12.

Henshaw H, Clark D, Kang S, Ferguson MA. (2012) Computer skills and Internet use in adults aged 50-74 years: influence of hearing difficulties. Journal of Medical Internet Research 14: e113.

Humes LE, Rogers SE, Quigley TM, Main AK, Kinney DL, Herring C. (2017) The effects of service-delivery model and purchase price on hearing-aid outcomes in older adults: a randomized double-blind placebo-controlled clinical trial. American Journal of Audiology 26: 53-79.

Johnson JA, Xu J, Cox RM. (2016) Impact of hearing aid technology on outcomes in daily life II: speech understanding and listening effort. Ear and Hearing 37: 529-540.

Kamil RJ, Lin FR. (2015) The effects of hearing impairment in older adults on communication partners: a systematic review. Journal of the American Academy of Audiology 26: 155-182.

Keidser G, Brew C, Brewer S, Dillon H, Grant F, Storey L. (2005) The preferred response slopes and two-channel compression ratios in twenty listening conditions by hearing-impaired and normal-hearing listeners and their relationship to the acoustic input. International Journal of Audiology 44: 656-670.

Laplante-Lévesque A, Hickson L, Worrall L. (2013) Stages of change in adults with acquired hearing impairment seeking help for the first time: application of the transtheoretical model in audiologic rehabilitation. Ear and Hearing 34: 447-457.

Lin FR, Hazzard WR, Blazer DG. (2016) Priorities for improving hearing health care for adults: A report from the national academies of sciences, engineering, and medicine. JAMA 316: 819-820.

Maidment DW, Barker AB, Xia J, Ferguson MA. (In press) A systematic review and meta-analysis assessing the effectiveness of alternative listening devices to conventional hearing aids in adults with mild-to-moderate hearing loss. International Journal of Audiology.

McCormack A, Fortnum H. (2013) Why do people fitted with hearing aids not wear them? International Journal of Audiology 52: 360-368.

Medical Research Council. (2006) *Developing and evaluating complex interventions: new guidance*. London, United Kingdom.

Meister HG, L. Meis, M. (2014) Intention to use hearing aids: a survey based on the theory of planned behavior. Patient Preference and Adherence 8: 10.

Michie S, van Stralen M, West R. (2011) The Behaviour Change Wheel: a new method for characterising and designing behaviour change interventions. Implementation Science 6: 42.

Michie S, Atkins L, West R. (2014) *The behaviour change wheel: a guide to designing interventions*. Silverback, London, United Kingdom.

National Institute for Health and Care Excellence. (2018) *Hearing loss in adults: assessment and management*. London, United Kingdom.

Ng SL, Phelan S, Leonard M, Galster JA. (2017) A qualitative case study of smartphone-connected hearing aids: influences on patients, clinicians, and patient–clinician interactions. Journal of the American Academy of Audiology 28: 506-521.

Patton MQ. (1990) *Qualitative evaluation and research methods*. SAGE Publications, Newbury Park, CA.

Pew Research Center. (2018) Mobile Fact Sheet, Washington, DC.

Prochaska JO, DiClemente CC. (1983) Stages and processes of self-change of smoking: toward an integrative model of change. Journal of Consulting and Clinical Psychology 51: 390-5.

Reed NS, Betz J, Kendig N, Korczak M, Lin FR. (2017) Personal sound amplification products vs a conventional hearing aid for speech understanding in noise. JAMA 318: 89-90.

Reed NS, Betz J, Lin FR, Mamo SK. (2017) Pilot electroacoustic analyses of a sample of direct-to-consumer amplification products. Otology & Neurotology 38: 804-808.

Rosenstock IM. (1966) Why people use health services. The Milbank Memorial Fund Quarterly 44: 94-127.

Saunders GH, Frederick MT, Silverman S, Papesh M. (2013) Application of the health belief model: development of the hearing beliefs questionnaire (HBQ) and its associations with hearing health behaviors. International Journal of Audiology 52: 558-67.

Southall K, Gagne JP, Jennings MB. (2010) Stigma: a negative and a positive influence on help-seeking for adults with acquired hearing loss. International Journal of Audiology 49: 804-814.

The National Academies of Sciences Engineering & Medicine. (2016) *Hearing healthcare for adults: priorities for improving access and affordability*. Washington, DC.

Thorén ES, Öberg M, Wänström G, Andersson G, Lunner T. (2013) Internet access and use in adults with hearing loss. Journal of Medical Internet Research 15: e91.

Timmer BH, Hickson L, Launer S. (2018) Do hearing aids address real-world hearing difficulties for adults with mild hearing impairment? Results from a pilot study using ecological momentary assessment. Trends in Hearing 22: 1-15.

Vas V, Akeroyd MA, Hall DA. (2017) A data-driven synthesis of research evidence for domains of hearing loss, as reported by adults with hearing loss and their communication partners. Trends in Hearing 21: 1-25.

Ventry IM, Weinstein BE. (1982) The Hearing Handicap Inventory for the Elderly: A New Tool. Ear & Hearing 3: 128-134.

Wallhagen MI. (2010) The stigma of hearing loss. The Gerontologist 50: 66-75.

Yardley L. (2008) Demonstrating validity in qualitative psychology. In: Smith JA, ed. *Qualitative psychology: a practical guide to research methods*, SAGE Publications, London, United Kingdom.

Figure 1. The COM-B model of behaviour change.
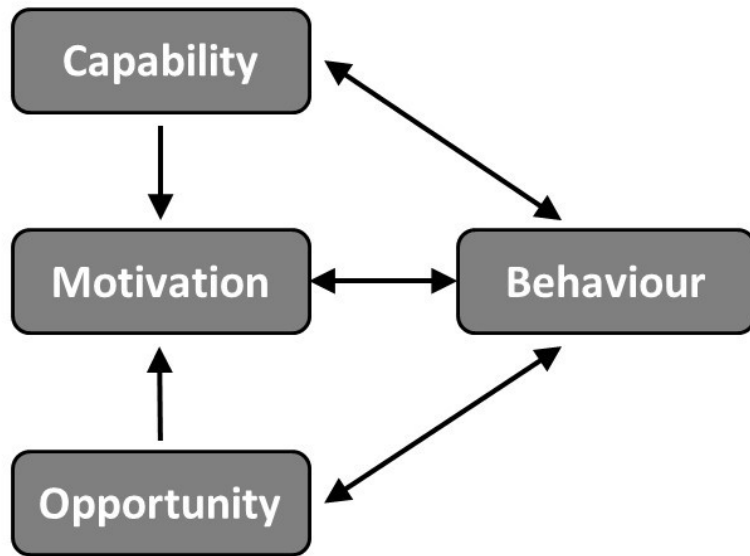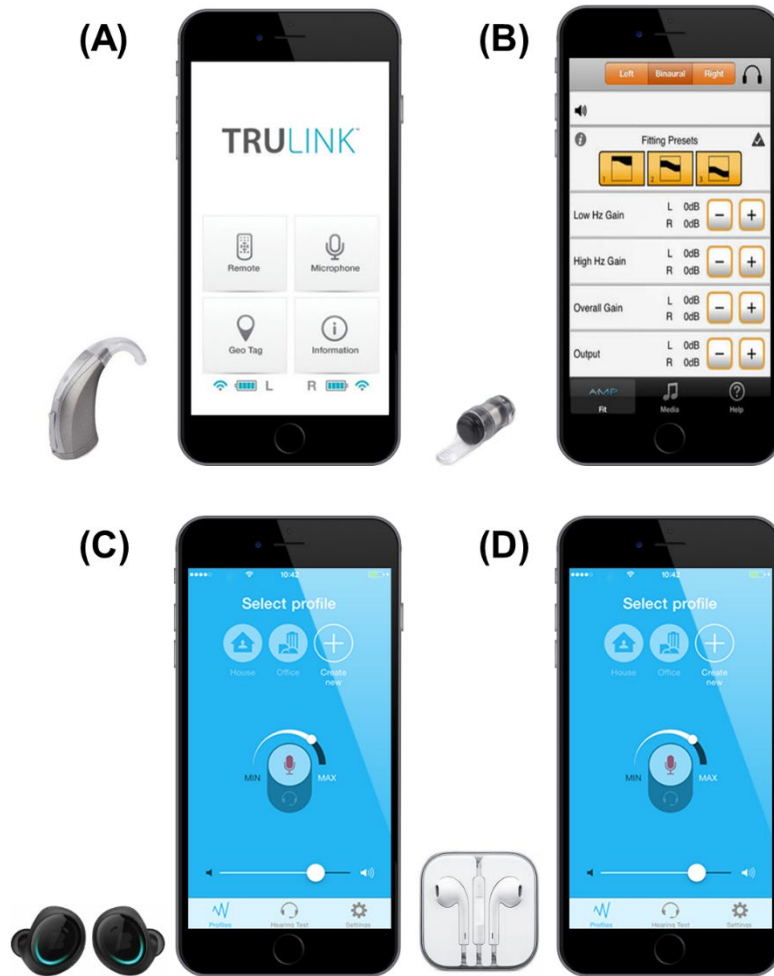
Figure 2. Images of the smartphone-connected listening devices trialled in the study. (A) *Smartphone-connected hearing aids*: behind-the-ear Starkey Halo i110 hearing aids, adjusted via the TruLink app. (B) *Personal sound application product*: in-the-ear Starkey AMP Personal Amplifiers, programmed and adjusted using dual-tone multi-frequency signals via the accompanying AMP app. (C) *Smartphone 'hearing aid' app with wireless hearable*: the Petralex smartphone app used with Bragi Dash wireless earphones that pair with the user's smartphone via Bluetooth. (D) *Smartphone 'hearing aid' app with wired earphones*: the Petralex smartphone app used with standard wired earphones provided with the user's smartphone.

Table 1. Demographic information of included participants.

Gender	n
Male	13
Female	7
Age	**Years**
Mean	62.25
SD	11.59
Range	21-81
Better ear pure-tone average (0.25-4kHz)	**dB HL**
Mean	30.49
SD	17.51
Range	3.4-65
Estimated hearing loss duration	**Years**
Mean	16.41
SD	13.96
Range	≤1-45
Employment status	**n**
Retired	15
Employed	4
Student	1
HHIE (unaided)	**Total score**
Mean	54.20
SD	11.02
Range	35-70

Table 2. A summary of themes generated across all smartphone-connected listening devices. Themes were mapped onto the Theoretical domains framework (TDF), which map onto a specific determinant of behaviour (capability, opportunity and motivation) on the COM-B model.

COM-B	TDF	Sub-theme
Capability	Skills	Digital literacy
	Knowledge	Awareness
	Memory, attention & decision processes	Simplicity (plug-and-play)
		Satisfaction with existing hearing aids
	Behavioural regulation	Adjustability
Opportunity	Social influences	Perception of others and self (stigma)
		Perceived sound quality
	Environmental context	Comfort
		Portability
		Affordability
Motivation	Social role and identity	Age
	Beliefs about capabilities	Empowerment
	Goals	Improved hearing

Usability of smartphone listening devices
Supplemental 1. Definitions of the Theoretical Domains Framework (TDF: Cane et al., 2012; Michie et al., 2014).

COM-B component	Theoretical Domain	Definition
Capability	Knowledge	An awareness of the existence of something.
	Skills	An ability or proficiency acquired through practice.
	Memory, attention & decision processes	The ability to retain information, focus selectively on aspects of the environment and choose between two or more alternatives.
	Behavioural regulation	Anything aimed at managing or changing objectively observed or measured actions.
Opportunity	Social influences	Those interpersonal processes that can cause individuals to change their thoughts, feelings, or behaviours.
	Environmental context & resources	Any circumstance of a person's situation or environment that discourages or encourages the development of skills and abilities, independence, social competence, and adaptive behaviour.
Motivation	Social/professional role & identity	A coherent set of behaviours and displayed personal qualities of an individual in a social or work setting.
	Beliefs about capabilities	Acceptance of the truth, reality, or validity about an ability or facility that a person can put to a constructive use.
	Beliefs about consequences	Acceptance of the truth, reality, or validity about outcomes of a behaviour in a given situation.
	Intentions	A conscious decision to perform a behaviour or a resolve to act in a certain way.
	Goals	Mental representation of outcomes or end states that an individual wants to achieve.
	Reinforcement	Increasing the probability of a response by arranging a dependent relationship, or contingency, between the response and a given stimulus.
	Emotion	A complex reaction pattern, involving experiential, behavioural, and physiological elements, by which the individual attempts to deal with a personally significant matter or event
	Optimism	The confidence that things will happen for the nest or that desired goals will be attained.

Usability of smartphone listening devices

Supplemental 2. Semi-structured interview schedule.

Main question	Optional probe questions
Tell me what you thought of the device and how you got on.	*What did you like?*
	What do you think were the benefits or advantages?
	What didn't you like?
	What do you think were the shortcomings or disadvantages?
Can you tell me how you used the device?	*How often did you use it?*
	In what situations did you use it?
	When did you use it?
Can you tell me what encouraged you to use/not use the device?	*Did you feel that you wanted or needed to use it? Why/why not?*
	Did you get into a habit of using it? Why/why not?
	Would you have liked support to use it? If so, from whom and why?
Can you tell me whether you already aware before the study that this device could be purchased online or on the high street (i.e. retail outlets)?	*Would you consider buying one? Why/why not?*
	How much would you consider paying for it?
	What would make paying for it worthwhile?
Can you tell me whether you are aware of anyone else that has used this device? If so, who?	*If more people used it, would it make you want to use it?*