UNIVERSITY OF SOUTHAMPTON

Faculty of Engineering and Physical Sciences

Improving Cochlear Implant Listening Using Vibrotactile Stimulation

by

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A thesis for the degree of

Doctor of Philosophy

October 2023

University of Southampton

Abstract

Faculty of Engineering and Physical Sciences

Institute of Sound and Vibration Research

Doctor of Philosophy

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Cochlear implants (CI) have revolutionised the management of severe to profound hearing loss. The development of CIs has significantly improved the quality of life of individuals with severe and profound hearing loss. Although CIs provide many benefits, there are still limitations, especially when it comes to challenging listening tasks such as speech perception in noisy surroundings, sound localisation and pitch perception. A potential method to enhance performance in these challenging tasks is supplementing poorly delivered cues through haptic stimulation in conjunction with cochlear implant electrical stimulation, which is known as electro-haptic stimulation (EHS). However, despite the potential benefits of EHS, further research is required to understand and maximise the benefits of this type of bimodal stimulation. Thus, the project's aim is to expand knowledge of EHS by optimising its speech-in-noise performance by evaluating different haptic cues and body stimulation sites, as well as to gather the perspectives and recommendations of CI users and professionals regarding the technology. To achieve this aim, three studies were conducted.

In the first study, three different speech cues – fundamental frequency (F0) and amplitude envelope (Env) and speech presence (SP, which involves providing haptic stimulation on the wrists when speech is present) were compared – to identify the most effective cue for enhancing speech-in-noise performance when delivered through haptic stimulation on the wrists. In this study, twelve CI-simulated participants were trained for 90 minutes in each of the following conditions: speech presence, amplitude envelope, F0, and without haptic cues. The speech reception threshold (SRT) comparison after training did not show statistically significant differences in the benefits between cues. In contrast to the findings of previous studies, the SRTs of various vibration conditions that successfully enhanced speech in previous research were not statistically different from the audio-only control condition.

The second study aimed to determine the optimal body site for haptic stimulation. The main aim was divided into two sub-aims: (a) to assess CI-simulated subjects' perceived benefit and comfort (using a questionnaire) and (b) to evaluate SRT in noise performance when applying amplitude envelope haptic cues to the fingertips, wrists, and forearms. The 24 subjects' SRTs were measured with and without

haptic stimulation at each site after the completion of four training sessions for all body sites. There was a clear advantage in speech-in-noise performance for haptic conditions over the audio-only condition, with an average improvement of about 2 dB SNR ($p < 0.001$). However, there was no statistical difference in speech-in-noise benefits among the three body sites. Similarly, the questionnaire did not reveal a significant difference between the three sites in terms of comfort and perceived benefits. In conclusion, effective haptic devices could be deployed at any of the evaluated body sites.

In the third study, the perspectives and preferences of CI users and professionals regarding the development of haptic devices were gathered. This study used a multi-method qualitative design that involved the administration of questionnaires and focus group discussions with ten CI users and seventeen CI professionals. Their perspectives in the focus group and the final questionnaire were thematically analysed. Six main themes emerged from the focus groups and questionnaires: (a) possible benefits of haptic devices, (b) potential candidates, (c) features and aspects to consider, (d) inhibiting factors influencing users, (e) factors likely to influence uptake, and (f) feedback on the proposed prototype. The participants in the study identified several challenges with CI listening, including hearing in noisy environments, difficulty understanding speech from a distance, difficulties with sound localisation, and difficulty enjoying music. They expressed the belief that a haptic device may help with some of these difficulties while also providing additional benefits such as increased awareness of sound and improved safety. Several potential users of EHS technology were identified including those who are deaf and blind. A haptic device should be designed with consideration of the needs of users. Generally based on the discussions, potential users are looking for haptic devices that are aesthetically pleasing, comfortable to wear, easy to use and have the ability to communicate wirelessly with other devices. Additionally, the focus group discussions revealed a priority for incorporating haptic stimulation into existing wearable devices for both aesthetic and functional reasons. This study provides insights into the desired preferences and requirements for haptic devices, which developers should consider when designing these devices.

Overall, these studies investigated various aspects of electro-haptic stimulation, using a holistic approach by integrating experimental studies with potential user perspectives. The findings suggest that EHS holds promise as a supplementary tool for improving speech-in-noise performance. Importantly, future studies should emphasise enhancing and optimising the design and training regimes for haptic cues to effectively observe their benefits. Moreover, the insights from CI users and professionals may provide potential guidance for the design and development of haptic devices. By synthesising this information together, this work can contribute to advancing the potential of haptic stimulation to enhance the lives of individuals with severe hearing loss.

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6. Where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself;

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Acknowledgements

I would like to begin by expressing my deepest gratitude to my supervisors, Dr. Ben Lineton, Dr. Mark Fletcher, and Prof. Nicci Campbell, for their unwavering guidance, support, and encouragement throughout my academic journey. Their willingness to share their knowledge and expertise was of immense help in refining my abilities.

I also want to extend my gratitude to Prof. Carl Verschuur and Dr. Sam Perry for their invaluable contributions to the studies presented in this thesis. Their insights and assistance have been instrumental in making this project a success.

I am also grateful to my family for their unwavering support and encouragement. My parents provided me with the love and strength to keep going, and my wife Yasmin and son Yousef have been a constant source of inspiration and motivation. I also want to express my thanks to my siblings for their support and encouragement.

In addition, I would like to take this opportunity to thank my PhD colleagues and friends, Ibrahim, Margaret, Michael, Hind, Manal, Rania, Ghada, and Robyn for their encouragement, motivation, and unwavering support throughout my PhD. I extend my sincere appreciation to all the participants, especially my friend Jazz, who generously gave their time and effort to take part in my studies. Their participation was crucial to the success of this research.

I am also grateful to King Saud University for providing funding for my PhD, without which this project would not have been possible. Lastly, I want to acknowledge the support of my friends in Southampton who made my stay in the UK memorable. To everyone who offered me moral support and encouragement, thank you. Your kind words, listening ears, and presence have been invaluable to me.

Definitions and Abbreviations

AGC	Automatic gain control
BKB	Bamford-Kowal-Bench
BSA	British Society of Audiology
CA	Content analysis
CI	Cochlear implant
CIS	Continuous interleaved sampling
dB	Bamford-Kowal-Bench
EHS	Electro-haptic stimulation
Env	Amplitude envelope
ERB	Equivalent rectangular bandwidth
F0	Fundamental frequency
F1	First formant
F2	Second formant
HA	Hearing Aid
Hz	Hertz
IEEE	Institute of Electrical and Electronics Engineers
ILD	Interaural level difference
ITD	Interaural time difference
JND	Just noticeable difference
MLS	maximum length sequence
MPEAK	Multipeak strategy
ms	Milliseconds

N	Newton
NAL	National Acoustic Laboratories
NHCIS	Normal-hearing listening to CI simulations
NHS	National Health Service
NICE	National Institute for Health and Care Excellence
No Vib	No Vibration
NPD	New product development
RMS	Root mean square
SAS	Simultaneous analogue strategy
SNR	Signal-to-noise ratio
SP	Speech presence
SRT	Speech reception threshold
TA	Thematic analysis

Chapter 1 Introduction

Cochlear implants (CIs) are one of modern medicine's accomplishments that allow individuals with profound hearing impairments to perceive sounds through electrical pulse stimulation of the auditory nerve. Thus, CIs can help those with severe to profound hearing loss who cannot obtain adequate benefits from acoustic hearing aids (HAs) as long as they have an intact auditory nerve to transmit the signal to the brain (Niparko, 2009). The CI fitting policy guidelines in many countries have become more flexible in recent years due to the hearing benefits and safety of CIs. The latest National Institute for Health and Care Excellence (NICE) eligibility criteria for CIs could increase the number of CIs received by 70%, reaching 2,150 people annually by 2025 in the UK (NICE, 2019).

Despite new advancements in CIs, users find certain listening tasks more difficult than normal hearing individuals. For example, hearing in noisy situations (Drennan and Rubinstein, 2008), sound localisation (Seebacher et al., 2023, Dorman et al., 2016), and music perception (Drennan and Rubinstein, 2008, Spriet et al., 2007). Some of these listening difficulties in CI users are partly due to the lack of spectral and temporal resolution, which results from a limited number of active electrodes, current spread, envelope-based encoding, and low stimulation rate (Galvin et al., 2009, Shannon et al., 2004).

A variety of approaches have been suggested to reduce the difficulties experienced by CI users in more challenging listening environments. Each has its advantages and drawbacks. For instance, there is increasing evidence that indicates bilateral implantation is advantageous and can improve some of the aforementioned challenging listening situations when compared with unilateral implantation (Brown and Balkany, 2007, Dunn et al., 2010a, Dunn et al., 2008, Steel et al., 2020). This approach, however, is expensive and involves surgical risks (Health Quality, 2018). It also risks loss of residual hearing (Yawn et al., 2018) and vestibular dysfunction (Hänsel et al., 2018), and may also restrict future treatment technologies such as stem cell treatments and hair cell regeneration. Another approach to improve hearing in a challenging situation is known as bimodal fitting, where the residual hearing of CI users' non-implanted ear is fitted with a hearing aid (Ching et al., 2006, Olson and Shinn, 2008, Veugen et al., 2016, Devocht et al., 2017). One of the main bimodal fitting advantages is that acoustic amplification enhances low-frequency sounds (in the non-implanted ear), while high-frequency sounds are encoded with CI electrical stimulation (Gantz and Turner, 2003). Although it is a useful, non-invasive, and cost-effective method, many referred CI candidates lack the required residual hearing (Verschuur et al., 2016).

Recently, a few experiments have shown that a CI users' performance in challenging listening tasks can be enhanced using vibrotactile stimulation to augment the electrical stimulation of the CI (Ciesla et al., 2022, Fletcher et al., 2018, Fletcher et al., 2020a, Fletcher et al., 2020b, Fletcher et al., 2019, Huang et al., 2019, Huang et al., 2017). Such devices are referred as electro-haptic stimulation (EHS) devices. Vibrotactile augmentation is a non-invasive and inexpensive approach, yet there is a lack of commercially produced EHS devices, and the majority of EHS experiments have been investigated in a laboratory setting. The main goal of this project is to further contribute to the field of EHS by comparing speech-in-noise outcomes with different speech cues and stimulation sites, alongside exploring CI professional and CI user perspectives in the development of a wearable device. To achieve this, the following aims were achieved by conducting three experiments:

1. Compare different speech cues for enhancing the speech-in-noise performance of normal-hearing listening to CI simulations (NHCIS) participants when they are delivered through vibrotactile stimulation.
2. Compare the outcomes and experiences of NHCIS participants when haptic stimulation is applied at three sites of the body: fingertips, wrists, and forearms.
3. Explore the perspectives and recommendations of CI professionals and CI users for the development of a wearable haptic device.

1.1 Overview of the Thesis Structure:

Chapter 1 (this chapter) provides a brief overview of the topic as well as a description of the research goals that will be addressed throughout the thesis.

Chapter 2 reviews the existing and relevant literature. It begins with a brief overview of the CI and how it processes sound and generates electrical signals. Afterwards, it discusses the main limitations of CI listening. This chapter also discusses how some of these limitations have been overcome using electro-acoustic and electro-haptic stimulation. Finally, a brief overview of the sense of touch and its psychophysics is provided in order to gain a better understanding of the limits of the haptic system that will be used to supplement the CI listening in this thesis.

Chapter 3 explains the instrumentation, calibration, CI simulation, and haptic cues extractions used in chapters 4 and 5 (studies 1 and 2).

Chapter 4 presents the first experimental study. Researchers have proposed applying a variety low-frequency cues, such as fundamental frequency (F0) (Ciesla et al., Huang et al., 2017) and amplitude envelopes (Env) (Fletcher et al., 2018, Fletcher et al., 2020a, Fletcher et al., 2019) to CI

users' skin to enhance their speech-in-noise performance. However, it has not yet been studied which speech cues, when delivered through haptic stimulation at the wrists, are most effective in improving speech-in-noise performance. Therefore, Chapter 4 compares the effect of different haptic speech cues on speech-in-noise performance of NHCIS participants.

Chapter 5 discusses the second experimental study. Several studies have evaluated the effectiveness of EHS on simulated and real CI users to improve speech-in-noise performance at different body locations, such as the fingertips (Ciesla et al., 2019, Ciesla et al., 2022, Fletcher et al., 2018, Huang et al., 2017) and wrists (Fletcher et al., 2020a, Fletcher et al., 2019). Positive enhancement in speech intelligibility was observed across all evaluated body locations. In addition, it is well known that haptic sensitivity and mechanoreceptor density differ from one body region to another. Considering this, comparing the outcomes and subjective perspectives of applying EHS to the speech-in-noise performance of simulated CI users is worthwhile. Therefore, the experiment in Chapter 5 of this thesis explores the outcomes and experiences of NHCIS participants when haptic stimulation is applied to three sites on the body (i.e., fingers, wrists, and forearms).

Chapter 6 presents a qualitative study related to EHS devices. The user-centred design approach has become increasingly popular in the design of medical devices. This design approach allows device users to become active participants in the design process, resulting in a richer data set than could be obtained through alternative data collection methods. In this context, a variety of factors are important to investigate, including the needs and lifestyles of the potential users as well as the environment in which the device will be used. To researcher’s knowledge, no other studies have examined the user preferences of EHS devices from the standpoint of CI users or professionals. Therefore, Chapter 6 of this thesis considers general ideas and suggestions that CI professionals and users had about the future EHS devices.

Chapter 7 Discusses the main findings from the experimental chapters of this thesis. Furthermore, key limitations of the experiments are discussed, as well as suggestions for future research. This chapter also concludes this thesis by providing a summary of the information gained.

1.2 Contributions to knowledge

This thesis contributes to the understanding of electro-haptic stimulation (EHS) and its potential application for CI users. The studies presented in this thesis provide new and valuable insights into the effects of different vibrotactile cues on speech-in-noise performance and the impact of vibrotactile stimulation at different body sites, as well as the views and recommendations of CI users and professionals regarding the use of EHS devices.

The unexpected findings of study 1 were none of the tested vibrotactile cues resulted in significant improvement of speech-in-noise performance compared to the no vibration condition. This finding highlights the need for future research with a larger sample size and optimised study design to determine the most effective haptic speech cues. The second study demonstrates that vibrotactile cues can significantly improve speech-in-noise performance in CI users when applied to different body locations (fingertips, wrists, and arms) indicating that all the tested body locations could be fitted with effective electro-haptic devices. The third study which is qualitative explores the challenges associated with listening through a CI and highlights the potential benefits of using EHS devices as a solution. Additionally, the third study provides valuable insights into the perspectives and preferences of CI users and professionals, which are crucial for the successful adoption and implementation of EHS technology.

In brief, the studies presented in this thesis offer insights into the use and study designs of EHS to improve speech-in-noise for CI users and provide valuable recommendations for EHS device developers based on the perspectives and preferences of potential users. These findings can inform future EHS designs and contribute to the development of more user-friendly and effective devices for CI users.

Chapter 2 Literature Review

2.1 Overview about Cochlear Implants

2.1.1 Components of CIs and how they work

CIs have internal and external components, as illustrated in Figure 1. The external part includes a microphone, a speech processor, and a transmitter. The surgically implanted, internal part consists of a receiver and an electrode array. Both the external and internal parts work together to produce electrical pulses. After the microphone(s) picks up the sound and converts it into digital electrical signals, those signals are sent to the processor, where they are analysed and processed (detailed in Section 2.1.2). The processed signals are sent by the transmitter, which sends the signals through the skin to the internal receiver, and then directs the electrical stimuli to the electrodes. These electrodes have a tonotopic arrangement in the cochlea (i.e., the electrodes close to the base of the cochlea encode high-frequency sounds, while lower frequencies are encoded near the apex). The electrodes' electrical impulses are then sent via the auditory nerve to the central nervous system to interpret acoustic stimuli.

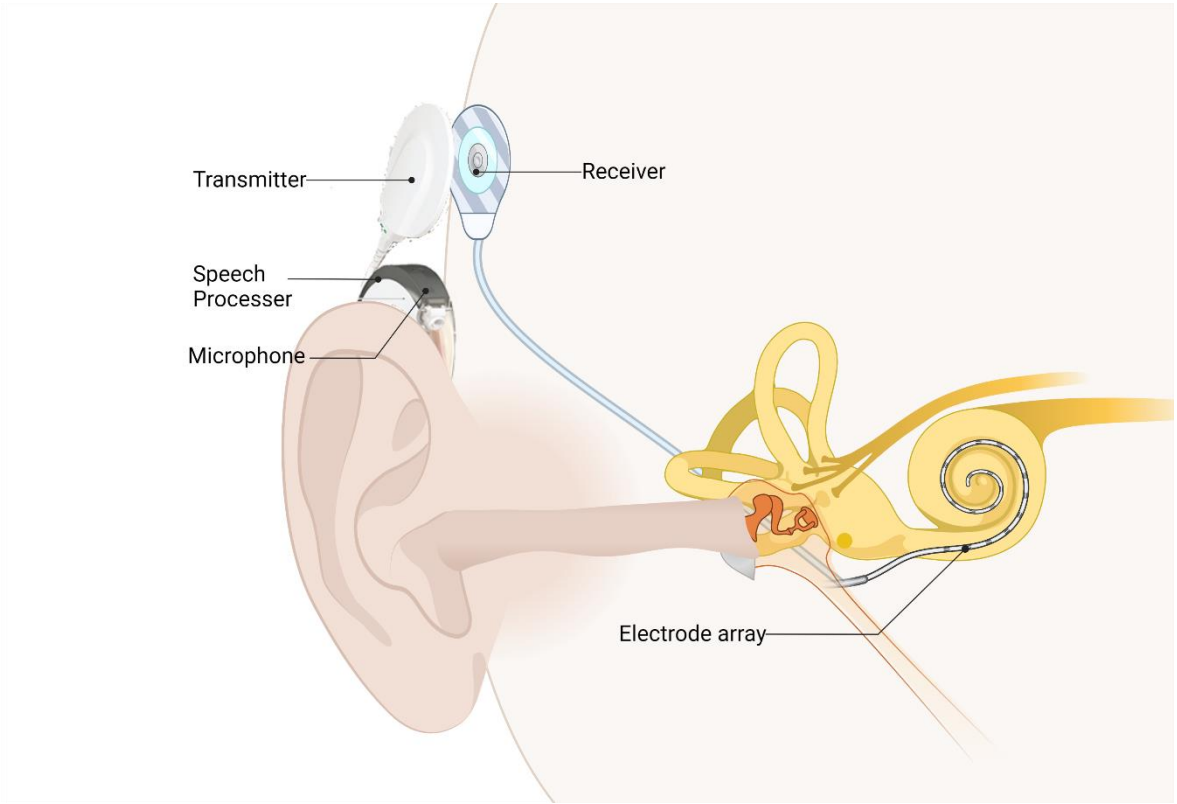

Figure 1. The main components of cochlear implant device.

2.1.2 Speech processing strategies in cochlear implants

Understanding spoken language is a critical aspect of human communication. However, speech is a complex signal, and it varies temporally and spectrally. Conveying this information via CIs requires signal-processing strategies that are used to transform speech signals into the most appropriate electrical impulse patterns, which are transferred via the electrode array. CI systems, therefore, offer a range of speech processing strategies that can be categorised into two primary groups based on how they extract information from speech: feature extraction strategies and waveform strategies. Waveform strategies extract information from the entire sound waveform, while feature extraction strategies focus on specific speech features like the F0 or amplitude envelope. This section will describe the main signal-processing strategies used in CIs. To date, these strategies have been unable to deliver all the details of the speech signal. Thus, exploring them can elucidate how they work and what they deliver. This information can help us determine which signals are poorly delivered and, consequently, which alternative augmentative methods can be used to support CI hearing.

2.1.2.1 Feature-extraction strategies

In the early generations of CIs, feature-based strategies that explicitly provided formant features were used. However, these strategies are now considered obsolete. This subsection provides an overview of some of these strategies.

In the 1980s, the F0/F2 strategy was introduced as one of the earliest feature extraction strategies (Clark et al., 1987). This strategy focused on the extraction of the F0 and the second formant (F2) using zero-crossing detectors. These detectors counted the number of cycles by observing the waveform transformation from positive to negative. The F0 was determined by performing zero-crossing detection on the 270 Hz low-pass filtered signal, while the F2 was estimated using zero-crossing on a 1,000–4,000 Hz bandpass filtered signal. An envelope detector was also applied to estimate the amplitude of the F2 by rectifying and low-pass filtering the band passed output at 35 Hz. The selected electrodes were electrically stimulated at a pulse rate corresponding to the F0. However, for unvoiced speech sounds that do not have an F0, the electrode stimulation was constant at about 100 pulses/sec. The pulse amplitude in the F0/F2 was proportional to the amplitude of the F2, and thus, two electrodes of the 22-electrode array were stimulated simultaneously.

The researchers subsequently improved the F0/F2 by adding the first formant (F1) to the F0/F2 (Blamey et al., 1987). This led to a more refined approach called the F0/F1/F2 strategy. To detect the F1, another zero-crossing detector was added, which used bandpass filter of 280–1,000 Hz. In

this strategy, two electrodes were stimulated simultaneously with biphasic pulses. One electrode carried the F1 information, and the other carried the F2 information. Each phase of the biphasic pulses lasted for 200 μsec and was separated from the second phase by 800 μsec to avoid temporal channel interaction. The amplitude of the biphasic pulses was proportional to the corresponding amplitude of the F1 and F2, whilst the pulse rate of this stimulation was determined based on the rate of the F0. However, the pulse rate for the unvoiced sound was fixed at 100 pulses/sec.

Comparing the F0/F1 with the F0/F1/F2 strategy, the sentence recognition score in the quiet improved from 30% to 63% with the F0/F1/F2 (Dowell et al., 1987). However, no significant improvement was found between the F0/F1/F2 and the F0/F2 in consonant recognition (Tye-Murray et al., 1990). This finding was expected because the modification emphasises low-frequency information, which is essential for vowel reception, while consonant recognition requires a good perception of high frequencies. Knowing that the F0/F1/F2 strategy did not significantly improve consonant recognition, researchers were encouraged to develop other feature-extraction strategies that included higher frequencies.

One strategy is the multipeak strategy (MPEAK), which extracts features of high frequencies using additional band-pass filters in addition to F0, F1, and F2 information. In a study by Von Wallenberg and Battmer (1991), MPEAK was compared to the F0/F1/F2 strategy and the results showed that MPEAK significantly improved the consonant identification from 44% to 54% (Von Wallenberg and Battmer, 1991). Moreover, MPEAK strategy also improved the sentence recognition by 16% in the same study.

2.1.2.2 Waveform strategies

2.1.2.2.1 Compressed analogue & simultaneous analogue strategy

Compressed analogue (CA) strategies are based on the signal waveform. In these strategies, automatic gain control (AGC) is used to compress the input signal before sending it to the filtering process (Laizou, 1999). Four bandpass filters are applied to the signal and the signal gain is adjusted and sent simultaneously to the four CI electrodes.

A refined strategy based on CA is the simultaneous analogue strategy (SAS) (Kessler, 1999). SAS incorporates a pre-emphasis filter to enhance high-frequency components of signal after the AGC. This is critical for perception of consonants as these rely heavily on high-frequency information. Following this, the signal is processed through seven bandpass filters, providing more spectral information than CA. The outputs of the filters are multiplied by gain factors and the signal is compressed to fit into the electrical dynamic range. The compressed signals are delivered

simultaneously in analogue form to the electrodes. Subjects using SAS strategy were able to achieve a sentence recognition score of approximately 40%.

One major limitation of analogue strategies is that simultaneous stimulation of the electrodes can lead to channel interaction (Wilson et al., 1988). This can occur when the stimulus from one channel interferes with the stimulus from another channel, leading to distortion of the speech signal.

2.1.2.2.2 Continuous interleaved sampling

Continuous interleaved sampling (CIS) is an important strategy for representing speech effectively, and it is still used in several current CIs. Moreover, many of the recent signal-processing strategies are based on its concept. CIS has addressed the channel interaction issue in analogue strategies by sending non-overlapping sequential biphasic pulses to the electrodes (White et al., 1984). In this strategy, the sound signal is pre-emphasised and sent through several bandpass filters that are similar to the number of electrodes. The envelopes of each channel are extracted and logarithmically compressed to fit the low dynamic range of electrical stimulation. The signal is then delivered to the corresponding electrodes in a time-interleaved, balanced, biphasic, sequential train of pulses. The pulse rate remains fixed for both voiced and unvoiced speech signals and usually exceeds 800 pulses/sec. CIS has been shown to significantly improve word recognition tests for CI users compared to CA strategy and many participants who were tested using CIS in quiet were able to achieve ceiling effects, indicating near-normal performance (Wilson et al., 1991).

Several modern strategies, such as CIS+, high-definition CIS, HiResolution (HiRes), and HiRes with a Fidelity 120 option (HiRes 120), are derived from CIS and are used in some clinical settings. While these modern strategies are adequate for environmental sounds (Reed and Delhorne, 2005) and speech in quiet settings (Wilson and Dorman, 2007), they severely degrade the perception of pitch-related features due to the limited number of active electrodes, which has an effect on the resolution of spectral information (Pretorius and Hanekom, 2008). Additionally, amplitude-related aspects are also affected, with CI users having a smaller dynamic range (Zeng et al., 2002) and reduced intensity discrimination (Galvin and Fu, 2009). These limitations of modern cochlear implants, as described above, have led to some challenges in CI listening. These challenges will be discussed in detail in section 2.1.3.

2.1.3 Limitations of CIs listening

Despite recent advances in these hearing prostheses, CIs provide a coarse representation of the signal that is only sufficient for speech perception in ideal or quiet situations (Zeng, 2004). Unfortunately, daily life does not always provide ideal conditions for CIs, and some signals and listening environments are complex. Therefore, CI users find some listening tasks more challenging than normal-hearing individuals. In this section, the three main functional limitations of CI listening and the possible reasons for them will be described.

2.1.3.1 Speech-in-noise perception

While many CI users exhibit sufficient speech perception in quiet environments, their ability to perform speech tasks in the presence of background noise is greatly degraded. The listener's ability to recognise speech in noise is quantified by their speech reception threshold (SRT), which is represented in the signal-to-noise ratio (SNR), where the subject can repeat 50% of the speech correctly. Normal hearing individuals can recognise 50% of speech with a low SNR of around -5 dB (Versfeld et al., 2000, Plomp and Mimpen, 1979), whereas CI users' SRT results are usually between 5 dB and 15 dB (Wouters and Vanden Berghe, 2001, Hochberg et al., 1992). Furthermore, it has been reported that hearing in noise requires extra effort from CI users, with a greater listening effort than normal hearing individuals required at the same SNR level (Hughes and Galvin, 2013). Furthermore, they reported that CI users required a 13.4 dB SNR to achieve the same listening effort as normal hearing listeners at 1.5 dB SNR.

The primary reason for speech perception in noise complications is that CIs have a limited number of electrodes, which are affected by the spread of electrical current along the cochlea, resulting in severe limitations in the spectral resolution of CI listening compared to normal hearing (Shannon et al., 2004, Limb and Roy, 2014). Despite researchers' efforts to address this limitation using processing strategies, such as those discussed in section 2.1.2.2.1, the spectral resolution issue persists. Furthermore, noise reduction algorithms have been used to improve CI listening, but their effectiveness is still modest (Carlyon and Goehring, 2021).

2.1.3.2 Music Perception

While CIs were created mainly to improve individuals' speech perception, many individuals with implants still struggle with speech perception in noise and music perception (Sladen Douglas and Zappler, 2015). Compared to individuals with normal hearing, CI users often exhibit imprecise perception of the fundamental components of music, lower enjoyment of music, and less

participation in musical activities (Drennan et al., 2015). This challenge may stem from the differences between music and speech perception. While speech has a narrow frequency range, music is a complex acoustic stimulus with a broad frequency and intensity range that encompasses different aspects, such as pitch, rhythm, and timbre (Drennan and Rubinstein, 2008). Therefore, many studies have aimed to explore the components of melody separately, with some showing that CI users had good rhythm recognition (Reynolds and Gifford, 2019), but most other aspects of music perception were deficient (Drennan and Rubinstein, 2008). Despite many efforts to improve cochlear implants, the perception of complex acoustic signals, like music, remains challenging.

Music perception is a challenging task for CI users for several reasons. The processing strategies in CIs detect the temporal envelope at a fixed rate, which is sufficient for speech perception in optimal environments but insufficient for processing the temporal fine structure that is vital for some music aspects, such as timbre and pitch (Galvin et al., 2009). In addition, the limited spectral channels in the CI cannot deliver the spectral resolution required for melody perception (Galvin et al., 2009, Limb and Roy, 2014). Additionally, the limited spectral and temporal fine structures in CIs cannot support the perception of the F0 and its harmonics which are highly important for musical perception. According to Smith et al. (2002), the perception of a complex musical melody requires at least 48 spectral channels, which is far more than the simultaneously discriminable number of electrodes in CIs. Consequently, music perception is coarse with poor quality for CI users.

2.1.3.3 Spatial hearing

Spatial hearing is a critical ability that helps individuals locate the sources of sounds. In normal-hearing listeners, localisation is complex, and this ability can be achieved using monaural and binaural hearing cues. Horizontal plane localisation is mainly achieved through the analysis of interaural time difference (ITD) and interaural level difference (ILD) at each ear (Hartmann and Kral, 2004). Vertical plane localisation can be obtained monaurally using spectral cues arising from the pinna shape, which acts as a direction-dependent frequency filter.

However, the spatial hearing of most CI users is disrupted due to various factors. For example, many post-lingually deafened adults receive one implant, as per NICE guidance, leading to a loss of binaural spatial benefits. Studies have shown that bilateral implantation is significantly better than unilateral implantation in terms of localisation error in the horizontal plane, in both quiet and noisy environments (Culling et al., 2012, Dunn et al., 2008, Litovsky et al., 2009, Rana et al.,

2017, van Zon et al., 2017). However, even among individuals with bilateral implants, their binaural localisation performance is still inferior to that of normal-hearing listeners (Verschuur et al., 2005, Jones et al., 2014, Majdak et al., 2011, Dorman et al., 2016).

Several factors might contribute to the degraded spatial hearing in bilateral CIs users. First, they have limited access to the temporal differences between the ears, meaning they must rely mainly on ILD (Laback et al., 2004, Aronoff et al., 2012, Brown, 2018). Second, the CI may have limitations in representing interaural level differences accurately due to the asymmetrical depth of the inserted electrodes. This may also result in a mismatch of intensity and place of the neurons' activation in the two cochleae (Goupell et al., 2013, Potts et al., 2019, Kan et al., 2013). Moreover, the separate pre-processing between implants can severely misrepresent this interaural level information (Kan et al., 2013). Third, the input signal's temporal fine structure is cast aside in many processing strategies and substituted with fixed-rate stimulation that represents slowly varying amplitude envelope (van Hoesel, 2004, Wilson and Dorman, 2008, Brown and Bacon, 2010). Lastly, microphone placement on the implant behind the ear removes some of the spatial cues of the pinna (Majdak et al., 2011).

2.1.4 Improvement of CI limitations with residual acoustic hearing

The criteria for CI candidacy vary across different countries, and they typically include specific requirements for speech and hearing abilities that must be met. In recent years, some countries, such as the UK, have relaxed their criteria to include those with residual low frequency hearing (≥80 dB HL for two or more frequencies between 500 and 4,000 Hz; NICE, 2019). Such relaxation has led to an increase in the number of candidates who qualify for CIs while still retaining some level of hearing ability (Leigh et al., 2016, Mudery et al., 2017). Adults in the UK are however only eligible for one CI.

For those who have received a CI in one ear, use of a HA in the ear with residual hearing, an approach known as bimodal fitting, is recommended (Sammeth et al., 2011). Bimodal fitting has gained popularity due to its non-invasive nature and cost-effectiveness (Theriou et al., 2019). One of the main bimodal hearing advantages is that the HA enhances low-frequency sounds, while high-frequency sounds are encoded with CI electrical stimulation (Gantz and Turner, 2003). In addition, bimodal stimulation has been shown to provide better spectral and temporal fine structure cues through the hearing aid at low- and mid-frequency sounds (Gifford et al., 2015, Stronks et al., 2020). This approach has several benefits, including improved speech-in-noise recognition, music perception and spatial hearing (Sammeth et al., 2011), which will be presented in the following sections.

2.1.4.1 Speech-in-noise perception with bimodal fitting

The brain's understanding of speech at a low SNR requires a good representation of low-frequency acoustic signal cues (Chang et al., 2006). Several studies have demonstrated an improvement in speech-in-noise recognition performance when acoustic low-frequency cues were simulated with the low-pass filtered speech in one ear and CI hearing was simulated with a vocoder in the other ear (Kong and Carlyon, 2007, Qin and Oxenham, 2006, Brown and Bacon, 2009, Chang et al., 2006).

Similarly, a large number of studies have investigated speech-in-noise performance in real bimodal users, and most have reported statistically significant benefits compared to using CI only (Berrettini et al., 2010, Dorman et al., 2015, Devocht et al., 2017, Hoppe et al., 2018). For instance, Devocht et al. (2017) observed that when speech and noise were coming from the front the addition of a hearing aid in the opposite ear to the CI provided a mean significant benefit of 4.2 dB SNR. However, the degree of improvement with bimodal varies in the literature (Gifford et al., 2014, Illg et al., 2014, Kessler et al., 2020), likely due to differences in patient characteristics, test settings, and procedures.

This improvement in speech-in-noise recognition could be partially attributed to the mechanism of improved spectral resolution. The provision of additional low-frequency information through supplementary acoustic cues improves spectral resolution, thereby facilitating better segregation of the signal from the background noise (O'Connell et al., 2017). Another factor that may also contribute to this improvement is redundancy (Avan et al., 2015, Ching et al., 2005, Yoon et al., 2012). By utilising a hearing aid in addition to a CI, individuals can benefit from duplicated auditory information. This redundancy enhances the ability to extract relevant speech cues from noise.

2.1.4.2 Localisation with bimodal fitting

Studies found that individuals using binaural hearing through bimodal fittings have a better ability to localise sound in the horizontal plane than those using a single cochlear implant (Jang et al., 2014, Goman, 2014, Morera et al., 2012, Potts et al., 2009, Seeber et al., 2004, Dunn et al., 2005, Ching et al., 2004, Choi et al., 2017, Vroegop et al., 2019). This could be because bimodal listeners may get fine structure cues in the ear that utilise HA, as HA provides low-frequency amplification that preserves fine structure.

2.1.4.3 Music perception with bimodal fitting

There have been numerous studies that have demonstrated the benefits of bimodal fitting in music perception. For instance, the study conducted by El Fata et al. (2009) revealed that the CI users' group with better residual hearing experienced a significant improvement in melody recognition with bimodal hearing. Melody recognition accuracy notably increased, improving from approximately 39% when relying on CI only to approximately 57% with bimodal fitting. Other research has similarly emphasised the positive impact of bimodal fitting on pitch perception (Chen et al., 2014), musical sound quality (D'Onofrio and Gifford, 2021), and emotional perception (D'Onofrio et al., 2020). These studies indicate that the acoustic low-frequency cues provided with bimodal hearing can improve the temporal fine structure required for melody and pitch perception (Dincer D'Alessandro et al., 2018).

2.2 Multisensory integration

Human senses are essential aspects to understand and communicate with the surrounding world. The process of integrating and analysing data from multiple senses (e.g., touch and sight) is commonly referred to as multisensory integration. The synthesis of different sensory inputs plays an essential role in forming an accurate, cohesive perception of the surroundings, and the inputs from various senses often complement and may affect each other.".

A seminal example of multisensory influence is the McGurk effect. Here, an auditory "ba" combined with visual "ga" fuses into the illusory perception of "da", demonstrating that visual cues can alter auditory speech perception (McGurk and Macdonald, 1976). Additional studies reveal similar effects with audio and tactile (puff of air) integration, where identifying aspirated sounds improved with the addition of tactile stimulation. Tactile stimulation may also enhance sound detection (Schürmann et al., 2004), and the perceived loudness (Gillmeister and Eimer, 2007).

This integration is influenced by several factors, influencing how data from different senses are combined. These factors include the temporal and spatial proximity of the stimuli being integrated, and their link with each other (Sanabria et al., 2004, Stetson et al., 2006, Parise and Ernst, 2016). To exemplify, several studies showed that temporal synchrony between visual and audio stimuli is critical for audio-visual integration (Romanski and Hwang, 2012, Parise et al., 2013). Despite differences in the transmission time for light and audio stimulations and the latency they arrive at the cortex, the brain is capable of effectively integrating visual and auditory information (King, 2005). Additionally, repeated exposure to asynchronous audio-visual stimuli

can realign the temporal binding window, known as a temporal recalibration, and enhance the brain's ability to integrate inputs over time (Vroomen et al., 2004).

The principle of inverse effectiveness also applies, whereby integration has the greatest impact when unisensory inputs alone are less effective. This helps explain why those with hearing loss utilise other senses to complement weakened auditory information. Audio-visual integration is one of the most common themes of multimodal research when it comes to enhance speech perception (Ross et al., 2007). However, others attempted to integrate tactile stimulation with other modalities such as audio- and visuo-tactile stimulation. They found that tactile stimulation could improve speech performance for the majority of the normal-hearing participants, as well as deaf individuals after undergoing specific training (Bernstein et al., 1991). Improvement in speech in noise performance, when compared with audio-only perception, was also documented in other studies that combined two or three sensory cues, including auditory-visual cues (Bernstein et al., 2004, Oh et al., 2022, Sumby and Pollack, 1954, Yuan et al., 2021), auditory-tactile cues (Ciesla et al., 2019, Fletcher et al., 2018, Fletcher et al., 2020a, Fletcher et al., 2019, Gick et al., 2008, Huang et al., 2017), and auditory-visual-tactile cues (Derrick et al., 2019, Oh et al., 2022).

The benefits of multisensory integration extend beyond immediate perceptual enhancements. Research shows multisensory experiences are also encoded and retrieved more effectively in memory compared to unisensory experiences alone (Lehmann and Murray, 2005). Moreover, an investigation of whether humans can learn to integrate arbitrary visual and tactile stimuli for object luminance and stiffness showed a significant change in discrimination performance before and after training (Ernst, 2007). This indicates that humans can learn to combine arbitrary sensory stimuli. The ability to transfer learning across senses can be exploited for rehabilitation or habilitation of individuals with hearing disabilities.

Given that this thesis is focused on audio-tactile multisensory integration an application of this multimodal integration will be presented in the next section, particularly in assisting individuals with hearing impairments. Moreover, it is crucial to have a thorough understanding of the fundamental aspects of the tactile system, as it will be employed for stimulus delivery. In 2.4 the physiology and perception of the sense of touch will be discussed in detail, which will cover the structure of the somatosensory system, the receptors and pathways involved in touch perception, and the factors that affect tactile sensitivity and discrimination.

2.3 Tactile Aids

Some individuals with severe to profound hearing loss may have limited benefit from conventional hearing aids, i.e., those with no or limited residual hearing (Turner, 2006). Tactile

aids were commonly used in the past to assist these individuals. During the early stages of CI technology use, tactile aids were regarded as a non-invasive alternative to the new CI devices for individuals who did not obtain enough benefit from conventional amplification. These tactile aids transform acoustic signals into a vibratory or electrical pattern on the skin by extracting relevant acoustic signals that could supplement or replace auditory perception. Recently, these types of aids have been suggested as supplementary devices that can be used to enhance the CI hearing in challenging tasks (Fletcher et al., 2020a, Fletcher et al., 2020b, Fletcher et al., 2019, Fletcher et al., 2020c, Fletcher et al., 2021a, Huang et al., 2017). The following subsections will present a brief history of tactile aids and different usages of tactile aids for individuals with hearing loss.

2.3.1 History of tactile aids

Prior to the establishment of electronic tactile aids, several natural methods were to help individuals with hearing impairment understand verbal speech. These methods relied on the sense of touch and didn't require any electronic or mechanical devices. One of the earliest and well-known methods was Tadoma, which was used for deafblind individuals. Tadoma involved placing one's hand on the talker's face and neck to feel the movements of their facial and vocal folds during speech (Alcorn, 1932, as cited in in Reed, 1996). The success of these natural methods provided empirical evidence that tactile stimulation could effectively aid hearing-impaired individuals in communication (Oller, 1995).

According to Roeser (1985), in the 1920s, Gault and his team developed a range of tactile aids for individuals with hearing impairment. In their initial experiments, they delivered acoustic signals to the skin via a hollow tube, with impressive results showing that a subject could recognise 34 words, as well as sentences composed from them. They achieved an accuracy rate of 88 to 95% when identifying 200 tactile impressions of familiar words after training. Further experiments involving a more sophisticated device with 15 severely hearing-impaired subjects showed promising results, with an average accuracy rate of 70 to 80% when discriminating between ten sentences composed of six monosyllabic words after 14 hours of practice. However, in a later vibrotactile experiment by Gault and his team, they aimed to determine whether speech interpretation using vibrotactile stimulation is primarily a result of a relationship between the senses of hearing and touch. The experiment did not confirm the hypothesised connection. The results of this experiment showed no significant difference in subjects' accuracy in identifying patterns, whether they represented actual sentences or positions in a list. This implies that the process of interpreting speech through vibrotactile patterns primarily relies on a learning process.

A major shortcoming of Gault's work was the failure to consider the limitations of the skin as a receptor of sound. This limitation was addressed by Levine and colleagues between 1949-1951, as cited in Roeser (1985), when they developed the first tactile vocoder known as Felix. The device filtered energy into seven discrete frequency bands and presented it to the skin as low-frequency vibrations that fell within the skin frequency range. The introduction of this tactual vocoder led to numerous studies applying the principles of this type of device to tactile aids.

Following the proliferation of psychophysical studies on tactile perception, the development of tactile aids and signal processing advanced significantly. Various types of transducers were employed at different skin sites, including the fingers, chest, and forearm. By the 1980s, wearable tactile devices were commercially available.

2.3.2 Tactile aids as an alternative to CIs

Tactile aids aim to extract specific features of the acoustic signal such as amplitude, frequency and/or duration (Oller, 1995). While these devices showed some success in improving speech perception for deaf individuals, they were limited in their ability to allow for open-set words and sentence perception, where speech is presented without additional cues (Oller, 1995).Although tactile aids provided some value to the users, their limited use today is mainly due to the widespread adoption of CIs as a more effective solution for speech perception, particularly in open-set scenarios.

Tactile aids for the deaf come in different forms, ranging from basic single-channel devices that apply processed vibratory signals (such as the amplitude envelope) to a single location on the skin, such as the wrist (Minivib3) or sternum (Tactaid I), to more advanced multi-channel devices that utilise the vocoder principle (Rönnberg et al., 1998). Multi-channel devices deliver vibratory information to various channels located at different places over the skin, including several different sites on the forearm (Tactaid V), neck (Tactaid VII), arm (AKL aid), and wrist (Telex KS 3/2). These multi-channel devices often utilise shaker location to convey information about speech frequency based on filter banks, while amplitude of vibration is used to encode the energy of the acoustic signal across various frequency bands. Training users on these extracted temporal vibratory features could enable them to recognise some acoustic input. However, it has been challenging to achieve open-set perception of words or sentences when tactile aids are used as the sole mode of speech perception (Oller, 1995). Studies have shown that using tactile aids with lipreading can significantly improve the ability to repeat sentences compared to lipreading alone (Weisenberger and Miller, 1987, Cholewiak and Sherrick, 1986). Therefore, tactile aids may be a

helpful tool for supplementing lipreading for deaf individuals who cannot or choose not to use cochlear implants.

2.3.3 Using tactile aids to supplement CI hearing

Tactile aid development was halted after significant advancements in CI technology resulted in speech recognition that was far superior to what could be achieved with tactile aids alone (Zeng et al., 2008). However, recent research has proposed a combination of tactile and CI electrical stimulation as an effective means of enhancing performance on challenging listening tasks for CI users. As previously mentioned, tactile aids were able to provide some speech features that are not available with CI hearing alone, making supplemental tactile information a promising strategy for enhancing hearing with CI. Several attempts have been made to investigate the benefits of supporting hearing with tactile stimulation. This section will first review relevant tactile multisensory literature that was applied to normal hearing subjects before discussing the literature related to EHS.

Drullman and Bronkhorst (2004) conducted a study to investigate the effects of tactile multisensory support extracted from the clean speech input on speech-in-noise performance in individuals with normal hearing. The study involved measuring SRTs while varying the number of interfering talkers in speech babble from one to eight male talkers. The results revealed that presenting low-frequency information via tactile stimulation significantly improved speech-in-noise intelligibility, and the average improvement with tactile support for one talker and two-talkers noise are 1.9 and 2.4 dB, respectively. Additionally, the study found that the level of enhancement from the tactile support was affected by changes in the competing noise. Specifically, the benefit from the tactile stimulation decreased when the interfering noise exceeded two talkers.

Another recent multisensory study by Oh et al. (2022) investigated the use of multisensory cues, specifically visual and tactile amplitude cues extracted from the clean targeted speech, to enhance the speech-in-noise performance. The speech recognition score of 20 normal hearing participants was measured for the following four conditions: audio-only, audio-tactile, audio-visual, and audio-visual-tactile. The speech recognition score was measured for sentences embedded within a speech-shaped noise masker at different degrees of SNR. Results showed that the addition of simultaneous amplitude envelope cues significantly improved speech perception in all multisensory conditions, especially at lower SNRs ($p < 0.05$). When each cue was presented individually, either tactile or visual, at the lowest SNR level (-7 dB) the average improvement in word recognition accuracy was around. Additionally, integration of both visual and tactile cues led

to the greatest improvement range of 14-25%. Together, these findings suggest that research on the effectiveness of multisensory support input on speech perception could have important implications for supplementing the hearing of individuals with hearing impairments, such as those with CIs who struggle in challenging listening tasks.

After discussing multisensory studies that applied tactile stimulation to normal hearing subjects, the focus will now shift to exploring studies related to EHS. EHS combines CI electrical stimulation with vibrotactile stimulation to the skin to deliver supplementary audio information. The following paragraphs review a range of EHS studies and their approaches to extracting and delivering acoustic information through tactile sensation.

Huang et al. (2017) suggested that EHS can enhance the speech-in-noise performance of CI users. This study involved the extraction of vibrotactile information from the F0 of speech materials, which was then delivered to the index fingers of ten CI users. The SRT in stationary noise was evaluated with and without the addition of vibrotactile supporting cues. The results showed that the addition of vibrotactile cues in the EHS condition was statistically significantly better than the CI-only condition by an average of 2.2 dB. This amount of improvement is comparable to the results achieved with electric-acoustic stimulation (when some hearing is preserved in the implanted cochlea) studies when the speech and noise are co-located (Gifford et al., 2010, Sharma et al., 2019, Dunn et al., 2010b). However, a key limitation of Huang et al. (2017) is that the authors extracted the F0 cues from clean speech instead of from speech-in-noise. This kind of extraction may be difficult to apply in real-life settings.

Fletcher et al. (2018) conducted a study to investigate the potential benefit of using EHS to supplement poorly delivered low-frequency signals in CI users. In contrast to Huang et al. (2017), Fletcher et al. (2018) extracted the temporal envelope and voicing cues from speech-in-noise with the aid of an amplitude envelope expander function and, thus, generated the vibrotactile cues. This addition of envelope expander aimed to enhance the prominence of speech envelope while mitigating the impact of background noise. The speech-in-noise performance was measured with and without vibrotactile cues at the participants' fingertips. Additionally, the speech performance was assessed before and after a 30-minute training session with EHS. The results indicated a statistically significant improvement in speech-in-noise recognition scores with vibrotactile cues after the training session, with an average improvement of 10.8% when the SNR level was equal to the baseline SRT measured in the first session. This level of improvement is consistent with earlier studies that evaluated the performance of CI users with residual low-frequency hearing (Gifford et al., 2013, Gifford et al., 2017). However, the study has some limitations. First, the authors conducted the experiment on normal-hearing listening to CI simulations participants,

which may only represent CI users with an ideal fitting. Furthermore, in real life, perfect CI fitting cannot be achieved in all CI surgeries due to individual differences and medical complications. Finally, the haptic stimulation was delivered to the fingertips, which may not be practical in daily life as the hand needs to be free for other activities.

Fletcher et al. (2019) conducted another study to investigate the potential benefits of using EHS to enhance speech-in-noise performance in ten CI users without residual functional hearing at low-frequencies. The study employed signal processing similar to that used in their previous work (Fletcher et al., 2018), but delivered the vibrotactile cues to the wrist instead of the fingertip, as it is a more practical site for an EHS device. The authors measured the speech in multi-talkers noise scores at a SNR level equal to the baseline SRT measured in the first session with and without vibrotactile cues before and after 40 minutes vibrotactile training divided into two days. The results indicated that there was no statistically significant improvement in speech-in-noise performance with EHS before the training. However, after the training, the EHS significantly improved speech-in-noise scores by an average of 8.3% compared to the CI only condition. The main limitation of this study's design is the lack of training with speech-in-noise without haptic stimulation, which could lead to a bias toward the EHS condition. The authors explained that the limited time available to participants precluded training without vibrotactile stimulation and that this time was better utilised for training with haptic stimulation.

Similarly, Ciesla et al. (2019) investigated the use of EHS utilising F0 vibrotactile cues extracted from clean speech and delivered to the fingertips (index and middle fingers of the dominant hand) to enhance speech recognition in noise for CI users. The results indicated that vibrotactile stimulation improved SRT significantly for normal-hearing participants listening to CI simulations by 6 dB compared to the audio-only condition, without any training.

Subsequently, Ciesla et al. (2022) conducted a similar study but with two types of training (Audio-only and audio-tactile training) as well as three testing conditions (audio-only, audio-matched-tactile, and audio-non-matched-tactile as the control tactile condition). Prior to training, the SRT results showed that the audio-matched-tactile condition was significantly lower than the audio-only condition by an average of 6.16 dB. However, after training both the audio-only and audio-matched-tactile training conditions resulted in statistically lower SRTs compared to the pre-training testing session, with the difference exceeding 12 dB. Moreover, the findings from the after-training session revealed that the speech-in-noise SRT was significantly enhanced by 4.82 dB for the audio-matched-tactile training group and 3.94 dB for the audio-only training group, compared to the audio-only testing. Notably, the audio-non-matched-tactile condition had the highest SRT scores compared to the other conditions for both training groups in the after-training

session. This condition resulted in a statistically significant increase in SRTs compared to audio-only condition by 3.7 dB. It is worth noting that the observed effect sizes calculated by Ciesla et al., (2022) were larger than previous studies conducted by other researchers, which reported an average enhancement with vibrotactile cues of around 3 dB (Fletcher et al., 2020a, Huang et al., 2017). The reason for this discrepancy is not clear and could potentially be attributed to several factors, with one prominent factor being the differences in the simulation parameters used.

Apart from these studies using co-located speech and noise sources, Fletcher et al. (2020a) have shown significant benefits of EHS when used with spatially separated speech and noise sources for unilateral CI users. In this experiment, vibrotactile stimulation cues similar to those used in their previous studies were applied to the wrists in response to the sounds picked up by devices placed behind the ears. However, unlike in previous studies, the expander was not used for reducing noise during vibrotactile cues signal processing. Despite this, the use of EHS enhanced SRTs by 3 dB when speech was presented in front of the CI listener and noise was coming from either side. An enhancement of this magnitude has been reported for CI users implanted bilaterally (Sivonen et al., 2021). One noteworthy outcome of the study was the absence of enhanced speech-in-noise performance when employing EHS in situations where the speech and noise sources were co-located. This observation raises the possibility that the expander, which has been utilised in previous co-located studies (Fletcher et al., 2018, Fletcher et al., 2019), may have played a critical role in the observed performance gains. As such, it may be advisable to integrate the expander as a means of attenuating noise when the speech and noise sources emanate from the same location.

Fletcher's research group has demonstrated that EHS can improve sound localisation in CI users in multiple studies, in addition to its ability to enhance speech-in-noise performance (Fletcher et al., 2020b, Fletcher et al., 2021a). The localisation performance is commonly quantified using the root mean square (RMS) error degree, whereby a smaller RMS error indicates better localisation performance. For example, a recent study by Fletcher et al. (2020b) investigated the effectiveness of providing vibrotactile cues to both wrists of unilateral CI users in improving localisation. Their findings indicated that RMS error results were significantly lower with the presentation of haptic stimulation than without. After just 15 minutes of training with vibrotactile cues, the average RMS error of the participants decreased by 17.2° (standard error ± 4°), from 39.9° to 22.7°. Another study by Fletcher and Zgheib (2020) examined the efficacy of using vibrotactile cues on NHCIS participants to enhance localisation. The results of the study showed a statistically significant reduction in the average RMS error with vibrotactile cues before and after training with these cues.

Along the same lines, few studies have investigated the use of haptic stimulation to enhance music perception in CI users. Data from recent studies suggest that appropriate haptic stimulation cues to the wrist or fingertip significantly improve the music-related performance of both CI users and CI-simulated subjects, such as melody recognition (Luo and Hayes, 2019, Huang et al., 2020) and pitch discrimination (Fletcher et al., 2020c).

Based on the reviewed studies, it appears that the use of EHS holds promise for enhancing speech-in-noise perception, sound localisation, and music perception in CI users. However, the benefits of EHS varied among the studies, and their effectiveness may depend on several factors such as training, listening task and the processing strategies used. Additional research is necessary to determine the optimal conditions for the use of EHS to improve cochlear implant hearing.

2.4 Perception via the sense of touch

This section aims to highlight the key characteristics and abilities of the skin's sensitivity to haptic stimulation. By reviewing the fundamental aspects, capabilities, and limitations of tactile perception, researchers can more effectively design efficient haptic devices for individuals with hearing disabilities.

2.4.1 Overview of the sense of touch

Human skin plays a critical role in several physiological functions, including protection, thermal regulation, and the perception of tactile stimuli. According to Hall (2015) the skin's sensory receptors can be categorised into three physiological categories based on the type of stimulation they receive. These categories include pain receptors that respond to threats of damage to the skin, thermoreceptors that detect temperature changes, and somatic mechanoreceptors that respond to mechanical displacement, such as touch, pressure, and vibration.

This literature review will focus on somatic mechanoreceptors in greater detail in the context of this thesis, as they will be utilised to deliver targeted haptic stimulation in EHS. It is worth noting that although haptic stimulation can refer to a wide range of tactile stimuli, including pressure, texture, temperature, and vibration (Shull and Damian, 2015), in this thesis, haptic stimulation solely refers to vibrotactile or vibration stimuli, without including other aspects.

By exploring the nuances of somatic mechanoreceptors, this thesis aims to explore the potential of EHS to enhance CI hearing. Through a deeper understanding of the underlying physiological mechanisms and careful design of electro-haptic devices, more effective EHS solutions can be developed that will benefit a wide range of CI users.

2.4.2 Anatomy and Physiology

The haptic sensation of a mechanical stimulation, such as touch, stretching, pressure or vibration, is detected and transduced by the skin's mechanoreceptors. There are four distinct types of mechanoreceptors in human skin, with each type specialised to respond to a specific type of mechanical stimulation. These mechanoreceptors include Meissner's corpuscles, Pacinian corpuscles, Merkel's disks, and Ruffini's corpuscles. All four receptors are found on hairless (glabrous) skin, such as finger pads, palms and soles of the feet; however, hairy skin has all the receptors except Meissner's corpuscles (Gescheider et al., 2009).

Mechanoreceptors in response to stimulation vary based on their speed of adaptation, receptor field size, and frequency response range sensitivity. The adaptation rate of skin mechanoreceptors refers to how quickly they stop firing in response to a constant stimulus over time. Based on this rate, mechanoreceptors are classified as either fast adapting (FA) or slow adapting (SA). The receptor field of a mechanoreceptor is the specific region of skin that, when stimulated, can activate the receptor and produce a response. The receptor field is categorised into two types: I-small and II-large (Gescheider et al., 2009). To gain insight about the distinct features of each mechanoreceptor based on the aforementioned criteria, see Table 1 and Figure 2.

Table 1. Properties of different skin mechanoreceptors (Bolanowski et al., 1988, Hall, 2015, Kaczmarek et al., 1991, Gescheider et al., 2009).

Receptor	Speed of adaptation	Receptor field	Type of skin	Most sensitive frequency range	Sensation
Pacinian (PC)	Fast	Large (10-1000 mm^2)	Glabrous and hairy	30-500 Hz	Vibration
Meissner's (RA I)	Fast	Small (0.5-100 mm^2)	Glabrous	5-50 Hz	Flutter
Ruffini (SA II)	Slow	Large (10-500 mm^2)	Glabrous and hairy	100-500 Hz	Stretch
Merkel's (SA I)	Slow	Small (2-100 mm^2)	Glabrous and hairy	0.3-5 Hz	Touch and pressure

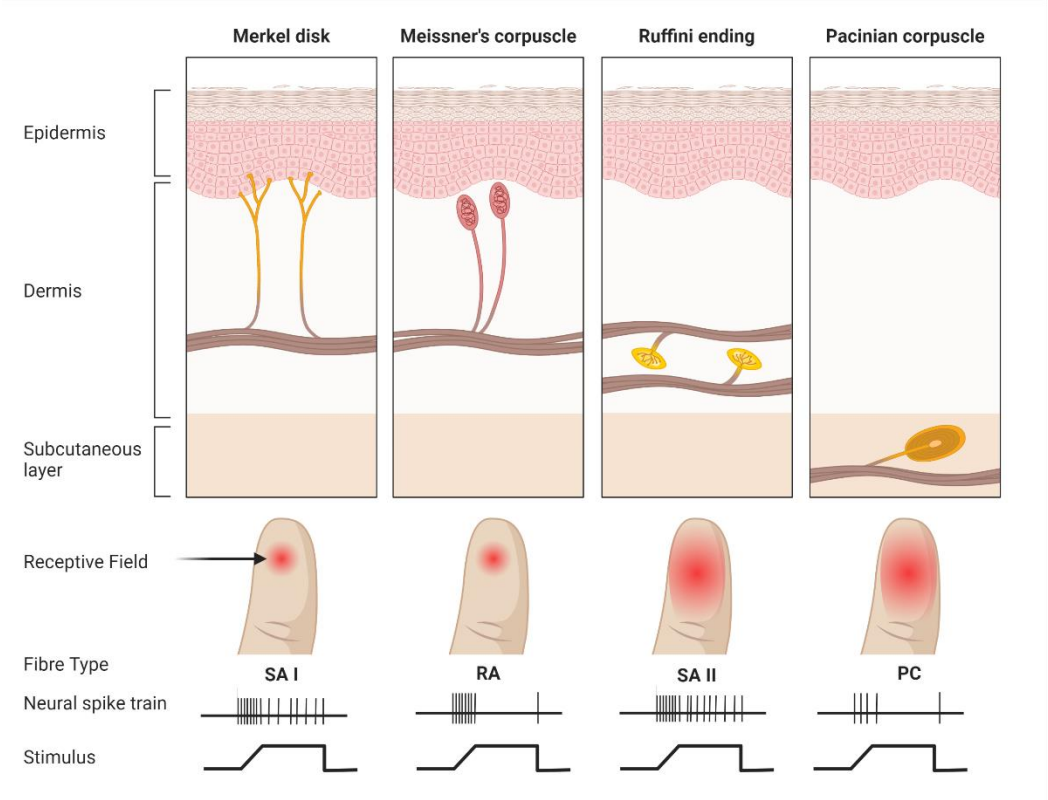

Figure 2. A diagram redrawn from Gescheider et al. (2009) illustrating the histology of mechanoreceptors and nerve fibre in glabrous skin.

When mechanical stimulation is applied to the skin, the mechanoreceptors produce electrical action potentials that are mainly carried on Aβ afferent nerve fibres through the dorsal column of the spinal cord (Hall, 2015). These nerve fibres are uninterrupted until they decussate at the synapse of the dorsal column nuclei. The neurons then ascend upward through the medial lemniscus to the thalamus. After that, the signals synapse in the ventrobasal complex of the thalamus, where they project to the cortical somatosensory areas (see Figure 3; Hall, 2015).

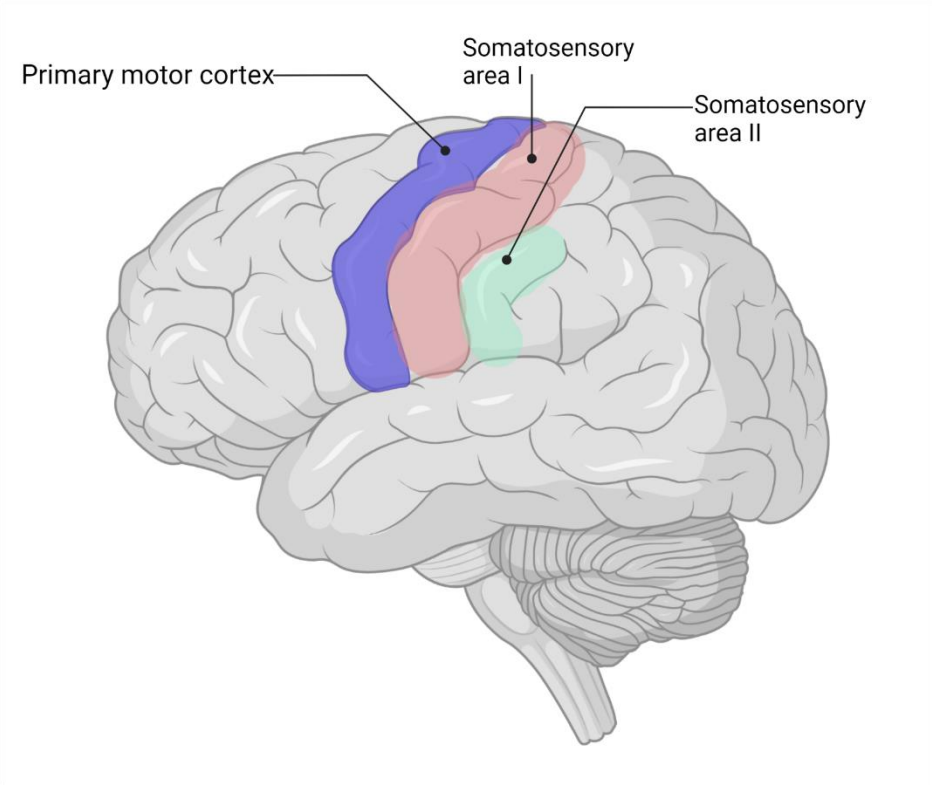

Figure 3. The main two cortical somatosensory areas. Redrawn from (Hall, 2015).

The central processing for somatosensory stimulation is divided into two cortical areas in each hemisphere, with each cortical area receiving sensory information from the opposite side of the body. Somatosensory area I mainly occupies the postcentral gyrus in the parietal lobe, while somatosensory area II is located in a small area at the lateral parietal cortex (see Figure 3). Each point of somatosensory area II receives sensory inputs from different body parts, which are mapped in a specific pattern called the somatosensory homunculus (see Figure 4). The size of the body part controlled by somatosensory area II is proportional to the density of receptors in that specific part. While much uncertainty still exists about the function of somatosensory area II, it is known that this area receives signals from both sides of the body. Furthermore, most of area II's input is secondarily received from area I and other sensory locations, such as the visual and auditory cortices (Hall, 2015).

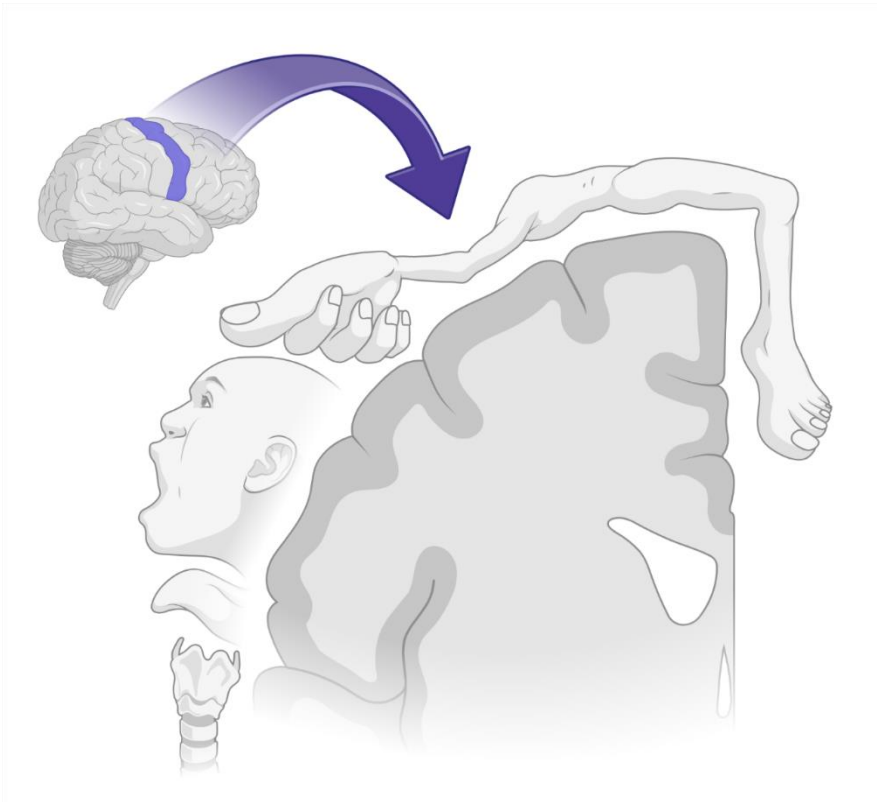

Figure 4. Displays a redrawn version of Penfield's (1968, as cited in Hall, 2015) cortical homunculus, which illustrates the various regions of the somatosensory cortex that correspond to different body parts. This figure provides a useful visual representation of the cortical organisation of tactile perception and the relative amount of cortical real estate allocated to various body parts.

2.4.3 Psychophysics of the somatic sensation

The aim of this project is to enhance the CI hearing using vibrotactile stimulation to the skin. To achieve this, it is crucial to understand the psychophysics of touch, an approach that studies the physical properties of somatic or haptic stimuli and reports subjects' behavioural responses. This approach can be used effectively to understand subjective somatic sensations. Therefore, an appropriate physical sensation applied to the skin should be considered when using this system for different purposes such as EHS. This subsection will review the psychophysics of different somatic sensation dimensions and compare them with psychoacoustics, which involves the behavioural perception of acoustic sounds, whenever applicable.

2.4.3.1 Frequency perception

Mechanoreceptors in the skin are capable of detecting and responding to mechanical stimuli within defined frequency ranges. According to Verrillo and Gescheider (1992), the skin's frequency range is between ≈20 Hz–1,000 Hz, which is much narrower than the auditory system's

range of 20 Hz- 20,000 Hz in young, healthy normal-hearing individuals. Verrillo's (1963) findings revealed that the detection threshold of the thenar eminence, which is the area of skin at the prominence on the palm at the base of the thumb, varied across different frequencies. In addition, the skin's detection threshold was most sensitive to frequencies between 250-300 Hz, with the lowest absolute vibrotactile threshold at around -16 dB (re: 1 μm) for the largest contactor (5.1 cm^2). Verrilo's (1963) study used a circular contactor attached to an accelerometer to measure the thresholds and evaluated the effect of changing the contactor size on the detection threshold. This experiment also evaluated the effect of changing the contactor size on the detection thresholds. Observations from the study indicate that the utilisation of a contactor larger than 0.08 cm^2 resulted in vibrotactile thresholds above 40 Hz being characterised by a U-shaped function in relation to stimulus frequency on the skin, as shown in Figure 5. Bolanowski et al. (1994) evaluated the detection thresholds across frequencies for the forearm when 2.9 cm^2 contactors were used and showed a similar U-shaped pattern of thresholds to the thenar eminence observed in Verrillo (1963), although detection thresholds for the forearm were higher (Bolanowski et al., 1994). Additionally, Verrillo (1966) showed that the volar forearm's (underside of the forearm) thresholds were higher by ≈11 dB at 25 Hz and ≈20 dB at 125 Hz than they were for the thenar eminence. These differences may be attributed to the variation in mechanoreceptor densities in different locations.

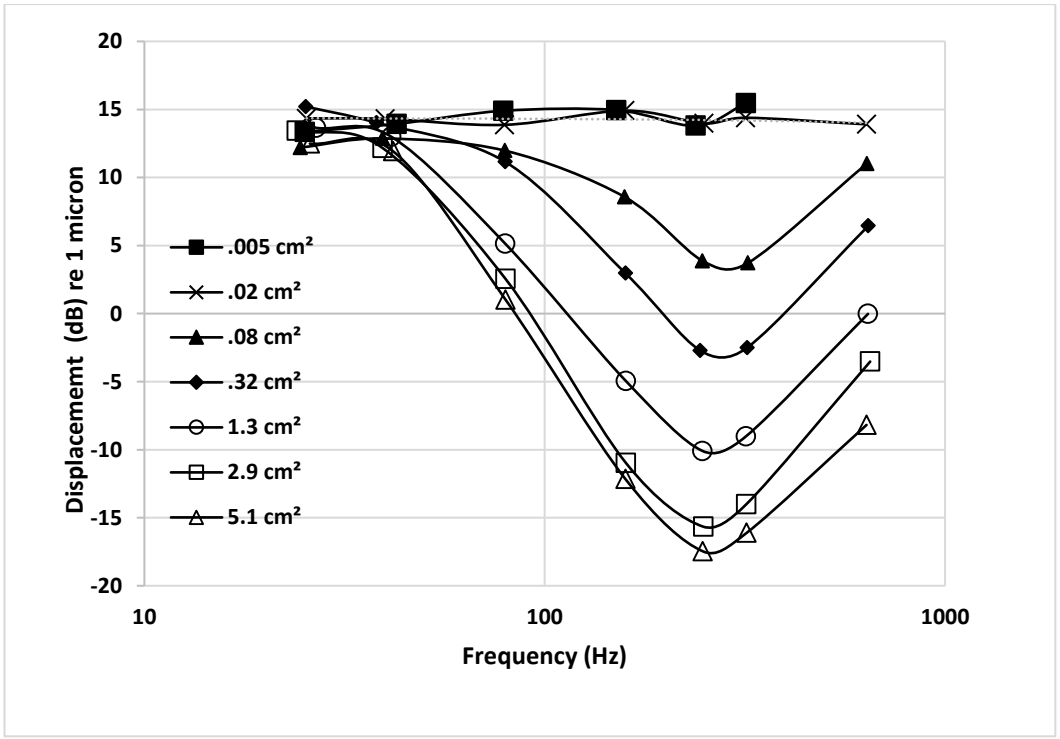

Figure 5. The detection threshold curves as a function of frequency for different contactor sizes, adapted from (Verrillo, 1963).

2.4.3.2 Frequency discrimination

Frequency discrimination refers to the subjective ability to differentiate between two stimuli that have different frequencies when presented sequentially at a suprathreshold level. However, in comparison to the auditory system, the frequency discrimination ability of the skin is limited, and this limitation further worsens as the frequency of stimuli increases (Verrillo and Gescheider, 1992). In a study by Goff (1967), the detection of frequency change was evaluated for vibrotactile stimuli applied to the fingertip for selected frequencies (25, 50, 100, 150, and 200 Hz) at 20 dB SL. The results revealed that the frequency discrimination ranged from approximately 20% at 50 Hz to around 35% at 200 Hz. Similarly, Rothenberg et al. (1977) evaluated the vibrotactile frequency discrimination of the forearm and reported similar discrimination to that reported by Goff (1967) for the fingertips, despite the fingertips having more sensitive detection thresholds. In contrast, the auditory system exhibits more sensitive frequency discrimination than the tactile system (Moore, 2012). Healthy auditory systems are capable of detecting changes in frequency of as little as 1% at 100 Hz and 10% at 10 kHz (Moore, 1973).

2.4.3.3 Intensity perception and discrimination

Compared to audition, the skin tactile system exhibits a considerably limited intensity dynamic range that extends up to approximately 60 dB above the detection level (Verrillo and Gescheider, 1992, Fletcher et al., 2021a). Several studies have explored the skin's ability to detect changes in vibrotactile intensity between successive stimuli presented at a suprathreshold level (Gescheider et al., 1990, Craig, 1974, Craig, 1972, Gescheider et al., 1996). Gescheider et al. (1996) reported a Just noticeable difference (JND) of intensity around 1.5 dB for the thenar eminence in response to 250 Hz signals, while Craig (1972) found JNDs of around 1.5 dB for 150 Hz stimuli at the fingertips. Similarly, Fletcher et al. (2021a), evaluated JNDs of intensity across wrists and obtained results similar to those of sequential stimuli, with discrimination threshold of around 1 dB. Furthermore, the tested stimuli with the higher sensation levels, which were controlled to avoid discomfort or pain, produced the lowest JNDs of intensity (Gescheider et al., 1996, Fletcher et al., 2021a). In contrast, the normal auditory system has a dynamic range of approximately 120 dB, using a reference level of 20 µPa, and can detect differences in intensity of less than 0.5 dB at 1,000 Hz (Moore, 2012). Overall, the tactile system's sensitivity for detecting changes in intensity is comparable to normal hearing's ability, with the JND of intensity in both senses dependent on the sensation level of the stimuli.

2.4.3.4 Adaptation

Sensory adaptation is a well-known phenomenon in sensory systems, whereby prolonged exposure to a stimulus results in a reduced response to that stimulus. For instance, in the tactile system, exposure to a high-intensity suprathreshold stimulus for an extended period can lead to a decline in the absolute threshold, which is commonly known as adaptation or fatigue (Gescheider and Verrillo, 1979). Moreover, it can result in a decrease in the perceived magnitude (a subjective metric) of the stimulus (Verrillo, 1985, Verrillo and Gescheider, 1977, Bensmaia et al., 2005). This decrease in perception is often temporary, and the duration of recovery varies from a few seconds to several minutes based on the stimulus's intensity, duration and frequency (Kaczmarek et al., 1991). Adaptation and fatigue are less pronounced in the auditory system compared to other sensory means. The auditory adaptation occurs when neural firing rates, in response to a steady stimulus, decrease over time until they reach a steady rate. As a result, the perceived magnitude (loudness) of the stimulus decreases for few minutes, followed by a period of constant magnitude. On the other hand, post-stimulatory auditory fatigue is similar to tactile adaptation and can result in a temporary threshold shift (TTS), which is an elevation of the hearing threshold due to prolonged exposure to high-intensity acoustic stimulation (Katz et al., 2015). Recovery from TTS can occur within hours, days or weeks, depending on the duration and intensity of the fatiguing acoustic stimulation (Ryan et al., 2016). While both auditory and tactile sensations may experience a threshold shift effect due to temporally prolonged high-level stimulation, tactile adaptation requires a lower sensation level to cause this shift but can recover more quickly than auditory fatigue. Therefore, when developing a device, it is essential to consider the potential impact of these adaptation phenomena on the device's signals.

In summary, an increase in threshold due to exposure to a temporally prolonged stimulation has been seen in both the auditory and tactile sensations. However, it should be noted that TTS in auditory stimuli only occurs with high-intensity sounds, while tactile adaptation requires stimuli at a lower sensation level to induce a threshold shift effect and has a shorter recovery time. Therefore, when developing a device, it is essential to consider the potential impact of these adaptation phenomena on the device's signals.

2.4.3.5 Temporal aspects of skin

To accurately represent acoustic stimulation through haptic means, it is crucial to have a thorough understanding of the skin's temporal response to vibration. This is particularly important since these stimuli exhibit fluctuations over time, which must be properly considered for sensory representation. Furthermore, the duration of stimulation could carry information that is required

to deliver messages through the skin. Therefore, understanding the skin's temporal response to haptic stimulation is essential when seeking to fully utilise this sensory modality.

Temporal resolution (or gap detection), an important temporal aspect, is the ability to detect the gap between two stimuli. The hearing and tactile sensations require a specific duration gap between stimuli to discriminate successive presentations; otherwise, the two stimuli would be perceived as one (Gescheider, 1967). A study conducted by Gescheider (1967) found that the minimum gap detection for tactile clicks between the index and ring fingers was around 10 ms when a 0.64 cm diameter contactor was used, whereas for auditory stimuli it was around 2 ms. The study also indicated that gap detection sensitivity improved with increasing sensation levels of the stimuli, as shown in Figure 6. Similarly, Fletcher et al. (2021a) conducted a study to evaluate the gap detection threshold across wrists using 250 Hz stimuli and a 1 cm diameter contactor. Their findings indicate that the minimum detection threshold across wrists was ≈10 ms. These findings suggest that tactile sensation exhibits a temporal resolution that is much inferior than that of hearing.

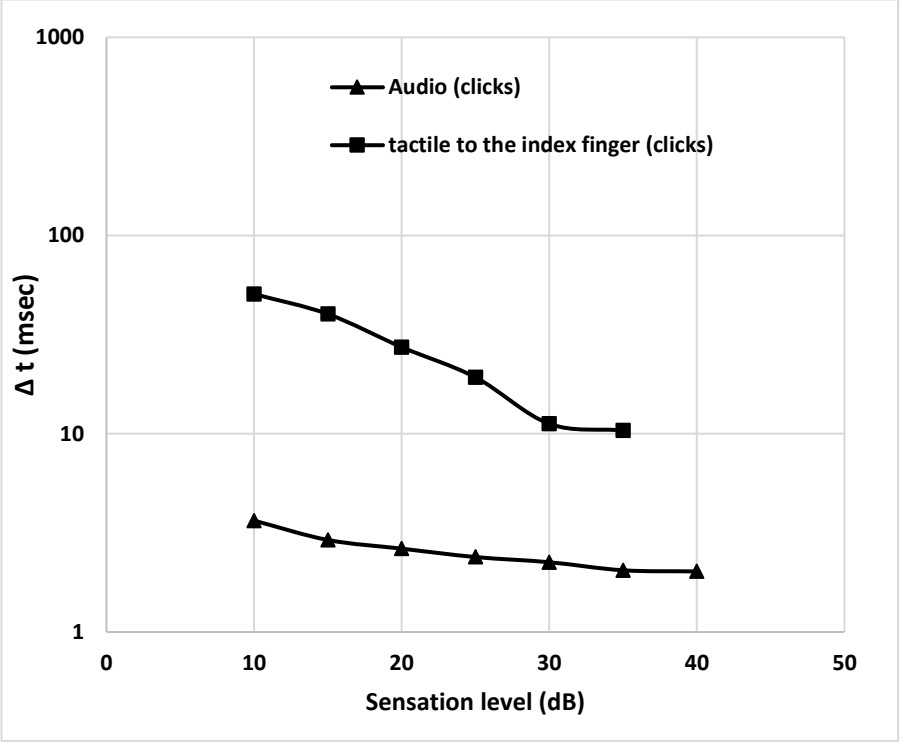

Figure 6. Tactile and auditory gap detection threshold between two clicks as a function of sensation level (Gescheider, 1967).

2.4.3.6 Spatial acuity

Spatial acuity is the ability to distinguish between closely spaced stimuli. This is an important aspect to look at because users need to discriminate between transducers if multi-channel haptic

device. Spatial acuity is related to the distance between the mechanoreceptors and size of corresponding receptive fields of the skin; therefore, it varies from one body part to another. This aspect of the tactile system has been studied with several methods. One such method is the two-point discrimination threshold, which is the minimum distance from which two simultaneous stimuli can be detected as two separate entities. The evaluation of healthy, young participants showed that they were able to discriminate the stimuli at the fingertip at approximately 1.0 mm (Johnson and Phillips, 1981). Similar measurements were applied to the forearm, and the results were higher, ranging from ≈25 mm–40 mm (Weinstein, 1968, Cholewiak and Collins, 2003). It is important to note that spatial discrimination between two different stimuli on the skin is greatly influenced by the type and characteristics of stimulus (Boldt et al., 2014). Moreover, it is crucial to recognise that the perception of multiple stimuli on the skin is complicated and can result in various effects, such as masking, enhancement, and suppression, which will be discussed in the following section.

2.4.3.7 The effects of multiple stimulation

The application of multiple tactile stimuli to different locations on the skin can elicit distinct perceptual phenomena. In the context of haptic devices, designers may aim to send signals with complex patterns at multiple sites, which requires an awareness of the possibility that a stimulus delivered by one stimulator may influence the response to another stimulus. Some of the phenomena that may arise from multiple stimulations will be shown in the following subsections.

2.4.3.7.1 Masking

The presentation of multiple stimuli can result in interference, particularly if they are presented simultaneously or separated by a short duration. As a consequence, the detectability of stimuli may decrease. The impact of this effect is contingent upon the physical attributes of the presented stimuli and masker, such as frequency, intensity, and temporal separation (Gescheider et al., 1989). Maskers can be presented either before the stimuli (i.e., forward masking), after the stimuli (i.e., backward masking), or at the same time (i.e., simultaneous masking) (Gescheider et al., 1989). Research has demonstrated that the masking effects persist even if a masker occurs before another haptic signal by around 650 ms (Gescheider et al., 1989). Moreover, a stimulus masker that primarily activates one type of mechanoreceptor tends to mask the detection of stimuli by the same type of receptor, but not by the other type (Gescheider et al., 1989). Furthermore, the tactile masking effect has been found to increase as the masker intensity increases and the frequency difference between the stimuli and the masker decreases (Gescheider et al., 1982, Makous et al., 1995).

In the auditory domain, a similar phenomenon occurs in which the audibility of a given sound is masked by the presence of another sound. The detection masking effect can be evoked by presenting either before the stimuli (i.e., forward masking), after the stimuli (i.e., backward masking), or at the same time (i.e., simultaneous masking) (Moore, 2012). Similar to the tactile masking effect within the mechanoreceptor channel, the effect of masking in hearing is more prominent when the stimulus and masker are temporally close (less than 100 ms) or if they are at a similar frequency critical band (Moore, 2012).

Recognition masking is an additional type of masking that can potentially occur within the auditory system and affect an individual's ability to perceive and recognise speech. This particular form of masking has recently been classified into two subcategories: energetic masking and informational masking (Middlebrooks, 2017). Energetic masking occurs when a competing sound cannot be segregated from the targeted signal due to overlapping frequency content or similar energy levels. On the other hand, informational masking is distinct from energetic masking because, in this case, the targeted signal can still be heard. However, due to cognitive factors, one or more aspects of the sound cannot be accurately recognised or identified. This can occur when competing sounds draw cognitive attention away from specific details of the target sound (Middlebrooks, 2017).

2.4.3.7.2 Enhancement

The enhancement of tactile stimulation refers to the phenomenon where a second stimulus is perceived as more intense when presented alongside a first stimulus, as opposed to when it is presented alone. To investigate this effect, participants were asked to evaluate the perceived intensity of the second burst of a pair of brief skin stimuli at various intervals between the first and second bursts (Verrillo and Gescheider, 1975). This was accomplished by adjusting the intensity of a third burst to match the perceived intensity of the second burst, and the intensity of the adjusted third stimulus was used to quantify the degree of enhancement. Notably, the enhancement effect was documented when the two stimuli were temporally separated by less than 500 ms. Furthermore, the enhancement effect decreases as the separation between stimuli increases. Additionally, the enhancement was documented in both high and low frequencies and low-frequency stimulus cannot enhance high-frequency stimuli and *vice versa* (Verrillo and Gescheider, 1975).

A comparable effect to the enhancement of tactile stimulation can be observed in the auditory system, and this is known as loudness enhancement. This effect is more pronounced when two test sounds fall within the same critical band and are temporally separated by less than 500ms, much like the findings observed in the tactile stimulation study. Furthermore, the loudness

enhancement effect has been shown to be influenced by several physical characteristics of the sound, such as intensity, frequency, and duration, which is similar to the observed effects in the tactile stimulation study (Zwlslocki and Sokolich, 1974).

2.4.3.7.3 Tactile suppression

The perception of magnitude of stimuli does not necessarily increase when two stimuli are presented in close temporal proximity. Suppression (or spatial masking) occurs when the perception of two stimuli that are presented at different locations reduces their perception of each other. The effect of suppression is more pronounced when the two stimuli are separated by less than 100 ms, and it only occurs when both stimuli share frequencies that fall within the same range of the processing mechanoreceptors (Verrillo and Gescheider, 1975, Gescheider and Verrillo, 1982).

2.4.4 Factors that affect the perception of tactile stimuli

2.4.4.1 Age

Tactile sensation is like hearing; it deteriorates with age. Verrillo (1980) evaluated the detection thresholds of six different age groups. The results revealed a progressive decrease at high-frequency thresholds, which were detected mainly by the Pacinian receptors. However, the thresholds of low frequencies (25 Hz and 40 Hz) remained the same for all age groups. Cauna and Ross (1960) suggested that the change in high-frequency thresholds is attributed to the reduction of Pacinian receptors.

In addition to the reduction in detection thresholds, sensory persistence is another phenomenon observed in older individuals. This occurs when the perception of stimuli persists after the stimulus has ended, which can impair the ability to discriminate between closely spaced stimuli in time. Verrillo (1982) found that the older subjects (mean age 66 years) were not able to discriminate between two tactile clicks that were separated by 100 ms, while it was an easy task for the 22-year-old group. Similarly, in the study conducted by Fletcher et al. (2021a), the younger group demonstrated improved gap detection thresholds across wrists: 31.03 ms (SD = 15.12 ms) for 100 Hz and 31.29 ms (SD = 14.49 ms) for 250 Hz, while older participants exhibited higher thresholds: 42.03 ms (SD = 19.04 ms) for 100 Hz and 43.10 ms (SD = 19.09 ms) for 250 Hz. As a result, it is possible to say that both detection threshold and some suprathreshold for vibration perception are adversely affected with age. Therefore, electro-haptic device designers should not ignore this issue when developing tactile aids for the elderly.

2.4.4.2 Body site

As shown in Figure 7, detection threshold values were measured at three distinct body locations: the volar forearm, middle fingertip, and thenar eminence. Although all measurements were performed using identical methods, it is evident that the fingertips were the most sensitive of the three sites investigated. Consequently, EHS devices intended for the forearm would require more energy than those intended for the fingertips.

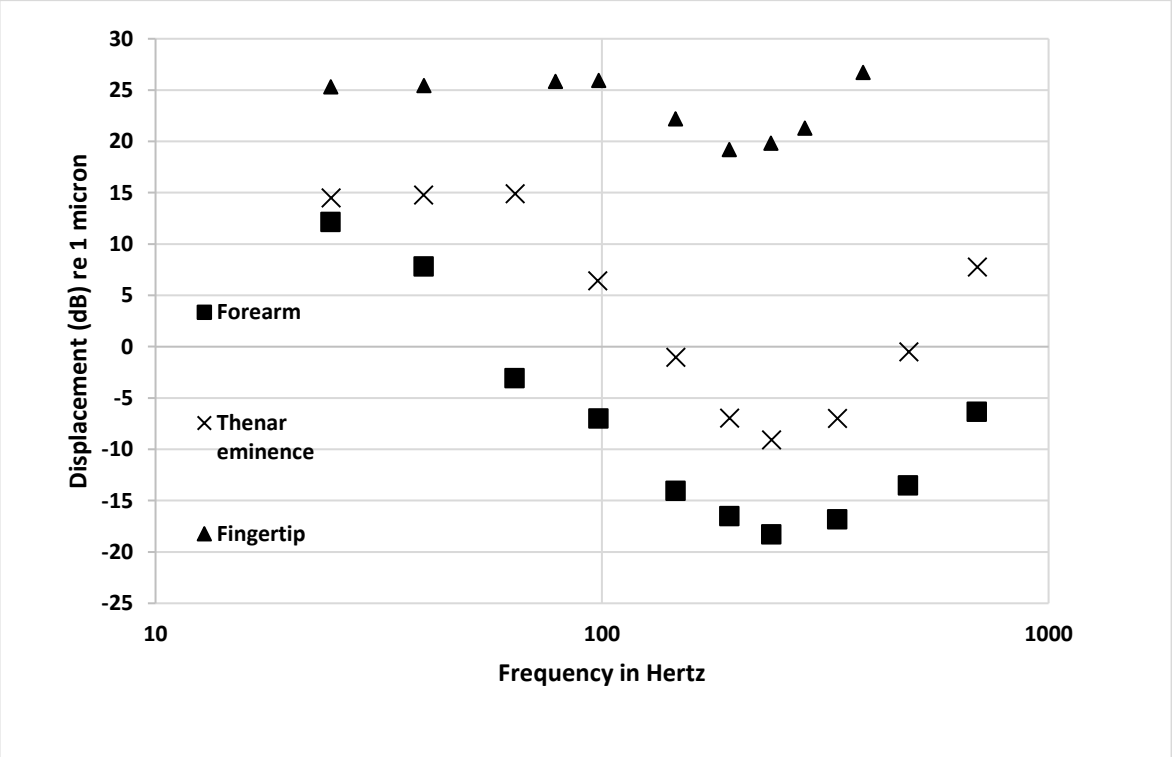

Figure 7. A comparison of the vibrotactile detection threshold measured using a 0.28 cm^2 contactor at three different body sites, namely the volar forearm (Verrillo, 1966), the middle fingertip (Verrillo, 1971), and the thenar eminence (Verrillo, 1963) – as a function of frequency. This figure is adapted from (Verrillo and Gescheider, 1992).

2.4.4.3 Temperature effect

Verrillo and Bolanowski (1986) evaluated the absolute thresholds of the thenar eminence and volar forearm for vibration as a function of temperature. Fourteen frequencies between 12 Hz–500 Hz were tested on skin temperatures of 15°C–40°C. The results showed a reduction in the absolute thresholds at 15°C–30°C while the thresholds at 30°C–40°C remained the same. The same findings were supported by several other studies that showed that temperature affects the absolute tactile thresholds (Bolanowski et al., 1988, Bolanowski and Verrillo, 1982).

2.4.4.4 Training effect

Training has been shown to enhance tactile discrimination in various psychophysical aspects. In one study conducted by Gescheider and Wright (2012), intensity discrimination was assessed over 23 days. The study involved applying two stimuli to the thenar eminence using a 2.9 cm^2 contactor at 20 dB SL for both 20 Hz and 250 Hz, with feedback provided after each trial. The results showed statistically significant improvement in intensity discrimination for both tested stimuli at 20 Hz and 250 Hz after training. For instance, training at 250 Hz in the PC channel reduced the average threshold by approximately 1.76 dB (from 2.61 dB pre-training to 0.85 dB post-training), while training at 20 Hz in the RA/SA I channels reduced it by approximately 1.0 dB (from 1.57 dB pre-training to 0.57 dB post-training). However, the training effect did not transfer across tactile receptors, as training with 250 Hz did not improve discrimination at 20 Hz, and *vice versa*. Another study by Stronks et al. (2017) examined the effect of training on intensity discrimination and spatial resolution of the lower back. The results showed a significant (36%) improvement in spatial resolution after a 5-minute training session, and a substantial (44%) improvement in the intensity discrimination threshold after an 18-minute training session. These findings suggest that training is an important factor in improving the discrimination of vibration stimuli.

2.4.5 Transferring audio information through a haptic system for CI users

The primary goal of EHS devices is to augment CI's audio perception with vibrotactile stimulation in order to convey critical auditory cues that are degraded or lost when electrical stimulation is used. However, the successful transfer of acoustic information through the haptic system may not straightforward and requires consideration of the skin's capabilities, the targeted information, and the processing strategy. The previous sections highlighted several capabilities and limitations of skin perception, as well as the similarities and differences between hearing and tactile perception.

Compared to normal acoustic hearing, CI users experience limitations in certain psychophysical auditory characteristics such as intensity discrimination (Galvin and Fu, 2009), dynamic range, and number of perceivable intensity steps (Zeng et al., 2002). Although it is not appropriate to directly compare tactile perception to CI perception, research suggests that tactile perception may be better at perceiving certain characteristics than sound stimuli if the vibrotactile characteristics are chosen appropriately. For example, CI users' ability to detect small changes in sound intensity is significantly reduced compared to normal hearing listeners (Galvin and Fu, 2009). In contrast, the skin tactile system is highly sensitive to changes in vibration intensity, with the ability to detect a difference of 1.5 dB in intensity (Gescheider et al., 1990, Fletcher et al., 2021a). Moreover, the

electrical dynamic range in CI users is limited to 10-20 dB, approximately one-eighth that of that observed in normal-hearing individuals (Zeng et al., 2002). In contrast to CIs, the tactile system dynamic range is approximately four times wider than the electrical dynamic range found in CIs (Fletcher et al., 2021b, Fletcher et al., 2021a). When it comes to the number of intensity steps that can be discriminated, tactile is superior to CI perception. Fletcher and Verschuur (2021) collated findings from multiple studies to report that tactile perception can discriminate approximately 40 intensity steps across the dynamic range (Gescheider et al., 1996), while CIs allow perception of only around 20 steps(Galvin and Fu, 2009, Kreft et al., 2004). As the tactile system is superior in these specific psychophysical aspects, haptic stimulation may be effective at supplementing signals for CI users.

Section 2.1.3 outlined some of the limitations of CI listening including speech perception in noise and localisation. As explained in that section, these tasks require accurate perception of specific acoustic information or bilateral hearing, which is often challenging for CI users. By utilising vibrotactile stimulation, missing information can be provided to improve the performance of these individuals on these tasks.

Delivering complex acoustic signals through vibrotactile stimulation requires careful processing to match the perceptual capabilities of the somatosensory system. An early "direct" approach simply transformed sound into mechanical vibration without alteration. However, this caused a significant loss of speech information above 500 Hz due to the rapid decline in tactile sensitivity at higher frequencies (Verrillo, 1963). Attempts to transpose frequencies using a vocoder to match the tactile range were made (Weisenberger, 1989), but faced challenges such as difficulty perceiving the transposed speech features and potential masking of important cues by less relevant components. More recent "processing" approaches extract specific acoustic features (e.g., amplitude envelope, fundamental frequency), and use these to modulate tactile stimuli tailored to the skin's perception (Eberhardt et al., 1990).

Recently, the second approach of extracting distinct features has been utilised in several EHS studies with positive outcomes in improving CI listening (Ciesla et al., 2022, Fletcher et al., 2018, Fletcher et al., 2020a, Fletcher et al., 2019, Huang et al., 2017). Although pitch is a crucial cue for speech perception, CI users experience limitations in their ability to perceive pitch due to the inadequacy of pitch information conveyed to the user by CI devices (Dincer D'Alessandro and Mancini, 2019, Zeng et al., 2002). This can make it difficult for CI users to perceive prosodic (e.g., intonation and stress) and paralinguistic (e.g., emotion) features of speech (Chatterjee et al., 2015, McRoberts et al., 1995, Meister et al., 2009, Protopapas and Lieberman, 1997), as well as to differentiate between speakers conversing in the presence of background noise (Carroll et al.,

2011). Despite the tactile system having poor frequency resolution (as described in 2.4.3.2), some EHS studies have successfully used F0 cues for vibrotactile stimulation to encode pitch information and improve CI users' ability to understand speech in noise (Ciesla et al., 2019, Ciesla et al., 2022, Huang et al., 2017). However, the poor frequency resolution of skin at a single site can be addressed by adjusting or expanding the haptic stimulation to cover a wider range of frequencies (available on the skin) other than the frequency of original sound (Bernstein et al., 1989). Alternatively, multiple stimulation sites can be used, where each site is associated with certain frequencies (Fletcher et al., 2020c).

Alternatively, some researchers focused on using different types of cues based on changes in amplitude or intensity of the sound over time (amplitude envelope) due to the limited intensity discrimination of CI users. Amplitude envelope cues also contain useful prosodic information like syllable number, lexical stress, and speech rhythm (Goswami, 2019, Kishon-Rabin and Nir-Dankner, 1999). Several EHS studies have shown that providing simple amplitude information for multiple frequency bands containing a significant amount of speech energy can lead to significant improvement in speech-in-noise perception for CI users (Fletcher et al., 2018, Fletcher et al., 2020a, Fletcher et al., 2019).

To improve CI users' localisation with EHS, it is important to deliver the limited accessible cues, such as time and intensity difference, across both ears (Dorman et al., 2016). Recently, researchers looked into how accurately individuals can detect differences in the timing and intensity of tactile sensations across their wrists (Fletcher et al., 2021a). The results showed that despite the poor sensitivity of the across the wrists timing difference, participants were able to detect intensity differences as small as 0.8 dB across their wrists, which is similar to the sensitivity of the across ears intensity difference. Earlier studies on EHS utilised vibrotactile stimulation to deliver spatial-hearing cues to individuals with CIs by converting audio signals from devices placed behind each ear into haptic sensations on the wrists. By doing so, this approach enabled the delivery of across-wrist time and intensity differences, resulting in considerable enhancements in sound-localisation accuracy that are even better than those of bilaterally implanted CI users (Fletcher and Zgheib, 2020, Fletcher et al., 2020b).

In summary, these findings suggest that using the tactile system through certain vibrotactile stimulation representation of auditory signals have a potential provide an advantage to many CI users in some difficult listening tasks.

2.5 Chapter summary and gap in knowledge

CIs are a revolutionary medical advancement that utilises electrical pulses to stimulate the auditory nerve and facilitate sound perception among individuals with profound hearing impairments. Despite the numerous benefits and advancements of CIs, users may still experience difficulties in challenging listening environments, such as hearing in noise, sound localisation, and music perception. These difficulties can be attributed to factors such as limited spectral and temporal resolution, as well as a lack of perception of interaural time and intensity differences. To overcome these challenges, various approaches have been proposed, including bilateral implantation and bimodal fitting. Recently, a promising inexpensive and non-invasive approach known as EHS has emerged, augmenting CI hearing by delivering information not adequately transmitted by CIs through the tactile system. However, given the differences in skin and hearing perception, certain information, such as frequency, time, and intensity, requires transformation to enable proper perception by the tactile system.

While there is a growing body of literature exploring the use of EHS to improve speech-in-noise performance in CI users, there is a lack of consensus regarding the most effective cues and placement for this type of stimulation. Additionally, little is known about the perspectives, barriers, and facilitators of potential users concerning haptic devices. To address these gaps, this PhD project aims to compare different vibrotactile speech cues to enhance speech-in-noise performance for NHCIS participants and to compare outcomes and experiences when vibrotactile stimulation is applied at three different body sites. Furthermore, this project will explore the ideas and recommendations of CI professionals and users regarding electro-haptic devices. Gaining this knowledge is crucial to optimising EHS benefits for CI users in real-life situations.

Chapter 3 General Methods

3.1 Summary of the chapter

This chapter describes the participants' inclusion criteria, instrumentation, calibration, CI simulation, and tactile cue extractions used in the subsequent chapters for studies 1 and 2.

3.2 Participants' inclusion criteria

Normal-hearing participants in study 1 and 2 were recruited via adverts at the University of Southampton. Participants were screened to ensure that they met the following inclusion criteria:

1) Native English speakers.
2) Aged below 50 years old (this age was chosen due to the changes in vibrotactile perception ascribed to age in 2.4.4.1).
3) Normal hearing pure-tone audiometry thresholds (≤20 dB HL for the frequency range of 0.25-8 kHz) for both eras, in accordance with British Society of Audiology (2018).
4) Normal touch perception thresholds at both right and left fingertips (below 0.4 m/s^2 RMS at 31.5 Hz and below 0.7 m/s^2 RMS at 125Hz), in accordance with ISO standards 13091-1:2001. The fingertip was chosen as the screening site due to the limited availability of normative data for other body locations utilised in this project, such as the wrist and forearm.
5) No sign of contraindications, as evaluated by otoscopy (e.g., infections, obstructions, abnormalities, or excessive wax) and reported by the touch issues questionnaire (Appendix A).

3.3 Instrumentation

The screening tests for hearing and tactile sensation were carried out in a double-walled soundproof booth. For the assessment of hearing, a Grason-stadler GSI-61 audiometer and TDH-50 headphones were used to conduct pure tone hearing testing following BSA (2018) guidelines. The BSA pure-tone audiometry criteria for defining 'normal hearing' include average thresholds of ≤20 dB HL for the frequency range of 0.25 kHz to 4 kHz. The tactile thresholds were evaluated in accordance with ISO 13091-1 using an HVLab vibrometer, which delivered vertical vibrations through a 0.6 cm diameter circular nylon contactor probe connected to a laptop running HVLab diagnostic software. The vibrometer comprises of an electrodynamic shaker (Ling V101) and a

piezo-electric accelerometer (PC30s8 B14). A hard circle surrounded the vibrometer's probe to reduce vibration distribution and allow pressure to be measured.

Individual training and testing were carried out in the same booth equipped with ER-3A insert earphones (Etymotic, IL, USA) and two HVLab tactile vibrometers connected to an amplifier (R150-plus; Inter M) and a digital-to-analogue converter (RME Babyface Pro sound card, RME Audio, Haimhausen, Germany). In the experiments, custom Max software (version 8.1.11, Cycling '74, CA, USA) was used to generate the CI simulation and vibrotactile signals. The Max software was installed on a laptop in the control room and delivered signals bilaterally to both sides of the body. The CI simulation was delivered diotically using insert earphones. The insert earphones (ER-3A) were used for CI simulation to passively attenuate the sound radiation generated by the HVLab tactile vibrometers. The booth also included a computer screen in front of the participant for providing feedback, as well as a microphone for transmitting the participant's responses to the examiner in the control room via the GSI-61 audiometer's headset. The original 0.6 cm probe on the vibrometers used for training and testing was removed and replaced with a larger 1 cm diameter probe. This was because earlier studies demonstrated that a larger contactor reveals better tactile thresholds due to the different receptive fields of each type of skin's tactile mechanoreceptor (Bolanowski et al., 1988, Verrillo, 1963). The decision to use a 1 cm diameter probe in the vibrometers for training and testing was based on its proven benefits in previous EHS studies (Fletcher et al., 2018, Fletcher et al., 2019), as well as its practicality and comfort. This size is also suitable for future real-world use since it can be incorporated into portable devices. To further enhance the vibration transmission across participants' skin, the rigid surround rings that are originally used in tactile threshold screening vibrometers to measure downforce were removed from the vibrometers used for training and testing. Figure 8 illustrates the experiment layout.

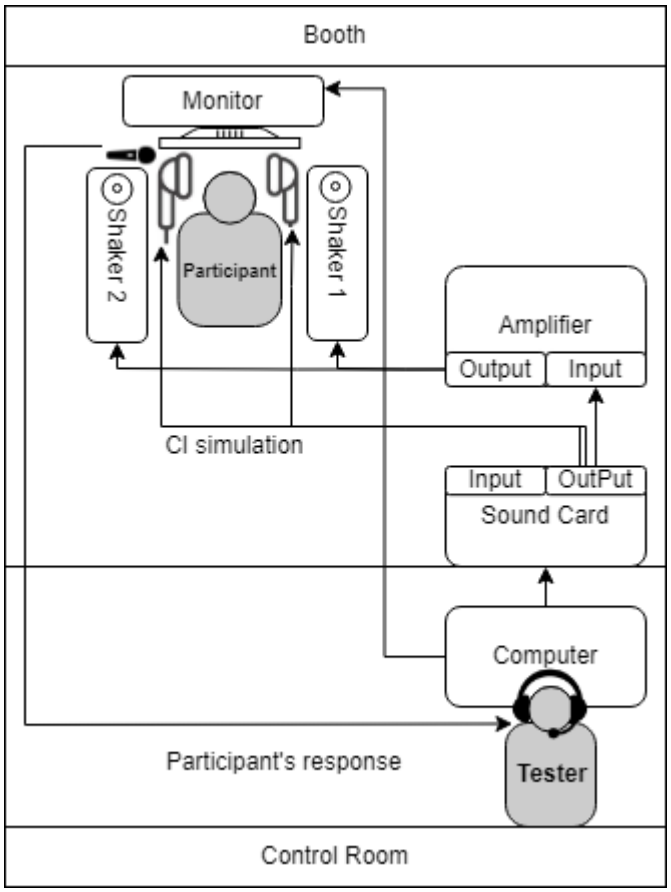

Figure 8. A schematic block diagram illustrating the instrumentation layout.

3.4 Calibration

3.4.1 Calibration of HVLab vibrotactile perception metres

The HVLab tactile vibrometers were equipped with a built-in accelerometer that allowed for recording the acceleration at the probe. To ensure accurate measurements, the accelerometer was calibrated using a reference tactile signal generated by a calibration exciter (Type 4294, Brüel and Kjær). The calibration signal had a constant frequency of 159.2 Hz and an acceleration of 10 m/sec^2. In this study, the amplitude of the target stimulus was determined by comparing it to the known calibrator stimulus. Thus, the vibrotactile cues for the sample sentences with the highest amplitude at different amplitude levels were recorded while a subject placed their wrist on the contactor (this provided a representative load to the shaker). The level that produced an acceleration of approximately 2.2 m/sec^2 was selected and used for the experiments because it is both large enough to be perceived and around the levels successfully used in previous EHS studies (Fletcher et al., 2018, Fletcher et al., 2020a, Fletcher et al., 2019).

3.4.2 Weighting filters to account for the frequency response of the shaker and vibrotactile sensitivity

The goal is to provide a voltage signal to the shaker that corresponds to the strength of the subject's perception of vibration. To achieve this, two frequency-dependent relationships need to be accounted for:

First, the physical transfer function of the shaker system, which converts the input voltage signal into the output acceleration signal. The frequency response of this transfer function was measured by delivering a maximum length sequence (MLS) signal to the vibrometer and recording the acceleration response using the built-in accelerometer connected to the contactor while a subject placed their fingertips on it. Based on the recorded shaker's response, an inverse filter was designed to model the inverse frequency response function of the shaker system. In other words, this first inverse filter converts from the desired acceleration signal to the required driving voltage signal.

Second, the relationship between the acceleration at the finger and the perceived strength of vibration needs to be accounted for. This relationship depends on the frequency-dependent sensitivity of the human tactile system, which has been characterised and modelled based on previous psychophysical experiments, as summarised in the vibration perception standard (BS-6842). The second filter applies a frequency-dependent weighting to the acceleration signal to approximate this frequency sensitivity of vibration perception.

By accounting for both the shaker frequency response and human vibration sensitivity in this way, the filtered voltage signal driving the shaker aims to evoke a vibration perception matched to the intended strength at each frequency.

The effectiveness of these filters was checked through a process involving two forward filters. These forward filters undo the effect of the two inverse filters, restoring the original unprocessed acceleration and voltage signals. The frequency responses of the forward filters are shown in Appendix B. By applying these forward filters to the already filtered signals, any discrepancies or artifacts introduced during the inverse filtering process can be detected, to ensure that the inverse filters accurately achieve their intended purpose.

3.4.3 Calibration of tactile threshold measurements

The vibrotactile thresholds were tested with a laptop running HVLab diagnostic software connected to an HVLab vibrometer with a 0.6 cm nylon contactor probe. To ensure consistent force application during threshold measurements for the inclusion criteria, the equipment for

tactile threshold measurements was calibrated using a 2 N weight on the tactile vibrometer's force meter ring, and the needle on the force meter gauge was set to the 'on' position (See Figure 9) before testing each participant.

Figure 9. The HV Lab tactile vibrometer for measuring the thresholds was calibrated with 2 N weights before measuring vibrotactile thresholds.

3.4.4 Calibration of speech stimuli

Audio stimuli were calibrated with a Bruel and Kjaer Type 2250 sound level metre and Bruel and Kjaer type 4157 Occluded Ear simulator. Before the calibration process, the sound level metre was calibrated with a Pistonphone calibrator (Bruel and Kjaer type 4220).

3.5 CI simulation

In this research, a CI simulation vocoder was used to mimic the hearing of CI users, allowing the study to be conducted on normal-hearing subjects. This enabled the researchers to recruit more participants within a shorter timeframe. Moreover, it reduced the inherent variability among CI users, such as the cause of hearing loss, the depth of electrode insertion, and the variation of speech-processing strategies.

The SPIRAL vocoder was selected for the present study due to its capability to provide an extensively validated simulation of the constraints associated CI listening. This included the inter-

electrode current dispersion in the cochlea, in contrast to conventional simulation methods such as noise-band or tone vocoders (Grange et al., 2017).

The SPIRAL CI simulation process used in this thesis is illustrated in Figure 10. The CI simulation began by resampling the audio signal with a 16 kHz sample frequency, and then the produced signal was passed to the initial high-pass pre-emphasis filter with a 6 dB per octave slope and a 4 kHz cut-off frequency, following the simulation approach used by Fletcher et al. (2018). This filter imitated the input filter of the CI speech processor (Chung and McKibben, 2011). Next, the signal passed through an FIR filter bank ranging from 0.25 to 8 kHz, with 22 equally spaced centre frequencies based on the equivalent rectangular bandwidth (ERB) scale (Moore and Glasberg, 1983). The 22-filter bank reflected the number of electrodes in devices manufactured by Cochlear Ltd. (Sydney, Australia). Within the 22-filter bank, the envelopes of each channel were extracted using the Hilbert transform and an initial 15 Hz low pass was applied. A reconstructing mixing function was applied to the envelopes to mimic the electrical stimulation interaction of CI electrodes in the cochlea. The signal was then sent to an array of 80 ERB-spaced tone carriers ranging from 0.3 to 8 kHz. Each carrier was modulated based on mixed envelopes calculated by the Hilbert transform and by the application of low-pass filters. The modulation process of the tonal carrier represents the neural excitation pattern of spiral ganglion cells in the inner ear. A -12 dB current decay per octave was used for this experiment, which is similar to the tuning curve slopes calculated with monopolar stimulation; the intensity decreases by 12 dB per octave (Nelson et al., 2011). The modulated carriers were then added together to make the signal that is needed for acoustical CI simulation.

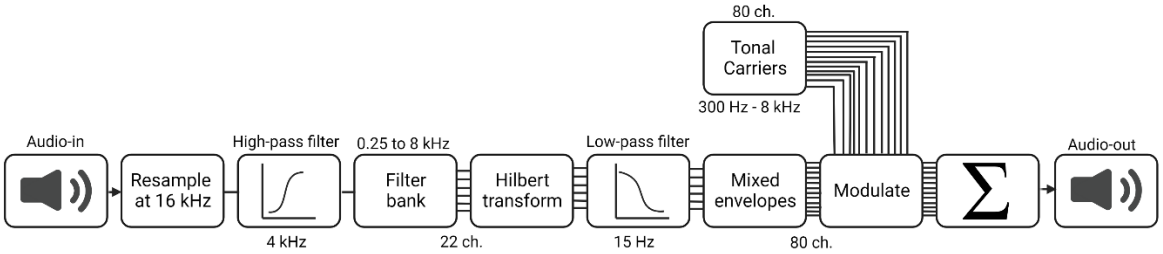

Figure 10.shows a schematic representation of the signal processing used in the SPIRAL cochlear implant simulation for generating audio stimuli in the experiments.

3.6 Noise for speech-in-noise training and testing

The National Acoustic Laboratories' (NAL) non-stationary multi-talker noise was used in the experiments for both training and testing sessions (Keidser et al., 2002). This noise was an actual recording taken at a real social gathering and had a spectral profile that was similar to the average

international long-term speech spectrum (Byrne et al., 1994). Therefore, this noise was chosen because it was standardised and had ecological validity. Additionally, it has been used in previous vibrotactile studies and could facilitate comparison of results (Fletcher et al., 2018, Fletcher et al., 2019).

3.7 Tactile cues

All tactile cues utilised in this thesis were pre-determined offline from the clean speech stimuli, rather than being calculated online from speech-in- noise, as would occur in real-world situations. While this approach does not reflect real-world conditions, it was chosen to assume perfect tactile cues extraction. The reason for this choice was to exclusively focus on determining the optimal cues or body sites for tactile stimulation to enhance speech-in-noise performance, rather than investigating the noise robustness of the algorithm.

within this thesis, three distinct tactile cues were employed: amplitude envelope cues, fundamental frequency (F0) cues, and speech presence cues. Figure 11 shows an illustration of vibrotactile cues waveforms extracted from one of the IEEE sentences. The first experiment incorporated all three vibrotactile cues, while the second experiment specifically utilised the amplitude envelope cues. Subsequent subsections will offer a more detailed explanation of the cue extraction process.

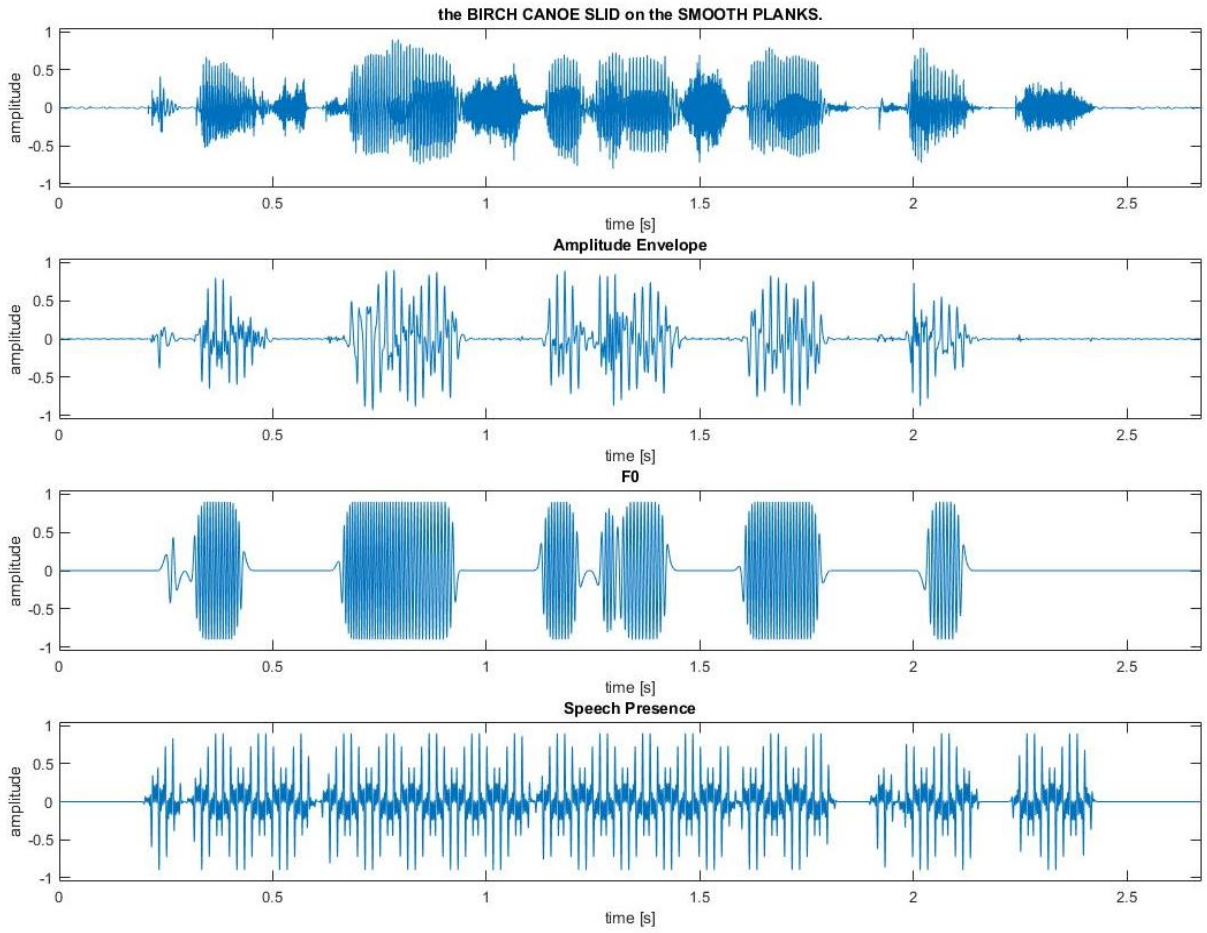

Figure 11. Illustration of extracted waveform tactile cues for the sentence 'the birch canoe slid on the smooth planks' from the IEEE dataset. The top panel displays the waveform of original speech signal, while the lower panels showcase the extracted tactile cues, with the name of each cue labelled at the top of its respective panel.

3.7.1 Amplitude envelope

In both experiments, the vibrotactile amplitude envelope extraction was conducted based on the setup proposed by Fletcher et al. (2019) and illustrated in Figure 12. This vibrotactile signal was produced by down-sampling the audio signal with a 40 kHz sample frequency, as the software required the maximum sample rate to be at this number. The signal then passed via an FIR filter with four equally spaced band-pass filters based on an ERB scale that provides a wider bandwidth for low-frequency filter banks (Moore and Glasberg, 1983). This four-channel filter bank has edges ranging from 100 and 1000 Hz, to extract the low frequencies that CIs cannot effectively deliver. The envelope extraction process involves using the Hilbert transform in conjunction with a low-pass filter with a cut-off frequency of 15 Hz applied to each filter bank. The channels then modulated the amplitude envelopes of four tonal carriers with fixed phase, centred at frequencies

of 50, 110, 170, and 230 Hz. The selection of carrier tone central frequencies and 60 Hz spacing between channels was based on several considerations. First, it falls within the skin's most sensitive frequency range (Bolanowski et al., 1994, Verrillo, 1963). Second, studies have demonstrated that a 60 Hz difference can be easily distinguished by the skin in various vibrotactile frequency discrimination limen tests (Rothenberg et al., 1977). The amplitude of each of the four carrier tone channels was modulated based on the four band-pass filters of the speech amplitude, and the modulated tonal carriers constituted the input signal for the HVLab tactile vibrometers applied to the participants' skin.

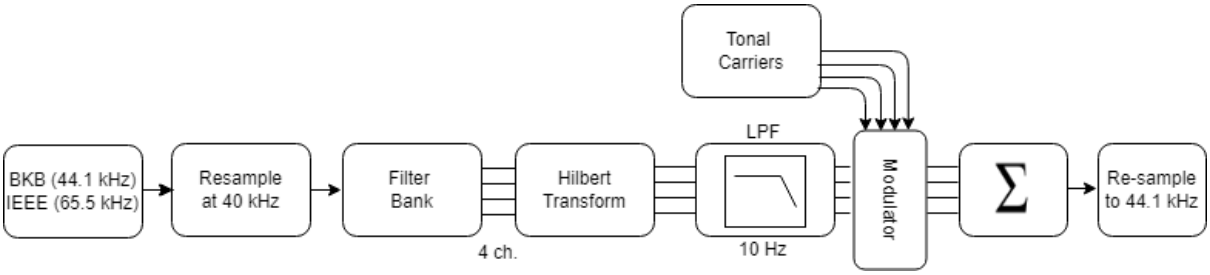

Figure 12. Schematic diagram of the generation of vibrotactile amplitude envelope information.

3.7.2 Speech presence

The speech presence was detected by computing the amplitude envelope of the audio signal using a combination of the Hilbert transform and a 6th-order lowpass Butterworth filter, followed by zero-phase filtering to preserve the original signal phase characteristic. A binary value of 1 was assigned to a gate if the amplitude exceeded 5% of the maximum envelope, indicating the presence of speech, while a value of 0 was assigned when the amplitude was lower than 5% of the maximum envelope, indicating the absence of speech. After assigning a binary value based on the speech presence criteria, the resulting signal was switch on and off four channels of carrier tones centred at 50, 110, 170, and 230 Hz with fixed phases, generating the tactile signal, as seen in Figure 13.

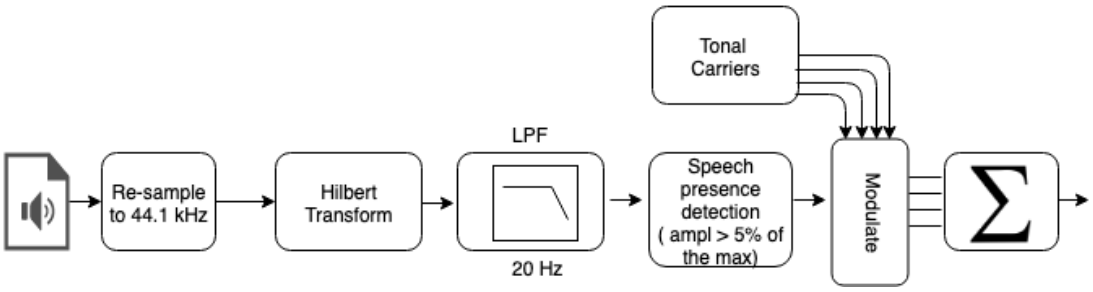

Figure 13. A schematic diagram illustrating the generation of vibrotactile speech presence tactile cues. The "speech presence" block produces a binary output of 1 when speech is present in the audio signal and 0 when speech is absent. The resulting signal then undergoes modulation with four channels of carrier tones to generate the vibrotactile signal.

3.7.3 Fundamental frequency

The YIN algorithm (De Cheveigné and Kawahara, 2002) was used to estimate the F0 of the audio signal over time using a window size of 40 ms and a step size of 10 ms and only the F0 values within the range of 50 to 300 Hz were considered for further analysis. The algorithm's best voicing estimate (De Cheveigné and Kawahara, 2002) was used as gates to segregate voicing segments based on periodicity (above 0.2) within each timeframe. The resulting F0 output was low-pass filtered using a 25 ms windowed moving average (Hamming). To produce a frequency-modulated signal based on the filtered F0 trace, voicing gates were created using 25 ms moving average filter ramps. The resulting FM signal following the F0 was delivered to the HVLab tactile vibrometers and applied to the participants' skin, as shown in Figure 14.

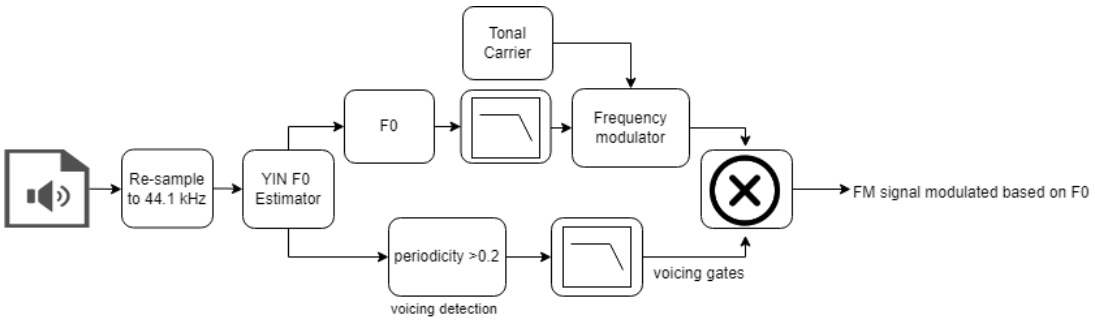

Figure 14. A schematic diagram of the generation of vibrotactile fundamental frequency cues.

Chapter 4 Study one: Evaluation of different speech cues for enhancing the speech-in-noise performance of CI when they are delivered through vibrotactile stimulation

4.1 Background

Understanding speech-in-noise constitutes one of the more challenging listening tasks for CI users. Notably, low-frequency cues are essential for effective speech comprehension (Chang et al., 2006), but the inserted electrode of a CI cannot always reach the apical end of the cochlea responsible for low-frequency perception (Skinner et al., 2002). Therefore, bimodal fitting, which involves using a hearing aid in the contralateral ear (that has some residual hearing), has been recommended for unilateral CI users. The use of a hearing aid in the contralateral ear has been recommended for subjects with unilateral CI to supplement their CI electrical stimulation (Offeciers *et al*., 2005) . Several studies have shown that bimodal fitting significantly improves speech-in-noise understanding in both real and simulated conditions (Berrettini et al., 2010, Gifford et al., 2007, Flynn and Schmidtke, 2004, Armstrong et al., 1997, Kong and Carlyon, 2007).

The available information regarding the auditory mechanism of the improvement that is observed upon the addition of low-frequency cues is currently insufficient. Moreover, it is not clear which specific cues are responsible for bimodal fitting improvement (Qin and Oxenham, 2006, Chang et al., 2006). It has been suggested that bimodal-fitted users compensate for the limited pitch information delivered by electrical stimulation by making use of low-frequency cues, such as F0 or voicing, that are conveyed acoustically to the ear (Qin and Oxenham, 2006). Furthermore, it has been proposed that F0 could improve the signal segregation from the competing noise (Brokx and Nooteboom, 1982, Assmann, 1999).

Although bimodal fitting offers various benefits, the many of referred CI candidates do not have the residual hearing that is required for its use (Verschuur et al., 2016). Thus, several researchers have proposed administering low-frequency cues to the CI users' skin to supplement the electrical stimulation (Ciesla et al., 2022, Fletcher et al., 2018, Fletcher et al., 2019, Huang et al., 2017). Huang et al. (2017) and Ciesla et al. (2022) showed that CI users' speech-in-noise recognition significantly improved when F0 cues were provided to the skin through vibrotactile stimulation. Additionally, Fletcher, Mills and Goehring (2018) and Fletcher et al. (2019) demonstrated that the

extracted amplitude and voicing vibrotactile cues significantly improved speech-in-noise recognition in both CI simulation and CI users.

However, the effectiveness of these cues delivered through vibrotactile stimulation cannot be directly compared, as previous studies have used different methods and stimulated different body sites. In a study by Brown and Bacon (2009), the role of different low-frequency audio cues was examined for improving speech-in-noise performance in simulated electric-acoustic stimulation (EAS) participants. A four-channel vocoder simulated electric stimulation which was combined with an audio tone carrying voice presence, F0 contours, amplitude envelope, or both F0 and amplitude cues extracted from the target speech. Performance was measured with different steady and modulated background noises. All cues significantly improved performance, though voicing cues were found to be slightly less beneficial than F0 or amplitude envelope cues (see Figure 15 that shows the improvement provided by these cues for the speech-in-babble noise condition). Therefore, the present study aims to compare the effectiveness of different vibrotactile cues, including F0, amplitude envelope (Env), and speech presence (SP), on speech-in-noise performance for NHCIS participants when delivered to the wrists.

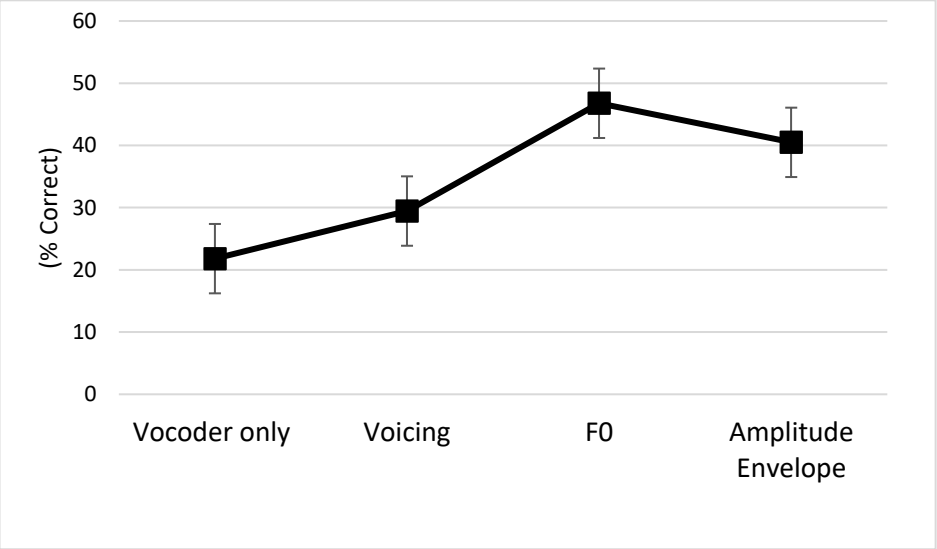

Figure 15. Mean keyword scores in percent correct for speech recognition in babble noise (+10 dB SNR) using simulated electric-acoustic stimulation. Results are shown for four conditions: a 4-channel vocoder alone, the vocoder combined with a tone carrying voice presence information, the vocoder combined with a tone modulated to match the fundamental frequency (F0) contour of the target speech (F0), and the vocoder combined with a tone following the amplitude envelope of the original speech. Data are adapted from Brown and Bacon (2009) Figure 1.

4.2 Study questions:

1. Which of the three vibration cues provides the best speech-in-noise performance?
2. How much of an advantage (if any) do the vibration cues have over the no vibration condition?
3. Is there an order effect on performance in the 'no vibration' control condition based on whether it is performed first or last in the sequence?

4.3 Methodology

4.3.1 Study design

Given the observed variability in the performance of previous studies involving vibrotactile stimulation, the current investigation utilises a within-subject, repeated-measure design where each participant serves as their own control, thereby reducing the impact of individual variability. This within-subjects design requires fewer total participants because each subject is involved in every condition, rather than needing separate groups for each condition as in a between-subjects design.

However, despite these advantages, the design is subject to a limitation known as the carryover effect, wherein the participant's performance in one condition affects their performance in another condition due to learning, order, sequence, or fatigue effects from prior conditions. To mitigate this issue, a full-factorial design was utilised to achieve counterbalancing for the three vibrotactile conditions. A full-factorial design includes all possible combinations of the conditions. Six subjects were required for counterbalancing in this study. This pattern of six was then repeated twice, administering the no-vibration (No Vib) condition first in one instance and last in the other (as presented in Table 2). The primary objective was to compare the three vibrotactile conditions with one another, thus the No Vib case was not included in the full-factorial design.

Additionally, unique lists of sentences were utilised in each training and testing session to minimise potential learning effects. However, it was not possible to perfectly counterbalance the testing lists (see the order of conditions and utilised list in each session in Appendix C), although there was no reason to believe that the lists differed in difficulty. If a list happened to be harder or easier than the others, it may have affected the results for one condition per participant. The effect of such a list on the overall analysis was likely minimised through averaging, list randomisation, and condition counterbalancing.

The study protocol was approved by the University of Southampton Ethics and Research Governance Office (ERGO 61502, Appendix D).

Table 2. The order of experimental conditions for each participant, with conditions being counterbalanced between subjects except for the no vibrotactile cues condition.

Participant	Condition 1	Condition 2	Condition 3	Condition 4
1	No vibration	Amplitude envelope	F0	Speech presence
2	No vibration	Amplitude envelope	Speech presence	F0
3	No vibration	F0	Amplitude envelope	Speech presence
4	No vibration	F0	Speech presence	Amplitude envelope
5	No vibration	Speech presence	Amplitude envelope	F0
6	No vibration	Speech presence	F0	Amplitude envelope
7	Amplitude envelope	F0	Speech presence	No vibration
8	Amplitude envelope	Speech presence	F0	No vibration
9	F0	Amplitude envelope	Speech presence	No vibration
10	F0	Speech presence	Amplitude envelope	No vibration
11	Speech presence	Amplitude envelope	F0	No vibration
12	Speech presence	F0	Amplitude envelope	No vibration

4.3.2 Sample size calculation

In determining the optimal sample size, a power analysis was conducted using G*Power software to allow the hypothesis to be tested that not all the vibrotactile cues give the same benefit. The calculations were informed by the mean difference in SRT between audio+vibrotactile cues and No vibration conditions (2.78 dB) and standard deviations (1.26 dB) obtained from a related study that assessed EHS improvement with amplitude envelope cues (Fletcher et al., 2020a).

Based on the assumption that the most effective cue in the experiment would yield results comparable to the improvement observed with Env cues in the Fletcher et al. (2020a), and the least effective cue would provide no benefit at all, it was calculated that a minimum of nine participants would be needed to detect a large effect size (dz = 0.82) with 80% statistical power at a 0.05 two-tailed significance level, using a paired t-test.

However, a total of 12 participants were recruited in order to account for counterbalancing the conditions and accommodating potential differences in the effectiveness of the cues compared to those used in the previous study and because the assumption that the effect size may be optimistic.

4.3.3 Participants

Seven males and five females between the ages of 21 and 40 (mean = 28.33, SD = 6.79) passed the eligibility criteria listed in Chapter 3 and took part in the study. Each of the participants was

compensated with £60 for their time and effort. A summary of the participants' vibrotactile and hearing thresholds and characteristics is provided in Appendix E.

4.3.4 Instrumentation

Chapter 2 provides a comprehensive description of the instrumentation employed in this experiment. Figure 16 shows the experimental setting for one of the vibrotactile cues conditions where the cues were delivered bilaterally to both wrists simultaneously.

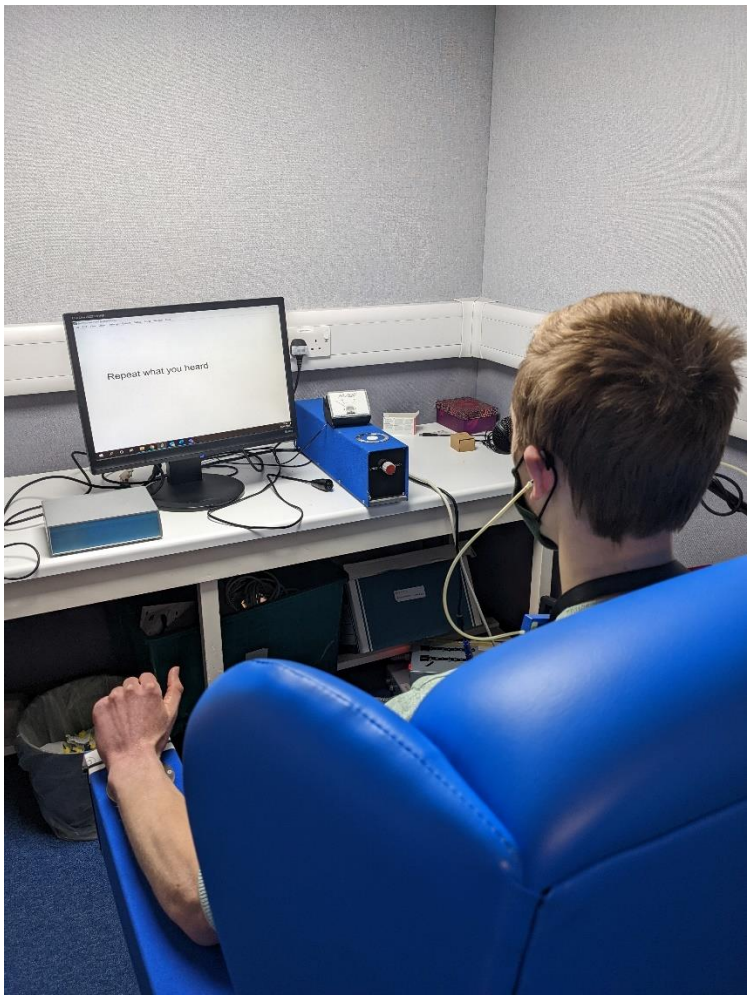

Figure 16. Participants were seated in front of a screen and instructed to verbally respond into a microphone throughout both the training and testing sessions.

4.4 Audio stimuli

4.4.1 Speech and noise stimuli

Three distinct speech corpora were utilised as stimuli to accommodate the large number of conditions and training sessions. Male speakers' lists were predominantly used in this experiment

whenever available, as they are frequently employed in EHS speech-related testing (Fletcher et al., 2018, Fletcher et al., 2020a, Fletcher et al., 2019).

The BKB sentences comprised of 21 lists each consisting of 16 short sentences spoken by British male and female speakers. In this experiment, male speakers' lists were primarily used to familiarise participants with CI simulation.

Matrix speech sentences produced by a British female speaker (HörTech gGmbH, 2019) were utilised for eight training sessions due to the challenge of finding a sufficient number of speech lists. The Matrix speech corpus contains a comprehensive list of grammatically identical sentences (Name, Verb, Numeral, Adjective, and Object) that differ semantically. For instance, an example of such a sentence is “Thomas gives twelve red toys”. The Matrix test uses a limited number of words combined in random order to generate a vast number of semantically unpredictable sentences (exceeding 18 thousand unique sentences). To ensure randomisation and prevent the repetition of the same sentences during training, these sentences were divided into 120 unique lists, each containing 156 sentences.

The ARU high-quality recording of Institute of Electrical and Electronics Engineers (IEEE) corpus comprises 72 lists of 10 phonetically balanced sentences, each available in different British accents by various male and female speakers (Hopkins et al., 2019). Each sentence includes five keywords determined by the experimenter for scoring. The IEEE sentences were selected for the prior-testing training and testing sessions because the keywords were not highly predictable (Rabinowitz et al., 1992); for instance, ‘GLUE the SHEET to the DARK BLUE BACKGROUND.’ Four lists, each containing 100 IEEE sentences, were used for the prior-testing training sessions, with each list being used once for each of the four conditions. The remaining 320 sentences of IEEE were divided into four lists of 80 sentences for testing the four conditions.

A multi-talker NAL noise, as detailed in 3.6 was incorporated into the speech stimuli within the CI simulation software for speech-in-noise training and testing.

4.4.2 CI simulation

The current study employed the SPIRAL CI simulation vocoder, which is outlined in section 3.5 of the Methods chapter.

4.5 Vibrotactile stimuli

In this study, three distinct vibrotactile cues, namely Env, F0, and SP were utilised. A detailed description of the methods employed to extract each cue is available in section 3.7.

4.6 Pilot study

The experiment was piloted with several pilot participants who offered feedback about the method, setting, and stimuli. Initially, the plan was to present the CI simulation in the tested ear and white noise in the other ear. Furthermore, it was intended to use only the Matrix sentences for all training sessions and IEEE sentences for testing. Based on feedback and the results from the pilot participants, minor adjustments were made to improve their experience and the study's results

During the piloting, native speaker participants performed worse than expected when tested with IEEE sentences using the adaptive track without feedback. The participants also reported finding the BKB and IEEE to be more challenging than the Matrix sentences, which ultimately impacted their performance during the testing session. Additionally, the noise presented in one ear proved to be a distraction for some participants. Some minor adjustments were made to the simulated audio signal in this study to facilitate the participants' familiarisation and improve their performance with CI simulation during training and testing. The decay slope of -8 dB/octave, which was used to simulate the current spread in CI users, was changed to -12 dB/octave. This new spread setting in the software falls within the current spread observed in CI users (Oxenham and Kreft, 2014). To help the participants acclimate to the CI simulation, the starting SNR was increased from 10 dB to 20 dB. The CI simulation was also presented to both ears instead of one, and each participant was trained with 100 unique IEEE sentences during the last training session for each condition to become more familiar with them.

To further investigate the cause of the issues that arose during piloting phase, the software developer was contacted to review the CI simulation within the software. After conducting a thorough examination, the software developer identified two main issues: one with a low-pass filter and the other with the routing of the vibration signal within the software. Both issues were promptly resolved. The updated experimental parameters were evaluated on another native participant were found to be suitable for achieving the study's objectives and comparable with other studies. Consequently, the results of this participant were included in the analysis.

4.7 Procedures

Each participant experienced twelve sessions, with three sessions allocated for each condition with the order of the conditions as given in Table 2. The procedure for the first condition is outlined in Figure 17. To reduce the impact of skill-fading, the three training sessions for each condition were split into three separate sessions, which were conducted over three working days,

within a single (working) week. Following the completion of the final training session for each condition, a testing session was conducted. After completing the first condition, the same procedure was repeated for the other three conditions, with the entire experiment spanning four weeks.

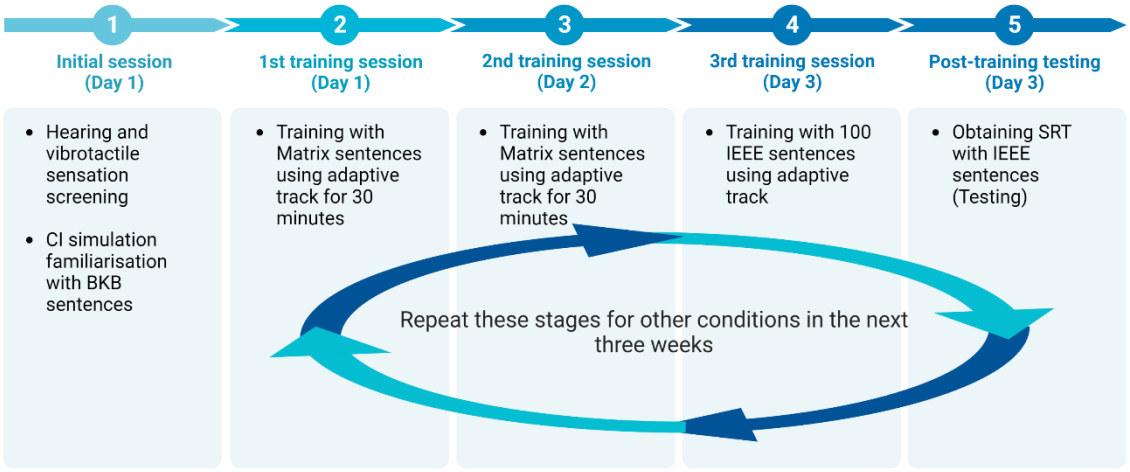

Figure 17. A summary of the study's procedure for the first condition. The other conditions (as per Table 2) used the same procedure without the initial session.

4.7.1 Consent form and screening (Session 1)

After reading the participant information sheet (Appendix F), interested participants were asked to sign the consent form (Appendix G) and carefully screened to ensure they met the inclusion criteria outlined in Chapter 3, Section 3.2. Prior to the hearing and tactile assessments, the participants were required to complete a touch-issues screening questionnaire (see Appendix A). Following this, otoscopy and pure-tone audiometry screenings were performed to ensure that the use of an insert phone would not present any issues and that their hearing was within normal limits. The HVLab system for threshold measurements (illustrated in Chapter 2, Section 1.3) was then utilised to determine the participants' tactile sensation threshold, using the Békésy staircase method. During this procedure, participants were instructed to *"press a button for as long as you feel the vibration, no matter how small, until it can no longer be felt and then press again when you feel it again."* When the button was depressed, the vibration reduced at a rate of 3 dB/second, and when it was released, the vibration increased at the same rate. The tactile threshold was determined by calculating the average of the peaks of the previous six reversals, and a typical run of tactile threshold measurement took between 45 seconds and one minute.

4.7.2 CI simulation familiarisation (Session 1)

In the first session, the participants were familiarised with CI simulation without tactile stimulation, using lists acquired from a male speaker's BKB sentences without noise and tactile stimulation at a loud but comfortable level (65 dB LAeq as measured in the occluded ear simulator). Participants began the familiarisation phase by listening to each sentence from the first BKB list with and without CI simulation, without the necessity to respond. For the subsequent five lists, participants were instructed to repeat each sentence for evaluation. If they successfully repeated two or more keywords, the sentence would be displayed on the screen before proceeding to the following sentence. If participants failed to repeat a minimum of two keywords within a sentence, the simulated and non-simulated speech would be replayed once before moving to the next sentence. Up to six BKB lists were provided to participants, who were required to achieve a minimum of 70% of the keywords in one list to be eligible for inclusion in the study. All twelve participants passed the familiarisation phase with a minimum score of 70%.

4.7.3 Study conditions

After familiarisation with CI simulation, participants completed training and testing in Four experimental conditions: SP, Env, F0, and No Vib cues. In each condition, they first underwent two 30-minute training sessions with Matrix sentences on two separate days. On the third day for each condition, they had a final training session with 100 IEEE sentences followed by the testing session (after a short break). These three training sessions were conducted across three days in one week. Consequently, each participant completed a total of 12 sessions (4 conditions x 3 sessions per condition).

During the training phase, CI simulated speech-in-noise was presented concurrently with vibrotactile cues to both wrists for the SP, Env, and F0 conditions. For the No Vib condition, only the CI simulated speech-in-noise was presented without vibration. The speech level was maintained at 65 dBA, while the noise level was adjusted based on individual participant responses. The presentation started at a 20 dB signal-to-noise ratio (SNR). After each presentation, the text was displayed on the screen in front of the participant. An adaptive staircase procedure with a two-down, one-up strategy was employed to adjust the SNR level. Three distinct step sizes were used: large (4 dB), medium (2 dB), and small (1 dB). The large step size was applied for the initial twenty reversals, the medium step size for the following thirty reversals, and the small step size for the remaining trials. The trial was marked correct if the participants could repeat a sentence containing a minimum of three out of five keywords. This

procedure persisted for 30 minutes in the first two training sessions or until the participant completed 100 IEEE sentences, for the last training session.

In the testing session, the SRT was assessed using an adaptive track method similar to the one used in the training sessions. However, the large step size was utilised for the first two reversals, the medium step size for the second two reversals and the final step size for the next six reversals. The SRTs were determined from the average of the last six reversals at the smallest step size.

4.8 Results

The findings of the study are presented in Figure 18, which displays the SRTs in dB SNR for each experimental condition. Additionally, the bottom panel of the figure demonstrates the individual benefit provided by each vibrotactile cue relative to the No Vib condition. These results were obtained by analysing the outcomes of the testing session that followed the three training sessions.

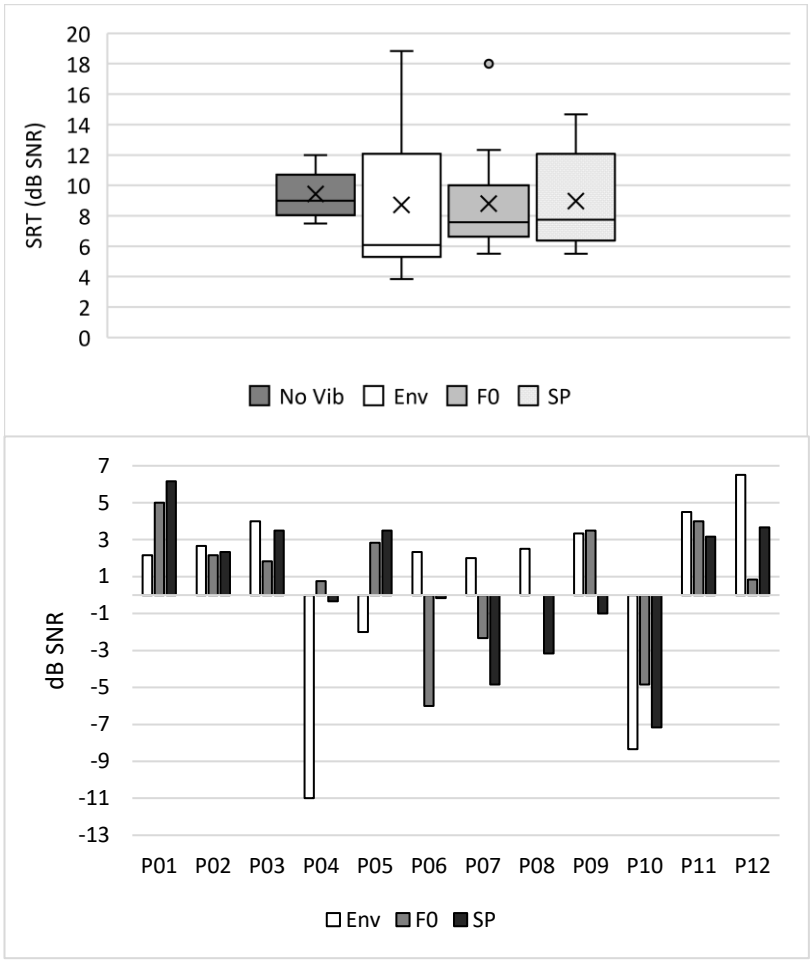

Figure 18. The boxplot in the top panel provides a summary of the SRTs in dB SNR for the four experimental conditions: no-vibration cues (No Vib), amplitude envelope (Env) cues, fundamental frequency (F0) cues and speech presence (SP) cues tested across all participants during the testing sessions. The upper and lower whiskers correspond to the maximum and minimum values, respectively, excluding any outliers. Outliers, which are indicated by circles in the boxplot, were identified as any data points that exceeded the distance of 1.5 times the interquartile range beyond the upper or lower quartile. The bottom panel shows the difference in SRT when different vibration cues were simultaneously presented with audio as compared to the condition with No Vib cues. A positive value in the bottom panel indicates that the performance improved with the use of vibrotactile cues.

4.8.1 Compare the effect of applying different vibrotactile cues on SRT

The main objective of this study was to evaluate the effectiveness of various vibrotactile cues on speech-in-noise performance when applied to wrists. The figure below illustrates the difference in

SRT between each vibration condition and the No Vib condition for the testing sessions in dB. In order to investigate the hypothesis that one vibrotactile cue may offer greater benefit than the others, a Friedman test was utilised. This test evaluated whether there were any statistically significant differences in the SRT benefit observed among the various vibrotactile cues following three training sessions. The choice of the Friedman test was appropriate as normality assumptions were violated due to outliers in the Env condition, thus precluding the use of repeated measures ANOVA. The results of the Friedman test showed no statistically significant difference of condition between the SRT benefits for different vibrotactile cues, where $\chi 2(2) = 1.167$, $p = 0.558$.

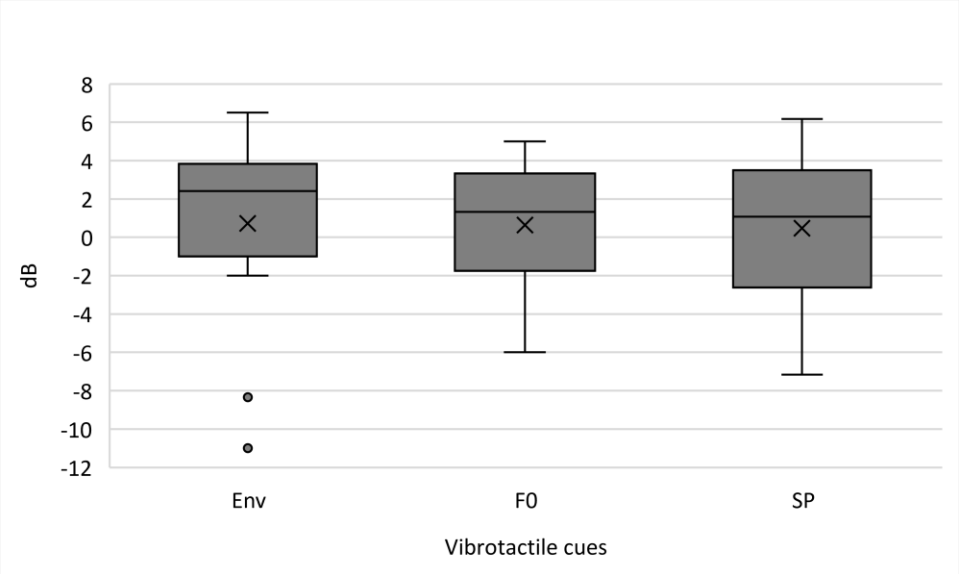

Figure 19. A boxplot that summarises the improvement in SRT in multi-talker across all participants under different vibration cue conditions, namely amplitude envelope (Env), Fundamental frequency (F0), and speech presence (SP) relative to the no-vibration condition.

4.8.2 Investigate the effect of vibrotactile stimulation on speech-in-noise performance

This study also aimed to determine whether vibrotactile cues enhance adult CI simulated subjects' speech-in-noise performance. Figure 20 displays the average SRTs (dB SNR) for all vibration cues (Env, F0, and SP) compared to the No Vib condition during testing sessions. The bottom panel of the same figure reveals that five participants performed worse with vibrotactile cues based on subtracting the average SRT of the vibrotactile cues from No Vib condition. A paired-sample *t*-test was conducted to determine whether there was a statistically significant difference between the average SRTs (dB SNR) when vibrotactile cues were applied to the wrists compared to no-vibration condition. The normality assumption was verified by visual inspection of the histogram and by conducting Shapiro-Wilk's test ($p = 0.249$), indicating no violation of the assumption. The

participants' average SRT for all the vibration conditions was 8.83 ± 2.87 dB SNR, while the SRT for No Vib was 9.44 ± 1.55 dB SNR. No statistically significant difference was detected (t (11) = 0.623, p =0.546) and a 95% confidence interval of -1.55 to 2.78 dB SNR was calculated.

To compare the findings of the present study with previous research, an exploratory analysis was conducted. The investigation focused on identifying any significant differences in SRT between two previously used vibrotactile cues and the No Vib condition, following three training sessions. Previous research has demonstrated that Env and F0 cues can improve SRT for individuals CIs (Ciesla et al., 2022, Fletcher et al., 2020a, Huang et al., 2017).

To determine whether there was significant improvement for both Env and F0 compared to No Vib, a Wilcoxon signed-rank test was conducted. However, no significant differences were observed between either of these cues and the No Vib condition (p > 0.05).

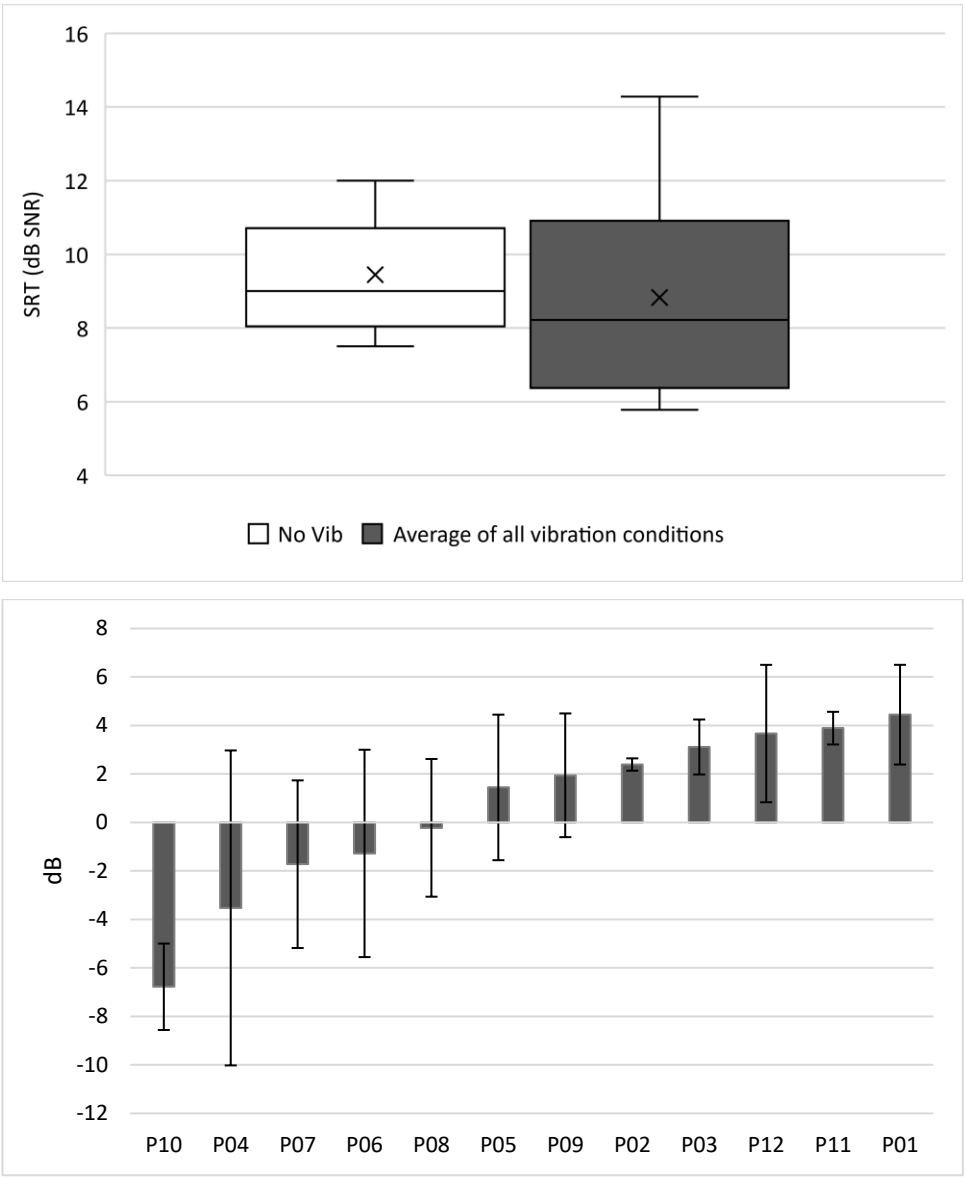

Figure 20. Upper panel: boxplots summarising the distribution of the average speech reception thresholds for all vibration cues among participants, and the average speech reception thresholds for no vibration condition during the testing session in dB SNR. Bottom panel: showing the individual improvement in speech reception threshold with vibrotactile stimulation (averaged across the different vibrotactile cues). A positive value indicates that vibrotactile stimulation improved speech-in-noise performance. The error bars represent the standard deviation of the mean improvement in speech reception threshold with vibrotactile stimulation. The order of the participants is based on how much their performance improved when they were provided with vibrotactile stimulation.

4.8.3 Comparing the difference between performing the no-vibration condition first and last

The comparison between the performance of the No Vib condition, when conducted first and last, was employed as an indicator of any potential learning or order effects, as well as the impact of long-term factors such as fatigue or boredom effect, that may have influenced the results during the testing phase as each test are carried out on different day from the other sessions. As shown in Figure 21, in the sample the mean SRT for the No Vib condition was slightly higher (9.86 dB SNR ± SD 1.3) when it was performed first compared to when it was performed last (9.03 dB SNR ± SD 1.78). To ascertain whether there were any statistically significant differences in SRTs for performing the No Vib condition first or last, a Mann-Whitney U test was conducted. However, there was no statistically significant difference in mean SRT between performing the no-vibration first and last, where $U = 10$, $Z = -1.29$, $p = 0.24$. These findings suggested that there was no significant effect of order in the No Vib condition on SRT, implying that the sample participants were not disadvantaged or advantaged by the order in which they received the no-vibration condition.

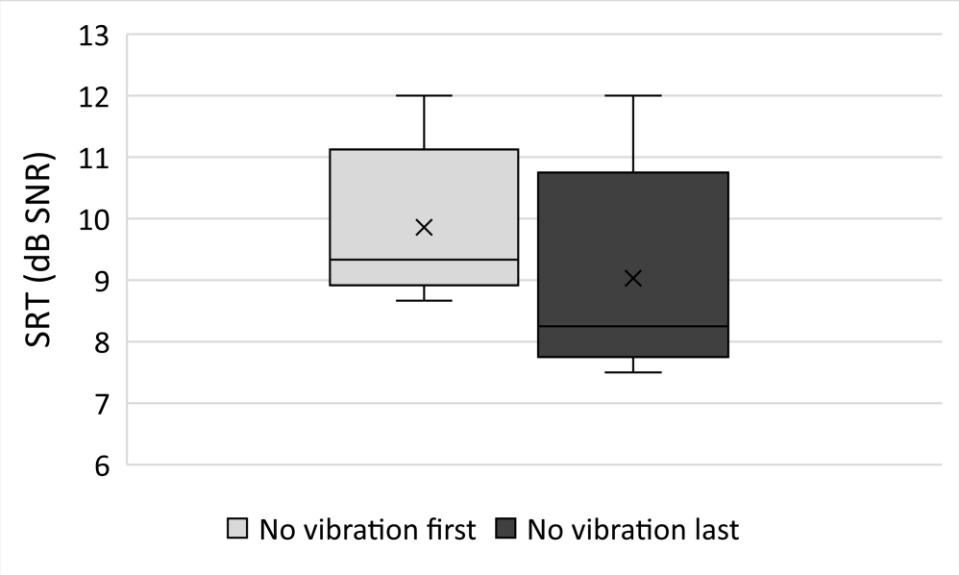

Figure 21. A boxplot showing the speech reception thresholds for the no vibration first and the vibration last conditions during the testing session in dB SNR.

4.8.4 Comparing the effect of performing vibrotactile conditions first and last on SRTs

An exploratory analysis was conducted to investigate the learning effect of vibrotactile conditions. Participants for this analysis were divided into two groups: participants 7-12 performed the three vibrotactile sessions before the No Vib case, while participants 1-6 performed the vibrotactile sessions after the No Vib case. A Mann-Whitney U test was run to assess the statistical

significance of the differences in SRTs between the average of the first vibrotactile testing sessions for participants 7-12 and the SRTs of the last vibrotactile testing sessions for participants 1-6 who received the vibration conditions after the No Vib condition. The average SRT for the first vibrotactile condition for participants 7-12 was higher (mean = 12.39 dB SNR, SD = 5.60) than the average SRT for the last testing session of vibrotactile conditions for the other group (mean = 6.20 dB SNR, SD = 0.88) as illustrated in the left-most boxplot and right-most boxplot in Figure 22. Each of these two boxplots comprises the results for two SP, two Env and two F0, as can be seen from the left-most for participants 7-12 and right-most for participants 1-6 columns in Table 2. This difference of 6.20 dB was statistically significant, where U =31, Z= 31, p = 0.037.

The difference between the SRTs of the first three vibrotactile testing sessions for participants 7-12, who received the vibration before the No Vib condition, and the SRTs of the last three vibrotactile testing sessions for participants 1-6, regardless of the type of condition, is clearly illustrated in Figure 22. Each of these six boxplots comprises the results for two SP, two Env and two F0, as can be seen from the three left-most columns for participants 7-12 and three right-most columns for participants 1-6 in Table 2. Thus, the three boxes for each group represent the same mix of vibrotactile cues. Any non-random difference between the boxes may be attributed to an order effect.

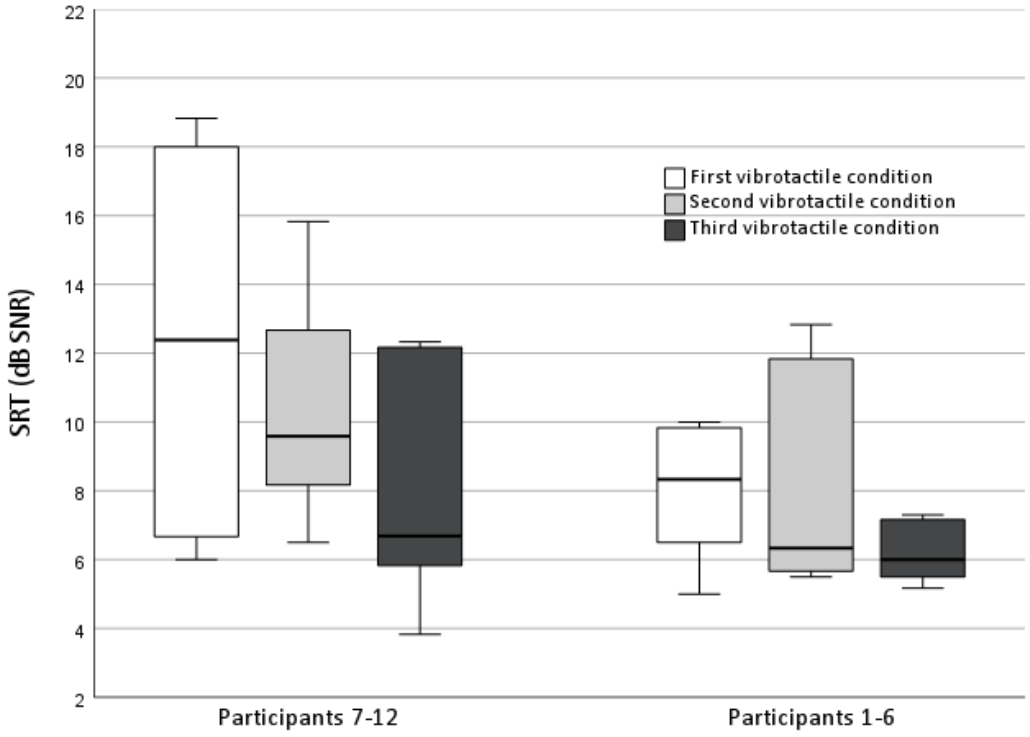

Figure 22. Boxplots comparing the SRT results between participants who received vibrotactile conditions first and those who received it last, after the no vibration condition, irrespective of vibrotactile cues. Each of these six boxplots comprises the results for two SP, two Env and two F0 testing sessions.

4.9 Discussion

4.9.1 The effect of applying vibrotactile cues on SRT

The primary aim of this study was to compare the effects of different vibrotactile cues on the SRT in noise for CI simulated participants. Contrary to expectations, no significant differences in speech-in-noise benefits were observed among the vibrotactile cues employed in this study.

Moreover, a comparison between the average SRT for the vibrotactile conditions and the No Vib condition after training revealed no significant difference. This outcome is inconsistent with previous studies that reported significant improvements using certain vibrotactile cues (Ciesla et al., 2019, Ciesla et al., 2022, Fletcher et al., 2018, Fletcher et al., 2019 7, Fletcher et al., 2020a, Huang et al., 2017). For instance, Huang et al. (2017) found that F0 vibrotactile cues significantly enhanced CI users' performance by 2.2 dB without any training. Similarly, Ciesla et al. (2022) found that F0 vibrotactile cues applied to participants' fingertips significantly improved the speech-in-noise performance of CI simulated participants by 4.82 dB. It is important to note that the results from real CI users, as reported by Huang et al. (2017), were also seen in simulated CI users, as demonstrated by Ciesla et al. (2022). Notably, these findings were consistent across real CI users (Huang et al., 2017) and simulated CI users (Ciesla et al., 2022), indicating that the results may be applicable to both populations.

Fletcher et al. (2020), employed another type of vibrotactile cues (Env) and reported a significant improvement in CI users' performance by 2.8 dB. Despite employing more challenging extraction methods and a shorter training duration (one session), their study demonstrated a better average improvement in SRT for the same cues than the present study's findings.

4.9.2 Potential factors for inconsistent findings

The reasons behind the inconsistent findings between the current study and previous research remain unclear. Consequently, an exploratory analysis was conducted to investigate the enhancement of specific cues (F0 and Env) after training, as well as to compare the current results with prior research. This analysis did not reveal any significant improvements when comparing these cues with the No Vib condition.

Several potential factors might have contributed to these inconsistencies. For example, the presence of outliers in the current study that could have influenced the results. Although large inter-subject variability has been reported in other studies, they did not report extreme outliers like those observed in the current study. The small sample size and variability in performance are

other possible explanations for the unexpected lack of benefit. It should be noted that while previous studies employed similar sample sizes to the current study, they utilised different experimental designs and focused on a single cue.

In an attempt to better compare to previous studies showing benefits, the data were re-analysed after excluding three extreme outlier participants in. This analysis showed significantly lower SRTs for combined F0/Env cues versus audio-only by 2.42 dB, along with significant benefits for each cue individually. These results are similar to those reported by Fletcher et al. (2020a) who applied amplitude envelope cues to the wrists and Huang et al. (2017) who applied F0 cues to the fingertips. However, as this exploratory re-analysis was conducted after reviewing the results, rather than pre-specified a priori, the findings should be interpreted very cautiously as, the findings are subject to issues like statistical fishing and bias.

It is speculated that issues with the design of the experiment may have contributed to the variability in the results. The training sessions for each condition were three 30-minute sessions undertaken on consecutive weeks, with each condition tested on a different day. This design could have introduced confounding cognitive factors, such as fatigue during one testing session, which would influence the results for that specific session but not for the others. For instance, one participant reported experiencing a headache during one testing session, which may have accounted for the particularly poor performance in that session; however, this result was included in the analysis. Cognitive and auditory processes are both required for listening to speech, particularly under adverse conditions (Rudner et al., 2019). Moreover, the usage of speech corpus in the first two training sessions (Matrix sentences) compared to the last training and testing sessions (IEEE) might have influenced the results. The closed-set nature of Matrix sentences was considerably simpler and possessed distinct structural and linguistic characteristics compared to those in the third training and testing sessions with IEEE. Additionally, the gender of the Matrix sentences speaker differed from the one used in the third training session and testing, leading to different acoustic characteristics. This abrupt shift in speech materials may have adversely influenced the results of the third training and testing, particularly for the first condition but not others, due to the learning effect.

4.9.3 Limitations and Future Directions

Future studies should address the limitations identified in this investigation. As previously noted, the study was limited by a low number of participants, resulting in insufficient statistical power during analysis. Additionally, the limitations of the training regimen used in this study, such as switching between corpora for training and testing, may have affected participant outcomes.

More focused training using the same corpus, or a more compatible corpus, could prove beneficial for future research. Lastly, conducting testing of each condition on different days may have contributed to variability if any unexpected factor arises during a specific testing session, such as fatigue or headache. It should be noted that Study 2 in Chapter 5 was designed taking these factors into consideration, and as will be presented in Chapter 5, a statistically significant benefit of Vibrotactile stimulation was found.

Moreover, several observations in this study might require some further investigation. One participant's performance with the presentation of all the vibrotactile cues was poorer than the No Vib and they reported that vibrotactile stimulation was distracting him. A similar decline was observed in a different multi-modal presentation involving audio-visual training aimed at enhancing speech perception (Bernstein et al., 2013). In that study, 10 out of 35 participants were unable to achieve high accuracy in associating the two sensory modalities within the three training sessions. Intriguingly, Fletcher et al. (2019) reported a similar phenomenon, wherein two participants found the vibrotactile stimulation distracting during pre-training sessions but not post-training, possibly due to adaptation.

Together, these highlight the need to carefully consider individual differences in perception and adaptability of multi-modal stimuli such as vibrotactile cues. In addition, the results of the participants were varied, with some experiencing greater benefits than others. Interestingly, previous vibrotactile studies have shown that participant performance is highly variable (Fletcher et al., 2018, Fletcher et al., 2019, Huang et al., 2017). As a result, further research is required to identify the users who will benefit the most from vibrotactile stimulation and the issues that may prevent other participants from achieving the benefits.

4.10 Conclusion

The primary objective of this study was to examine the effectiveness of three vibrotactile cues (F0, amplitude envelope, and speech presence) in enhancing speech-in-noise performance for CI users. Unexpectedly, the results revealed no statistically significant differences between the cues. Moreover, no significant advantage was found for the vibrotactile cues compared to the no vibration condition, and there was no difference in outcomes when the no vibration condition was performed first or last.

To the researcher's knowledge, this is the first study to compare three augmentative vibrotactile cues (F0, amplitude envelope, and speech presence) for enhancing speech-in-noise performance in order to determine which cues are the most helpful for CI users. However, the unanticipated

results require further investigation, as no advantages were detected, presenting an inconsistency with the findings of prior research.

A number of possible factors were proposed to explain the observed findings, such as potential issues with the study design and high variability among participants. It is recommended that future research employs a more effective methodology, incorporates a larger participant sample, and addresses any additional variables that might impact participants' when applying vibrotactile stimulation. It is worth mentioning that these considerations were taken into account in the design of Study 2, as described in Chapter 5.

Chapter 5 Study two: The optimal place for electro-haptic speech enhancement device

5.1 Introduction

Supplementing CI electrical hearing with certain vibrotactile cues was found to improve speech understanding in noisy environments (Ciesla et al., 2022, Fletcher et al., 2018, Fletcher et al., 2020a, Fletcher et al., 2019, Huang et al., 2017). Although previous studies have evaluated the efficacy of vibrotactile stimulation on fingertips (Ciesla et al., 2022, Fletcher et al., 2018, Huang et al., 2017) and wrists (Fletcher et al., 2020a, Fletcher et al., 2019), the speech-in-noise benefits were observed at both sites.

There are several potential places on the body where haptic wearable devices can be placed. Ideally, the site for the device should be sensitive enough to facilitate the efficient transfer of targeted vibrotactile stimulation with a maximum level of comfort and minimal interference with normal daily activities. Therefore, the main aims of this study were to explore and compare the outcomes and experiences of CI-simulated participants when vibrotactile stimulations were applied at three potential sites on the body (fingertips, wrists, and forearms). These body locations were selected in this study for practical reasons and some of them had been tested in previous EHS studies (Ciesla et al., 2022, Fletcher et al., 2018, Fletcher et al., 2019, Huang et al., 2017, Fletcher et al., 2020c). Additionally, a study that evaluated the participants' perspective revealed a preference for wearing sensors on the wrists and arms over other body regions (Bergmann et al., 2012). The sub-aims were (1) to investigate whether the use of vibrotactile stimulation could enhance speech-in-noise performance among NHCIS participants, (2) to assess whether vibrotactile stimulation at a specific site would yield greater improvements in speech-in-noise performance for NHCIS participants compared to other sites, and (3) to explore the subjective experiences and preferences of NHCIS participants when using vibrotactile stimulation at different sites.

5.2 Hypotheses

1. The speech-in-noise outcomes of audio plus vibrotactile stimulation will be better than No Vib when averaged across different body sites.
2. Speech-in-noise may vary depending on the location of the vibrotactile stimulation on the three tested sites: fingertips, wrists, and forearms.

5.1 Methodology

5.1.1 Study design

This study employed a within-subject, repeated-measure design, with the order of the four conditions (No Vib and vibrotactile conditions: fingertips, wrists, and forearms) fully counterbalanced to minimise the potential carryover effect. For further information about this design's advantages and disadvantages, please refer back to 4.3.1 in Chapter 4.

The placement of the index fingertip and wrist was clear but for the forearm condition, the participants were instructed to position the shaker somewhere above the wrist, at a distance of more than one-third the length of the forearm from the wrist while sitting comfortably. There was a variation in vibrotactile stimulation placement due to the differences in subjects' arm-lengths. This distance between the forearms' stimulation site and the wrist was then measured during the final testing session and the average distance was found to be 12.28 cm.

5.1.2 Ethical approval

This study was reviewed and approved by the University of Southampton Ethics Committee (Faculty of Engineering and Physical Sciences ERGO ID: 61502.A1, Appendix H).

5.1.3 Sample size

A power analysis was conducted (using GPower 3.1.9.4) to determine the sample size for this study. The analysis showed that at least 24 participants were needed to detect a medium effect (Cohen's f = 0.25) with 80% statistical power in a one-way within-subjects analysis of variance (one group, four measurements, alpha = 0.05, correlation = 0.5, non-sphericity correction = 1). This number of subjects also allows full counterbalance for conditions.

5.1.4 Participants

Ten females and fourteen males between the ages of 18 and 35 (mean = 22.21 years, SD = 5.28) passed the eligibility criteria listed in Chapter 3 and took part in the study. None of these participants had previously participated in the study described in Chapter 4. Each of the participants was compensated with £30 for their time and effort. A summary of the participants' characteristics and their vibrotactile and hearing thresholds is provided in Appendix I.

5.1.5 Instrumentation

The vibrotactile cues were delivered bilaterally, with stimulation provided simultaneously to matched locations on both sides of the body (e.g. both fingertips) via two HVLab shakers. The instrumentation details used in this experiment are provided in Chapter 3. As shown in Figure 23, the experimental setting had three vibrotactile stimulation body sites (i.e., distal phalanx of the index fingers, the volar wrists, and the volar forearms). To ensure the comfort of participants during testing, a cushion was provided for the forearm condition.

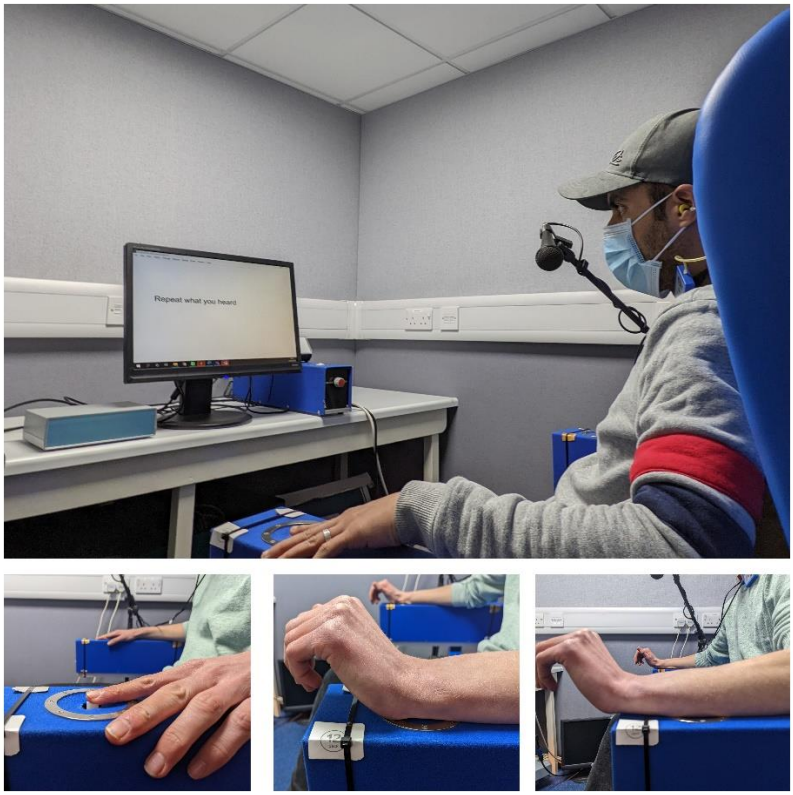

Figure 23. During the training and testing sessions, participants sat facing the screen and spoke into a microphone (top). This figure also shows the three tested haptic locations during the experiment, i.e., fingertips (bottom left), wrists (bottom centre), and forearms (bottom right).

5.1.6 Audio stimuli

5.1.6.1 Speech and noise stimuli

Due to the large number of conditions and sessions in this experiment, two distinct speech corpora were used: ARU IEEE (Hopkins et al., 2019) and The Bamford-Kowal-Bench (BKB) Institute of Hearing Research.

The ARU IEEE sentence lists comprise 72 lists of 10 sentences, each spoken in different British accents by male and female speakers. The male Kent speaker from ARU IEEE sentences was used for the CI familiarisation and the first three training sessions. Six lists of 10 sentences were used for the familiarisation; these sentences were excluded from the training sessions. The remaining 660 were divided into 12 lists of 55 sentences used for the first three training sessions of the four conditions.

The BKB sentences comprised of 21 lists consisting of 16 short sentences spoken by British male and female speakers (i.e., 336 sentences in total). A total of 128 sentences of BKB sentences were divided into four lists of 32 sentences used for the short pre-testing training. The remaining 208 sentences were divided into four lists of 52 sentences for testing the four conditions.

Each training and testing list were uniquely used for different conditions and fully counterbalanced across subjects.

5.1.6.2 CI simulation

The SPIRAL CI simulation vocoder, described in Section 3.5 of the methods chapter, was used in this study.

5.1.7 Vibrotactile stimuli

5.1.7.1 Tactile stimulus to determine sensation levels

To equalise sensation levels across body sites with differing detection thresholds, the vibrotactile stimuli were scaled relative to each participant's measured threshold at each body site using a representative noise signal while accounting for the maximum deliverable output. This noise stimulus was produced by summing all the vibrotactile stimulus files on a time-point basis and dividing by the square root of the file number. This process resulted in a noise spectrum resembling the long-term average of the vibrotactile experimental stimuli.

Based on the three thresholds obtained with the vibrotactile noise, three distinct gain values were used to scale the sensation level of each body location for each participant during the experiment. The gains determined the voltage driving the shaker and resulting acceleration, equalising sensation levels across body sites while avoiding exceeding the maximum output where shakers started to clip. For example, if the maximum deliverable level was X and the detection threshold for the fingertips was 0, for the wrists was 5, and for the forearms was 10 with the noise signal, then based on those measured thresholds, the gains were adjusted proportionally. The forearm

stimuli would have a vibrotactile level of X since it had the worst detection threshold, the wrist X-5, and the fingertips X-10.

5.1.7.2 Tactile cues

This study used the amplitude envelope cues following the vibrotactile stimuli extraction explained in section 3.7.1.

5.1.8 Procedures

Each subject completed four sessions, with each session separated by at least one day. The first session included a preliminary screening, CI familiarising, and training session. The following two sessions were just training, while the final session included a brief training and testing session. To prevent training effects from diminishing over time, the sessions were conducted over a period of no more than a week, with an average of 5.1 days between the initial and final sessions. Figure 24 provides a summary of the procedure.

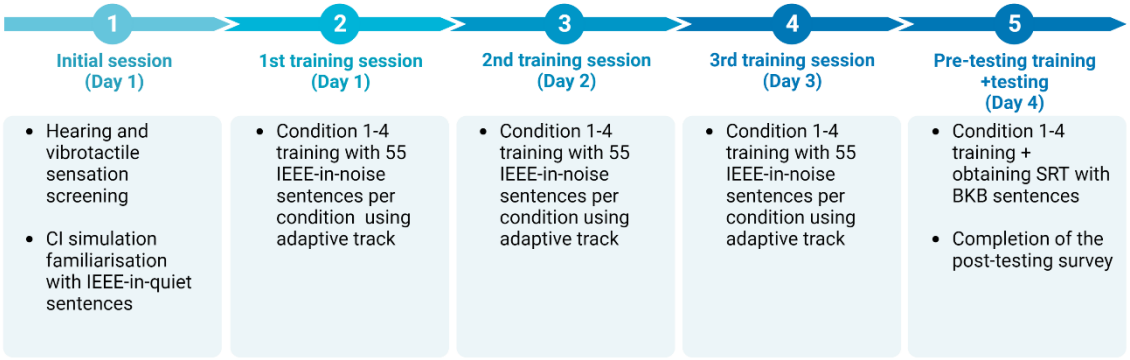

Figure 24. A schematic illustration of the procedure used in the study.

5.1.8.1 Consent form and screening (Session 1)

Once the participants expressed their interest in continuing, they were asked to fill out the screening questionnaire (Appendix A). Following this, their hearing, tactile sensations and other potential contraindications were assessed using a similar process outlined in Chapter 4 to confirm their eligibility.

5.1.8.2 Determination of the gain at the tested body locations (Session 1)

The noise file produced in 5.1.7.1 was delivered via the audiometer to both HVLab shakers simultaneously to measure the detection threshold of each subject in the three-body locations. The tactile threshold measuring procedure was similar to the BSA pure-tone audiometry but

started at a comfortable and easy-to-detect level with a one-dB step size as opposed to 10 dB down and 5 dB up. So, the subjects were instructed as follows: "*I'm going to test your tactile threshold by measuring the lowest level of vibration that you can detect in your fingertips, wrists, and forearms. Regardless of which side (right or left) of the body you feel the vibration, respond when you feel vibration by saying "yes" as quickly as possible. Whatever the vibration is, and regardless of how faint it is*". The thresholds of each participants' wrists and forearms referenced to those of their fingertips are shown in Figure 25. Consistent with prior research on tactile thresholds, the figure indicates that all of the thresholds of non-glabrous skin (hairy skin) were greater than those of the subjects' glabrous skin of the fingertips (Verrillo and Bolanowski, 1986). Based on the measured thresholds, the gain values for the three different body locations were calculated and used to scale the sensation level for each subject's vibrotactile signals presented during the experiment.

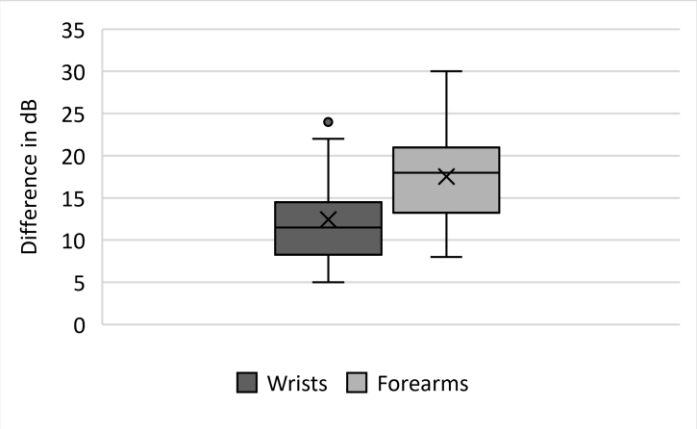

Figure 25. The boxplot presents the voltage gain in dB required to drive the shaker when the vibration-shaped noise stimulus was used to reach the detection threshold at the wrist and forearm, relative to the same threshold measurements at the fingertips. This data was obtained by calculating the difference between the thresholds measured and those of the wrists and forearms for the 24 participants.

5.1.8.3 CI familiarisation (Session 1)

The simulated speech was presented in a quiet setting without concurrent vibrotactile stimulation to familiarise participants with the CI simulation. At the start of the familiarisation phase, participants listened to each IEEE sentence from the first list with and without CI simulation. For the other lists, participants were instructed to repeat each sentence to the researcher for scoring. If they could repeat three or more keywords, the sentence would be shown to them on the screen before moving to the next sentence. However, if they could not repeat three or more keywords, the simulated and non-simulated speech would be presented again before moving to the next sentence. Up to 5 IEEE lists were made available to participants, and they must have achieved

70% or more of the keywords on one list at least to be included in the study. During the familiarisation phase, all 24 individuals attained a score of 70% or more, and no one was excluded.

5.1.8.4 Training (Sessions 1, 2, 3 and 4)

After their familiarisation with CI simulation, the participants attended four training sessions (on different days). During each training session, they were trained on all experimental conditions: fingertips, wrists, forearms, and no Vib cues (no signal to shakers, and it was not touched). The order of the conditions was fully counterbalanced and this order was used for both the training and testing sessions for each participant.

In training, the CI simulated speech-in-noise and vibrotactile cues were presented simultaneously. The level of speech was held at 65 dB, while the noise was adjusted based on each participant's response. The presentation started at a 20 dB SNR. After each presentation, the text was presented on the screen in front of the participant. An adaptive staircase track following two-down one-up was used to adjust the SNR level. Different step sizes, namely, large (4), medium (2) and small (1) sizes were used. The large step size was utilised for the first two reversals, the medium step size for the second two reversals and the final step size for the rest of the trials. The trial was marked correct if the participants were able to repeat the sentence with at least three keywords of IEEE sentences and two keywords of BKB sentences. For the first three training sessions, a total of 55 sentences from the IEEE ARU (Kent male talker) were used per condition. For comparison with experiment 1, the first training sessions in this study took roughly less than an hour. However, in the last pre-testing training session, 32 sentences from BKB were used for each condition.

5.1.8.5 Testing (Session 4)

During the testing session, the same method employed during the training session was used to measure the four SNR thresholds (fingertips, wrists, forearms, and No Vib). However, the testing session was terminated when six reversals were achieved at the small step size. The SRT was determined by averaging these reversals.

5.1.8.6 Post-testing Survey (Session 4)

After the test session, the subjects completed an online Microsoft Forms Survey (see Appendix J). This survey comprised of two sections. The first section included two questions concerning vibration comfort and benefit of vibrotactile cues on speech-in-noise performance at different evaluated body locations. A single-item five-point ordinal Likert scale ranging from

"uncomfortable " to "very comfortable" for comfort and from "makes speech perception much harder" to "makes speech perception much easier" for benefit was used. In the second section, respondents were asked to suggest other body parts that could be stimulated with vibrotactile stimulation or to give any further information.

5.2 Pilot study

The pilot study was conducted to determine the best way to measure each of the parameters and to become accustomed to the research tools.

During the pilot study, participants reported that the intensity of vibrotactile stimuli felt different across the three body sites when a single level was used for all sites. Therefore, it was planned to equalise the sensation levels for each participant's three body locations. For this purpose, the researcher created a vibration-shaped noise stimulus, as described in 5.1.7.1. At the highest allowable software gain setting, the pilot subjects' vibration sensation levels were around 23 dB above their threshold at each of the three body locations.

Finally, one native English speaker acted as a pilot subject for the full experiment with its new parameters. During this phase of piloting, no technical issues were identified. Furthermore, none of the survey questions required rephrasing. Considering this, it was agreed to proceed with the data collection using 24 individuals.

5.3 Data analysis

To address the study's aims, three distinct analyses were carried out. First, a paired t-test was conducted to investigate if vibrotactile cues could enhance the speech-in-noise performance of adult CI simulated subjects. This was done by averaging the SRT of all the vibrotactile conditions and comparing it to the SRT of the No Vib condition. Second, a one-way repeated-measures analysis of variance (ANOVA) was performed to compare the effects of vibrotactile stimulation on simulated CI individuals' speech-in-noise performance when applied at three different body sites. Third, the Friedman test was used to test whether the participants' subjective ratings of the vibration differed between the three different sites. The results were considered significant if the *p*-value was less than 0.05

5.4 Results

The SRTs in dB SNR of participants after the four training sessions are shown in Figure 26 for each experimental condition.

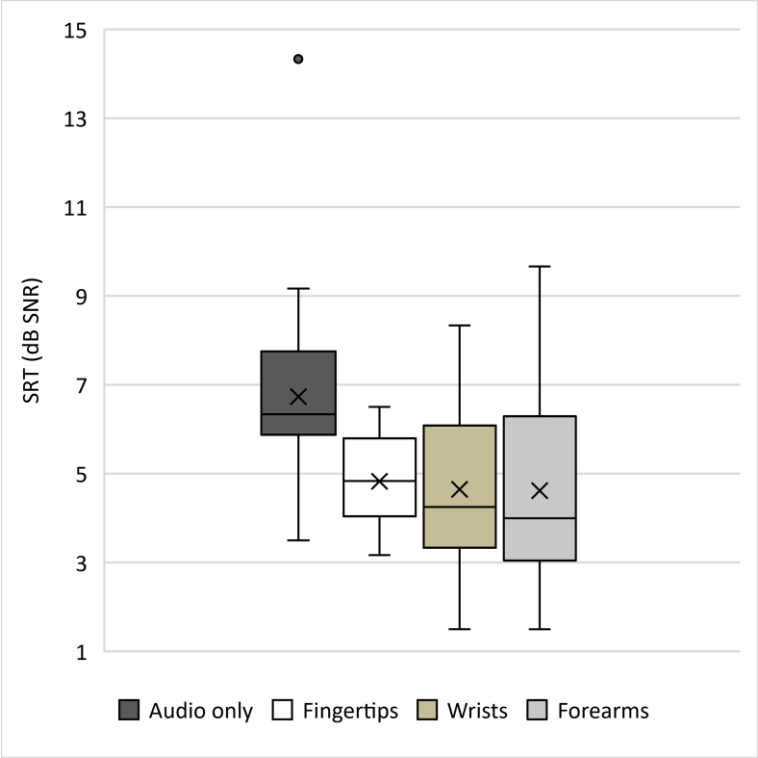

Figure 26. Summarises the 24 participants' speech reception thresholds in dB SNR in the testing session for the four experimental conditions. The top and bottom edges of each box show the interquartile range. The thick lines inside the boxes show the median. The maximum and minimum, excluding outliers, are shown by the upper and lower whiskers. Outliers that are at least 0.67 times the upper quartile or at most 0.67 times the lower quartile are shown by circles in the boxplot.

5.4.1 Investigate the effect of vibration on speech-in-noise performance

One of the objectives of this study was to assess whether, using this experiment set-up and training regimen, the application of vibrotactile cues can improve the speech-in-noise performance of adult simulated CI participants. Figure 27 shows the average SRTs (dB SNR) for the vibrotactile conditions at the three body sites and No Vib in the testing session. A paired-samples t-test was conducted to determine if there was a statistically significant mean difference between vibrotactile conditions (the average of the SRTs at the three locations) and No Vib. Upon inspection of outliers, three outliers (-1.40 ≤ one outlier< 0.08 dB and 4.04 < two outliers ≤ 5.52 dB) were detected in the difference between the average of vibrotactile conditions and No Vib condition, and two extreme outliers (-1.72 and 6.44 dB) were detected. All outliers were included in the analysis because they can contain valuable information and removing them might distort the results. The assumption of normality was not violated, as assessed by Shapiro-Wilk's test (p = 0.102). The results revealed that, on average, participants' SRTs were better when vibrotactile cues were applied (mean = 4.70, SD = ±2.15 dB) as opposed to No Vib (mean = 6.74, SD = ±1.40

dB), a statically significant mean improvement of 2.04 (95% CI, 1.37 to 2.71 dB), $t(23) = 6.28$, $p < 0.001$, $d = 1.28$. The greatest SRT improvement with vibrotactile cues for one of the participants following four training sessions was on average 6.44 dB SNR, for all the vibration conditions. However, the performance of two participants deteriorated by -1.17 dB SNR SD = ± 0.79 on average when vibrotactile stimulation was introduced (Figure 27; lower panel).

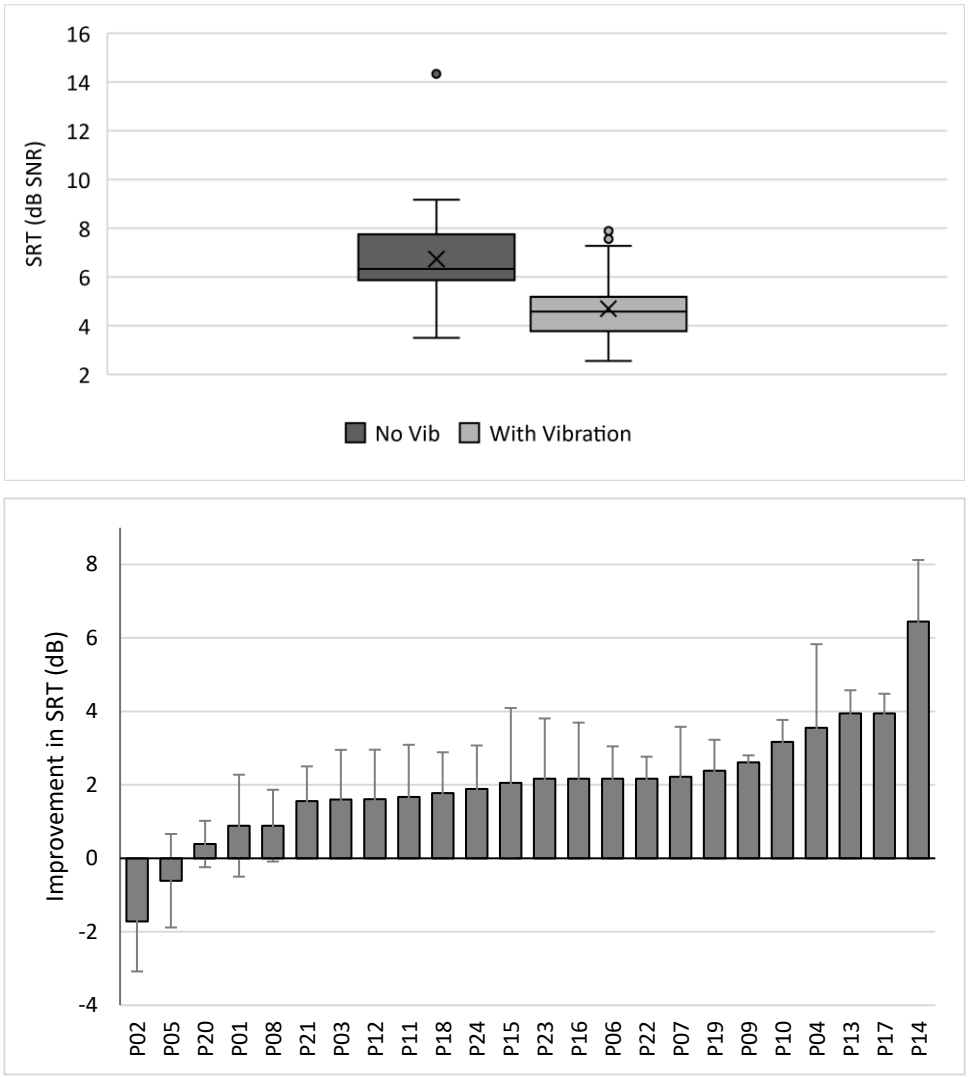

Figure 27. Box plot summarising the distribution of the average speech reception thresholds (SRTs) for all participants in dB signal-to-noise ratio (SNR) when vibrotactile stimulation cues were applied at three body sites, as well as the SRTs for the No Vib condition during the testing session (top panel). The bottom panel displays the benefit of listening to the CI simulation with vibrotactile cues (averaged across the three body locations) on the speech reception threshold for each participant. A positive change in performance indicates that vibrotactile cues improved speech-in-noise performance. The participants were ranked in ascending order based on the degree to which their performance improved with vibrotactile cues.

5.4.2 Compare the effect of applying vibrotactile cues at different body locations on SRT

The primary objective of this study was to compare speech intelligibility when vibrotactile cues were delivered to different body locations. The participants' speech intelligibility benefit with vibrotactile cues in dB SNR for the three examined body locations is displayed Figure 28. A one-way repeated measures ANOVA was conducted to examine if there was a statistically significant difference in the benefits of SRTs when vibration was applied to three different parts of the body: the fingertips, wrists, and forearms. The data was normally distributed at each location, as assessed by the Shapiro-Wilk test ($p > 0.05$). The assumption of sphericity was met, as assessed by Mauchly's test of sphericity, $\chi^2(2) = 074$, $p = 0.964$. The different body placements did not lead to statistically significant changes in SRT benefit, $F(2, 46) = 0.191$, $p = 0.817$, partial $\omega^2 = 0.008$.

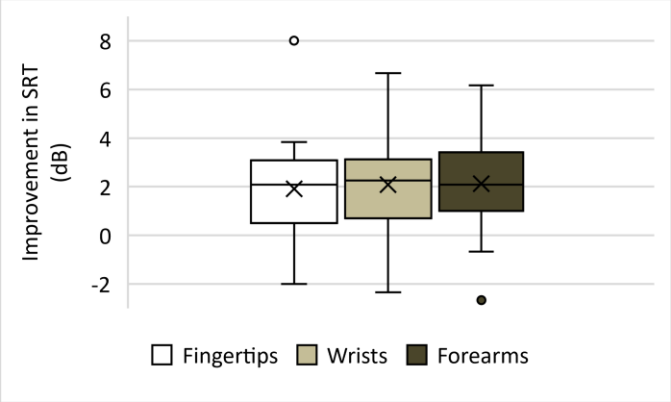

Figure 28. The boxplot displays the participants' speech intelligibility benefit with vibrotactile cues in dB SNR for the three examined body locations.

5.4.3 Exploring the subjective benefits and comfort of vibrotactile cues at tested body sites.

After completing the experiment, all 24 participants filled out the post-testing questionnaire. Figure 29 summarises participants' five-point Likert scale responses to speech benefit and comfort questions. Table 3 indicates that the majority of participants subjectively rated that vibrotactile cues made their speech easier (the average rating for applying vibration at the three locations was >3.41). Furthermore, fingertips were their preferred stimulation site in terms of both speech performance and comfort.

Each response to the Likert-scale questions was scored for numerical analysis on a scale ranging from 5 (for expressions of favour) to 1 (for expressions of disfavour). The mean values and standard deviations of the Likert scores are presented in Table 3. The mean values for comfort and speech performance for vibrotactile stimulation on the fingertips were slightly higher than other body sites. A Friedman test was run to determine if there were statically significant

differences in the participants' rating for comfort and speech benefit when the vibrotactile stimuli were presented at the tested body sites. There were no statistically significant differences between different body locations for the subjective speech benefits and comfort.

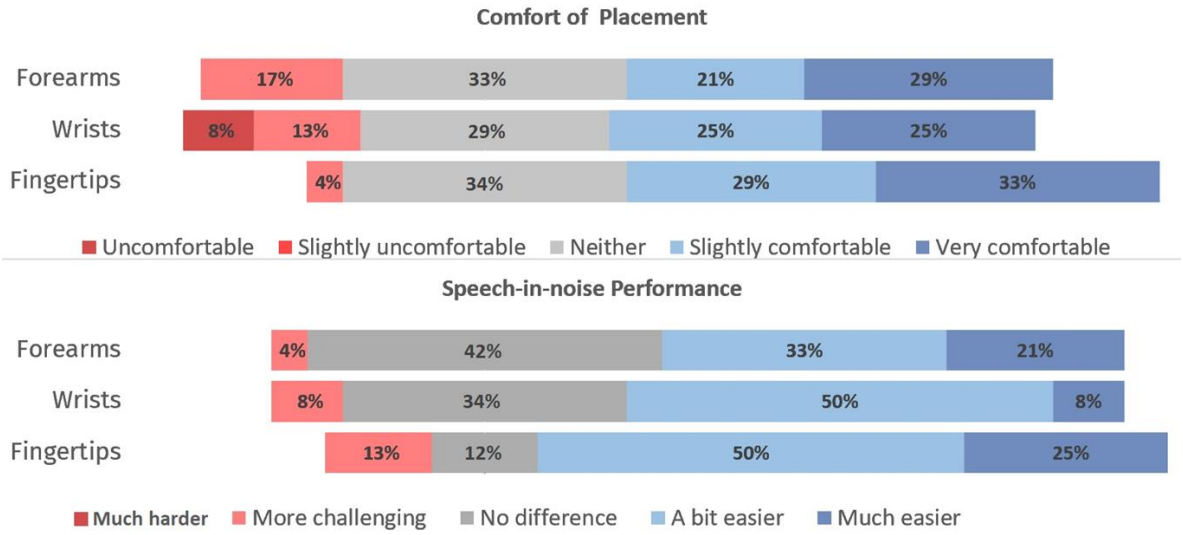

Figure 29. Diverging stacked bar charts showing respondents' ratings from a 5-point Likert scale to assess speech-in-noise benefit and comfort in the three vibrotactile conditions. The percentages within the bars represent the percentage of the responses.

Table 3. The mean values and standard deviations of the Likert scores for both speech performance and comfort at three of the body locations.

	Impact on speech performance	Comfort of placement
Scale	1 to 5	1 to 5
Measure	Mean (SD)	Mean (SD)
Wrist	3.58 (0.78)	3.46 (1.25)
Arms	3.71 (0.86)	3.63 (1.10)
Fingertips	3.88 (0.95)	3.92 (0.93)

Note SD = standard deviation
Impact on speech intellgibility:1= makes speech perception much harder;5= makes speech perception much easier
Comfort of placement: 1= uncomfortable; 5=very comfortable

5.5 Discussion

5.5.1 The effect of vibrotactile cues on the speech-in-noise performance

It is worth noting that this study used the same equipment to study 1 but differed in the design and the used corpora. Notably, unlike the previous study, this study demonstrated a vibrotactile benefit. It seems that modifications made to this study based on potential factors that may limit the benefit of vibrotactile cues, discussed in Chapter 4, may be the main reason for lack of benefit in the previous study.

The results of this study support the existing evidence that vibrotactile stimulation cues have a robust effect on speech-in-noise intelligibility for CI users (Ciesla et al., 2019, Ciesla et al., 2022, Fletcher et al., 2018, Fletcher et al., 2020a, Fletcher et al., 2019, Huang et al., 2017). Upon completion of training sessions, vibrotactile cues enhanced the SRT of the participants by an average of 2.04 dB (CI, 95%, 1.37 to 2.71 dB). While the 2.04 dB SRT improvement with vibrotactile stimulation was statistically significant, it falls within the estimated just-noticeable difference range of approximately 3 dB for hearing aid users (McShefferty et al., 2015). However, it does not reach the higher just-meaningful difference in SNR, which is typically 6-8 dB SNR, considered clinically relevant for intervention seeking or device uptake, regardless of hearing ability, as reported by McShefferty et al. (2016). Nevertheless, this modest improvement is on the lower end of the 3-5.3 dB SNR improvement provided by bimodal hearing (Morera et al., 2012), which are still clinically valuable and improve outcomes for users. Thus, these results may reflect a small but meaningful effect.

This study extends the findings of Fletcher et al. (2018, 2019, 2020a), who demonstrated that using similar vibrotactile cues on the fingertips or wrists can improve the speech-in-noise performance for both simulated and real CI users. However, different methods or outcome measures make direct comparisons challenging. (i.e., % of correctly repeated keywords). Nonetheless, useful insights can still be drawn by comparing current findings with related research by this group. For instance, Fletcher et al. (2020a), who used the same outcome measures as this study and found evidence that vibrotactile stimulation significantly enhanced speech perception in multi-talker noise for CI users after just 30 minutes of training. However, the SRT improvements of 2.8 dB (for noise on the same side as the CI) and 2.6 dB (for noise on the opposite side) were only seen when the speech and noise originated from different locations. This indicates spatial separation between speech and noise may be an important factor in observing benefits. Although Fletcher et al (2020a). extracted vibration cues from speech-in-noise stimuli in real time, which is more difficult than extracting cues from clean speech, the ipsilateral improvement was slightly better than the 95 % confidence interval (1.37 to 2.71 dB) of the current study. This slight improvement in the results may be explained by the fact that Fletcher et al (2020a). recruited real CI users. Despite contradictory findings in the literature about whether tactile processing improves or deteriorates in individuals with hearing loss, some research has revealed that deaf individuals have increased tactile sensitivity (Levänen and Hamdorf, 2001). This phenomenon is known as "compensatory plasticity" that happens after hearing loss (Good et al., 2014).

Unlike the current experiment, which utilised amplitude envelope cues, Huang et al. (2017) found that applying fundamental frequency vibrotactile cues to the fingertip can enhance speech-in-

noise performance for CI users without training. Even though Huang et al. (2017) utilised different vibrotactile cues extractions (F0) without training, the average SRT improved from 13.1 dB to 10.9 dB with vibrotactile cues. These SRTs are greater than the SRTs reported in the current study (6.74 dB to 4.70 dB), but the mean change is comparable. A possible explanation for this might be related to a lack of training, type of noise (stationary vs. multi-talker), speech materials and type of subject (old vs. young and real CI users vs. simulated CI users). In fact, training has a very important role in this multimodal approach, and several electro-haptic stimulation studies found that training has a significant positive effect on speech-in-noise performance (Fletcher et al., 2019, Fletcher et al., 2018). Along the same lines, Ciesla et al. (2019) found that providing tactile cues for the fundamental frequency on two fingertips (index and middle fingers of the dominant hand) to simulated CI users can improve their SRT by 6 dB. Although they used English sentences on non-native English speakers without any form of training with vibrotactile stimulation, the improvement in the current study was more modest. It is unclear how these robust results were obtained, but a potential cause for this discrepancy could be attributed to the utilisation of different CI simulation processing. Recent research by Ciesla et al. (2022) revealed that 30 to 45 minutes of training reduced the mean effect of SRT with vibrotactile cues to be 4.38 dB. The results of these studies confirm that vibrotactile stimulation has a lot of potential to help CI listeners understand speech in noise.

5.5.2 The effect of applying vibrotactile cues at different body sites on the speech-in-noise performance

This study found no significant differences in SRTs for vibrotactile cues at different sites on the body (i.e., index fingertips, wrists, and forearms). These body locations were selected in this study for practical reasons. Additionally, Additionally, a separate study evaluating the participants' perspective revealed a preference for wearing sensors on the wrists and arms than other body regions (Bergmann et al., 2012). Furthermore, earlier electro-haptic research has shown that applying vibrotactile cues to fingertips (Ciesla et al., 2022, Fletcher et al., 2018, Huang et al., 2017), wrists (Fletcher et al., 2020a, Fletcher et al., 2019, Fletcher et al., 2021a, Fletcher et al., 2020b), and forearms (Fletcher et al., 2020c, Fletcher et al., 2021b) can successfully improve some of CI users' hearing-related tasks. However, no studies have directly compared the benefits of vibrotactile cues at different body locations, except for Fletcher et al. (2021b), who investigated vibrotactile localisation cues and found similar sensitivity across three sites: the lower triceps, palmar wrist, and dorsal wrist. In contrast Fletcher et al. (2021b), the current study specifically examined the potential benefits of vibrotactile cues for improving speech-in-noise perception in individuals with cochlear implants, which provides new insights into this research area.

It is important to bear in mind that the fingertips have higher sensitivity and touch receptor density than other tested body locations (Johansson and Vallbo, 1979, Summers et al., 2005, Morioka et al., 2008). Thus, this study attempted to compensate for this disparity in sensitivity by equalising the sensation level across different sites. Despite the fact that the fingertips are more sensitive, research has shown that other body locations such as the wrists, can be comparable in terms of some suprathreshold aspects such as, sensitivity to frequency, gap detection, and amplitude discrimination (Summers et al., 2005). In fact, Summers et al. (2005) found that the wrist outperformed the fingertips only in amplitude discrimination, which can be explained by the rapid growth of subjective intensity magnitude at less sensitive sites, such as the forearm compared to the finger tips (Verrillo and Chamberlain, 1972). These findings may explain why the current study found no significant differences in speech-in-noise performance across different placements, as we used suprathreshold stimuli. Additionally, our findings are in line with those of Fletcher et al. (2019, 2018) who found the speech-in-noise benefits of applying vibration to the fingertips were similar to applying it to the wrist. As previously stated, it is hard to directly compare our results with those of Fletcher et al. (2019, 2018) because they employed different outcome measures. However, the benefits of the current study for the wrists and forearms are similar to Huang et al. (2017) benefits when the F0 vibrotactile cues were applied to the fingertips. Taken together, it is plausible to conclude that vibrotactile augmentation of speech-in-noise performance for CI users is attainable at any of the investigated locations.

A designer may decide to place wearable technology on one body location over another for various reasons such as practicality and comfort. Using the tactile aids that were used in the past for individuals with hearing loss as an example, the wrists, arms and chest have all been used as stimulation sites to deliver audio information to users' skin (Reed and Delhorne, 1995). The majority of body site considerations require balancing the intended function of the device with the body's location capabilities. For instance, some parts of the body are more sensitive to the vibration than others. Furthermore, some devices require more than one vibrotactile stimulator to be used, so it is crucial to understand other skin characteristics such as the just noticeable difference, which is how near stimuli can be to each other and still detected as separate stimuli. However, certain functional and technological limitations can be associated with the device's placement on the body. For example, vibrotactile stimulation of body locations with low sensitivity may require more powerful stimuli that might consume more power which lead to short battery life. Also, some body sites such as wrists or arms can be more practical for a real-world application than other body sites such as chest or fingertips. Because of this, the EHS devices' developers should choose a place that is convenient for the wearer, provides optimal comfort, and does not interrupt daily tasks. Moreover, functionality and aesthetics are another

important variables that could also influence the success of wearable technology (Harrison et al., 2015, Profita et al., 2016). One way to ensure the acceptance of the wearable technology in everyday life is to understand users' preferences about devices (Bergmann et al., 2012).

This study also explored the participants' perceptions (a subjective metric) of vibrotactile stimulation at different body locations in terms of speech benefit and comfort. Their responses to the Likert scale questionnaire did not show a significant difference between the three tested body locations in terms of subjective comfort and perceived speech-in-noise benefit, although the majority of the subjects believed that vibrotactile cues improved speech perception. However, several participants at the end of the experiment reported that all the tested body sites were appropriate in terms of comfort and benefit, but they favoured the wrist and arms more than fingertips due to practicality. These comments mirror those of Bergmann et al. (2012), who found in a questionnaire that participants preferred wearing devices on their wrists and arms over other body regions.

In addition to the three body locations tested in this study, participants were also given the option to suggest other potential body locations. Several respondents mentioned areas closer to cochlear implants such as the back of the neck, temples, clavicle (collarbone, and shoulders, as they believe these areas could be closer to the natural site of hearing). Some of the proposed stimulation sites, such as the nape of the neck, forehead, or sternum, had already been employed in previous commercial tactile aids such as Tactaid II and Tactaid 7 (Audiological Engineering Corp.), which were shown to provide some speech benefit to deaf people (Sorgini et al., 2018). The open-ended questions in Bregmann et al.'s (2012) study revealed that wearable technology must be compact, unobtrusive, and discreet, and should be integrated into other common devices. Further work is required to investigate the potential benefits of other discreet vibrotactile stimulation sites.

In this study, the vibrotactile stimulation was delivered through two contactors on each side. Further work is needed to evaluate the effect of multi-vibrotactile transducers (multichannel stimulation) at different body sites on the speech-in-noise performance of CI users. Some previous tactile devices conveyed speech information to the user via multichannel devices. These multichannel devices were created based on the idea that the insufficient spectrum resolution ability of the touch system (Goff, 1967, Rothenberg et al., 1977) would significantly degrade the perception of the spectral features of a single-channel device's vibratory signal. Therefore, in several multichannel devices, the acoustic stimulus features are recoded into locations on the skin, substituting a dimension along which the tactile systems exhibit high resolution (Weinstein, 1968). According to a number of studies, multichannel devices deliver more acoustic information

than single-channel devices (Brooks et al., 1986, Weisenberger et al., 1991, Weisenberger et al., 1989). This multichannel option could influence the choice of where to place EHS devices on the body, and the spatial acuity of touch perception should be considered.

5.5.3 Limitations and future direction

A number of limitations should be considered regarding the present study. First is the absence of a vibrotactile control condition that excludes the possibility of placebo effects. Nonetheless, several past EHS studies have addressed this factor in several ways. Ciesla et al. (2022) added a non-matching vibrotactile cue as a control condition. After training, Ciesla's participants were able to receive the benefits of vibrotactile stimulation under matched vibrotactile conditions but not under the control condition. Fletcher et al. (2020a) suggested that the benefit of EHS may not be attributed to a placebo effect. They arrived at this suggestion based on their observation that the positive effect of EHS on speech-in-noise performance was not present when both speech and noise were coming from the same location. This was due to the ineffective noise cancellation processing, resulting in participants receiving NAL noise fluctuation for vibration cues. Consequently, an unmatched cue was created in that condition. However, in the current study we used co-located speech and noise, but the vibrotactile cues were extracted from clean speech which could explain the obtained benefit from the vibration conditions. Another study by Fletcher et al. (2019) attempted to control the placebo effect by falsely informing participants in the No Vib condition that they were receiving audio enhancements. Yet, the participants performed better in the EHS condition. Together, these pieces of evidence suggest that the benefits of EHS is not predominantly due to a placebo effect, as large effects have been observed with either control condition.

Using normal, young hearing participants listening to CI simulation instead of real CI users was a second drawback of the study. Simulations of CI are a well-established method in the field of audiology which provides normal-hearing participants with degraded signals containing a similar amount of helpful information as CI users (Grange et al., 2017). In the current study, SRTs for simulated users were found to be quite comparable to those found in EHS studies conducted on real CI users of different ages (Fletcher et al., 2020a, Huang et al., 2017). A possible reason for these similar results is that this work utilised an advanced simulation that included channel interactions the range of values that exist in real-world CIs (Grange et al., 2017). This simulation mimics the signal heard by well-fitted CI users with optimally working electrodes; however, this is not always the case. Nevertheless, studies showed that congenitally deaf people show behavioural enhancement in tactile sensitivity detection and tactile frequency changes (Levanen and Hamdorf, 2001) and can integrate audio and tactile information effectively (Nava et al., 2014).

Therefore, this study's vibrotactile stimulation may benefit some CI users with limited acoustic auditory information more than simulated users. More research is needed to find out how EHS performance is affected by things like being young or old and being born deaf or becoming deaf later in life.

5.6 Conclusions

The present study found that vibrotactile stimulation at different body placements on the arm did not lead to any statistically significant differences in SRT between placements. Therefore, effective haptic devices could be deployed at any of the evaluated body locations. However, it is important to consider practical constraints when identifying a suitable location for a haptic device. For example, some locations require more powerful shakers to produce the desired level of vibrotactile stimulation, while others may have limited design space. Additionally, the placement of the device could affect the level of comfort and convenience of for the user. Designers may therefore decide to place wearable haptic device on one body location over another for various reasons including functionality, practicality, and body site capabilities. Consistent with most of the previous EHS research on CI users, this study found that vibrotactile stimulation significantly enhanced the speech-in-noise performance of normal-hearing participants listening to CI simulation after training. The results are also in agreement with prior EHS studies on CI users, which have demonstrated the potential of vibrotactile stimulation to augment the gaps in electrical stimulation and improve speech perception in noisy environments.

Chapter 6 Study three: the perspectives and recommendations of cochlear implant professionals and users for the Development of a Wearable Haptic Device.

6.1 Introduction

As described in Section 2.1.3, CI users find certain listening tasks more difficult than normal hearing individuals, for example, hearing in noisy situations, sound localisation, and music perception (Dorman et al., 2016, Drennan and Rubinstein, 2008, Spriet et al., 2007). The addition of certain vibrotactile cues to the CI's electrical stimulation, known as electro-haptic stimulation (EHS), was found to improve their performance in some of these challenging tasks, as explained in Section 2.3.3 (Ciesla et al., 2022, Fletcher et al., 2018, Fletcher et al., 2020a, Fletcher et al., 2019, Huang et al., 2020, Huang et al., 2017). This type of augmentation is a non-invasive and inexpensive approach, yet there is a lack of commercially produced EHS devices and the majority of EHS experiments were investigated in a laboratory setting.

While EHS devices are not clinically validated yet, developing a successful novel medical device must meet user needs. In this context, a range of factors needs to be addressed, such as the users' requirements, lifestyles and the context in which the device will be used. However, if the potential users of the device are not adequately involved prior to device development, incorrect assumptions may be made about the users. Thus, getting the users' input early in technology development is crucial to further enhance the product based on their needs (Choi, 2015). As a result, the user-centred design approach has become a preferred method in the design of medical devices (Martin et al., 2008). Indeed, this design approach enables device users to take an active part in the design process, which provides a rich data source that cannot be obtained through other data collection approaches.

Along the same lines as the user-centred design approach, new product development (NPD) models also place considerable emphasis on involving the end-users in the process (Durisin et al., 2010). User involvement at all stages in the development process was found to increase the likelihood that a new product will be successful (Gruner and Homburg, 2000). The Stage-Gate Model, shown in Figure 30, is an example of one of the structured and organised procedures for NPD that has been widely adopted and utilised in industry (Cooper, 2019). User input is sought at all stages of new product development, from idea to launch and beyond.

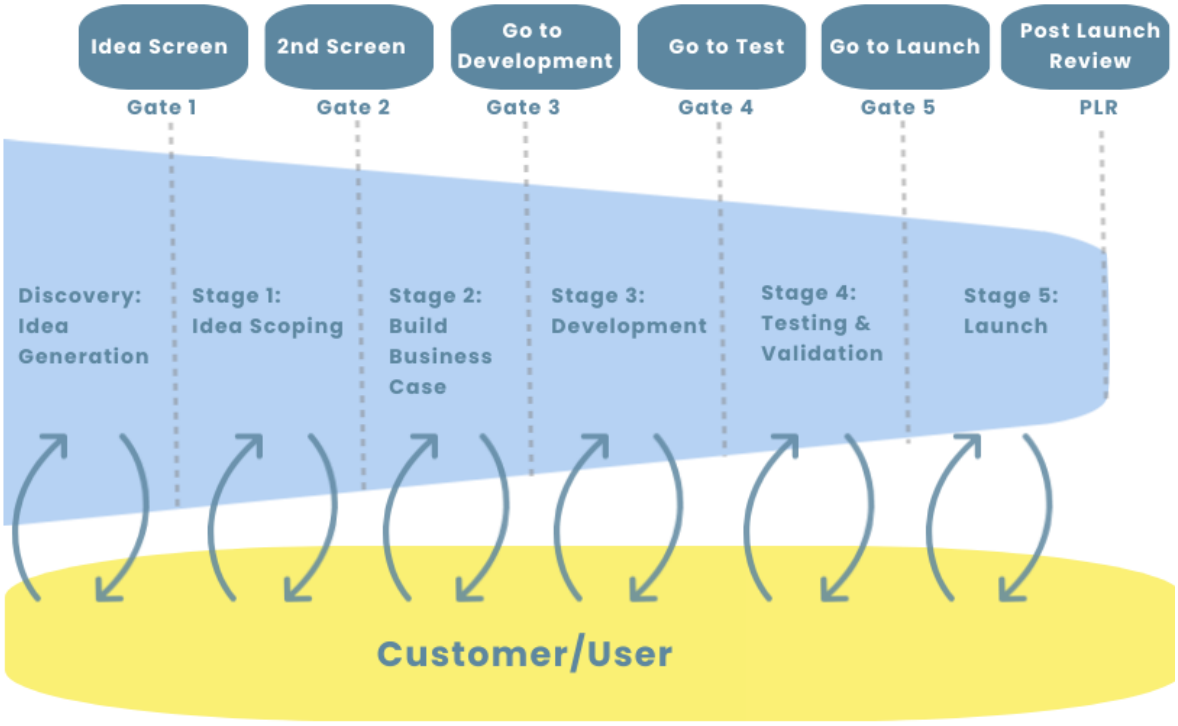

Figure 30. Cooper (2019) Idea-to-launch five-stage model. Each stage of the new product development process corresponds to a distinct set of actions. Gates (1-5) are decision points in a project at which decisions are made on whether or not to proceed.

Developers of hearing technology are increasingly engaging the end user during the development process to ensure that the product's functionality and usability meet the needs of end users (Convery et al., 2020). To the best of the researcher's knowledge, no studies have investigated the user preferences of EHS devices from the perspectives of CI users or professionals. Thus, at the preliminary stage, it would be beneficial to explore the perspectives of both cochlear implant users and professionals. The aim of this qualitative study was to explore the perspectives of CI professionals and users regarding the use of EHS devices in general and an early prototype design and to provide relevant recommendations that can inform the further development of these devices. Given that this study had a translational focus, it was essential to consider the limitations and practical challenges that may arise during the real-world use of the devices. As a result, the findings of this qualitative study could provide important insights into the potential perceived benefits and challenges of using EHS devices, ultimately guiding the development of more effective user-friendly devices.

6.2 Aims

The sub-aims were to explore: (1) the hearing challenges experienced by adult CI users; (2) the current strategies and technologies used by CI users to manage these challenges; (3) the ideas

and recommendations of CI professionals and users to inform the development of haptic devices and finally; (4) feedback with regards to a prototype electro-haptic device.

6.3 Methodology

6.3.1 Study design

This study used a multi-method qualitative design that involved the administration of questionnaires and focus group discussions. This design served to: (1) understand the participants' perspectives; (2) use different methods to complement each other (i.e., capture demographic/background information using a questionnaire to free up time in the focus group for discussion); (3) allow participants to take part in the study through a method that is best suited to them and their hearing ability, i.e., a synchronous focus group (either with or without a BSL interpreter) or an asynchronous focus group (written word format). Some CI users preferred the latter in the light of their hearing difficulties.

6.3.2 Ethical approval

This study was reviewed and approved by the University of Southampton Ethics Committee (Faculty of Engineering and Physical Sciences ERGO ID: 61075.A1, Appendix K).

6.3.3 Participants

The participants were CI professionals and CI users. The professionals included CI audiologists and rehabilitationists, including speech therapists, hearing therapists, psychologists and teachers of the deaf/educational audiologists. Eligible professionals were those who had at least one year of clinical experience working in the field of CI rehabilitation. This criterion was set to ensure that the participants had adequate knowledge about the needs of CI users, thereby enriching the focus group discussions and qualitative questionnaires.

The inclusion criteria for the CI users were as follows: (1) adults aged 18 and older; (2) individuals implanted (uni- or bi-laterally) for at least 12 months to ensure the stability of speech perception performance (Hamzavi et al., 2003) and fitting parameters (i.e., a stable map) (Hughes et al., 2001); (3) full-time implant users; (4) had the computer literacy required for the study, i.e., using a computer to complete the online questionnaires and participation in the focus groups.

6.3.3.1 Cochlear implant professional participants

Seventeen CI professionals from UK CI services were recruited for this study. The degree of experience of these participants with CI users ranged between 1 and 30 years (mean= 17.66, SD=

9.47). Professional backgrounds included audiologist (n = 7), speech and language therapists (n = 4), educational audiologists (n = 2), teachers of the deaf (n = 2), and clinical psychologists (n = 2). The participant characteristics are presented in more detail in Table 4.

Table 4. Characteristics of the CI professionals.

Number of participants	17
Professional training	Audiologists: 7 (41.2%) Clinical Psychologist: 2 (11.8%) Educational Audiologist: 2 (11.8%) Speech and Language Therapists: 4 (23.5%) Teacher of the Deaf: 2 (11.8%)
Years of experience	Range: 1-30 years Mean: 17.66 Standard deviation: 9.47
Highest level of qualification	Bachelor: 2 (11.8%) • 2 Speech and Language Therapists Postgraduate Diploma: 2 (11.8%) • 1 Speech and Language Therapist • 1 Educational Audiologist Masters: 7 (41.2%) • 4 Audiologists • 2 Teachers of the Deaf • 1 Educational Audiologists Doctor of Philosophy: 3 (17.65%) • 2 Audiologists • 1 Speech and Language Therapist Clinical Psychology Doctorate: 2 (11.8%) Doctor of Audiology (AuD): 1 (5.9%)
Geographical region	Southampton, England: 14 (82.4%) Rhyl, Wales: 1 (5.9%) Centres on South coast: 2 (11.8%)

6.3.3.2 Cochlear implant users participants

This qualitative study was conducted on ten adult CI users (8 females and 2 males). The sample consisted of one participant in the age range 18-34, two participants in the age range 35-44, four participants in the age range 45-54, and three participants in the age range 55-64. These CI users the devices of a variety of different CI manufacturers). Six participants (60%) reported onset of hearing loss after childhood. Of the 10 participants, two (20%) were bilaterally implanted. Further demographic information and audiologic factors about the CI users are summarised in Table 5.

Table 5. Statistical summary of the Demographics and audiological factors of the participated cochlear implant users.

Number of participants	10
Sex	Females: 8 (80%) Males: 2 (20%)
Age group	18-34: 1 (10%) 35-44: 2 (20%) 45-54: 4 (40%) 55-64: 3 (30%)
Aetiology of hearing loss	Genetic: 3 (30%) Infection or Diseases: 2 (20%) Sudden Hearing Loss: 1 (10%) Unknown: 4 (40%)
Age of hearing loss onset (years)	Range: 0-52 Mean: 14.5 Standard deviation: 16.53
Nature of hearing loss	Progressive: 5 (50%) Sudden: 5 (50%)
Age at cochlear implantation (years)	Range:0-53 Mean: 28.5 Standard deviation:20.18
CI experience (years)	Range: 1.17-20 Mean: 7.17 Standard deviation:6.65
Hearing device(s)	Unilateral CI with no contralateral HA (6) Unilateral CI with contralateral HA (1) Unilateral CI with linked HA (1) Bilateral CI (2)
CI company	Cochlear (Unilateral 3; Bilateral 1) Advanced Bionics (Unilateral 3) MED-EL (Unilateral 2; Bilateral 1)
Geographical region	Southampton, Hampshire (3) Gosport, Hampshire (1) Warminster, Wiltshire (1) West Sussex (1) Bournemouth, Dorset (1) Cambridge, Cambridgeshire (1) Portsmouth, Hampshire (1) Manchester, Greater Manchester (1)

6.3.4 Materials/apparatus

A password-protected computer was used to run the software for the online focus group, to send and receive questionnaires. Additionally, the NVivo analysis software (version 12) was installed on the same computer for data analysis.

The focus group discussion was carried out in two different ways: synchronous (live online video discussions where participants participate at the same time) or asynchronous (written format discussions where subjects participate at different times) discussions in written format. Both types of focus groups were conducted on Microsoft Teams (see Table 6) and CI participants were given the opportunity to choose their preferred method.

The questionnaires were sent to the participants via Microsoft Forms, which was selected for its data security as it is supported by the University of Southampton.

For the data analysis, the recorded focus group discussions were transcribed verbatim.

Table 6. Overview of focus group discussion types used in the study and the used platforms to conduct them for various participants.

Focus group type	Platform	Eligible Participants	Explanation
Synchronous (live online video discussions during which participants participate at the same time)	Microsoft Teams	CI professionals & CI users	This type of focus group was used for professionals and CI users who had good verbal communication skills and sufficient confidence to join a live synchronous discussion. The help of a qualified BSL sign-language interpreter was also offered.
Asynchronous (subjects participate at different times) discussions in written format	Microsoft Team (chat function within Microsoft Team Groups)	CI users	This session was used for CI users who preferred this format or who thought an online live meeting would be too challenging given their hearing difficulties.

6.3.5 Procedures

Given lockdown during the COVID-19 pandemic, direct face-to-face contact with the participants was not possible. Online contact and meetings were used for all stages of this study. Figure 31

represents the journey of the participants from recruitment to completion of the three phases of the study: (1) the initial questionnaire, (2) the focus group, and (3) the post-focus group questionnaire.

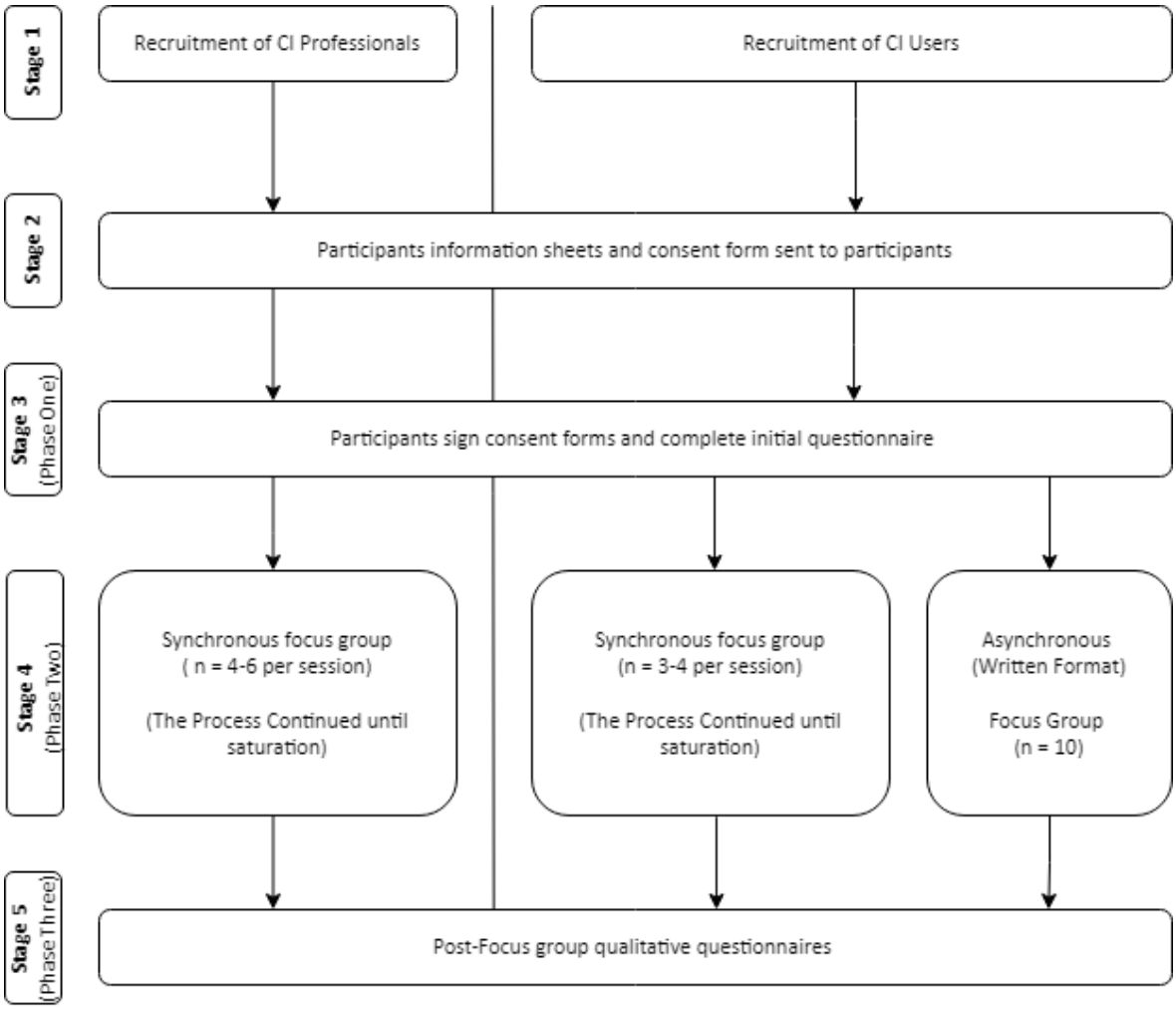

Figure 31. Flow chart of the study's stages for both CI professionals and users.

6.3.5.1 Stage one

As previously stated, CI professionals and CI users were recruited. An invitation to participate in the study was sent to CI professionals using the contact information obtained from the British Cochlear Implant Group website.

To send an invitation to CI users, the researcher contacted CI user groups in the UK, such as the National Cochlear Implant Users Association and regional CI support groups. The above information is available to the public.

These groups were asked to share information about the study with members of their group, and those interested then responded directly to the researcher. This recruitment approach allowed the enlistment of participants from different services and locations in the UK, thereby ensuring a comprehensive representation of perspectives from professionals and CI users across the country.

This recruitment method minimised direct communication between researchers and prospective participants, thus eliminating the risk of coercion in the process.

6.3.5.2 Stage two

Interested participants from each group received (1) a tailored participant information sheet (i.e. CI users or professionals) (Appendix L.1 and L.2), and (2) a consent form (Appendix M). They were required to respond to the consent form electronically through the following statement: *''Through this email, I hereby confirm that I have read and understood as well as agree with all the consent form information that I have received in the attachment of the previous email.''* After receiving the declaration statement, the initial questionnaire was sent via email with a link to Microsoft Form where the questionnaire can be accessed.

The participant information sheet was structured in such a way that it explained the study in detail. It also outlined the objectives of the study and why the participants were being invited. The participant information sheet also outlined what would be required of respondents and the advantages and disadvantages of the study if they want to engage with the research.

The initial questionnaire had two versions; one for CI users (Appendix N.1) and the other for CI professionals (Appendix N.2) , with the purpose of obtaining contextual/demographic data about the participants (Part 1 of the questionnaire) and information about the hearing challenges experienced by cochlear implant users and the assistive devices used to overcome these challenges (Part 2 of the questionnaire).

The questionnaire for CI professionals included questions concerning their occupation, the geographical area where they work and their years of experience as a CI professional (in Part 1). The questionnaire for CI users consisted of questions related to gender, age, CI device, geographic location, and causes of hearing loss (in Part 1).

The second part of both versions of the initial questionnaire comprised of open-ended questions about the hearing challenges encountered by CI users, the strategies and assistive technologies used to minimise these obstacles and any experience that they had with haptic devices. This section of the questionnaire was mainly added to elicit CI professionals' and users' perceptions of the hearing challenges experienced post-implantation and the ways by which to overcome them without limiting them to specific responses. This offered a better understanding of their perspectives, and it also allowed comparisons between the two groups.

6.3.5.3 Stage three

When the initial questionnaires were received, the researcher arranged the date, time and type of focus group discussion with the participants via email. When participants agreed on the time and date of the focus group discussions, a confirmation email was sent summarising these details and providing them with background information on the focus group session and ground rules (Appendix O). The main purposes of the imposition of ground rules are to maximise the richness of the discussions and maintain a relaxed atmosphere in which to participate in the exchange. A follow-up confirmation email, with the same information, was re-sent to the participants 24 hours prior to the focus group discussions as a reminder.

Focus group discussions are exchanges that encourage participants to raise specific ideas and issues, identify areas of consensus and conflict and reflect on previous experience (Rabiee, 2004). The focus groups facilitated discussion around recommendations regarding the development of a potential electro-haptic device. The CI professionals took part in synchronous sessions only, but CI users were given a choice to take part in either synchronous or asynchronous discussions. The latter was added to accommodate those with hearing loss who may not be able to participate or may prefer written format. CI participants in synchronous focus groups were also offered the services of a British Sign Language interpreter to improve accessibility and capture the ideas of those who struggle with verbal communication. The use of both options ensured broader participation from CI users. For more information on the advantages of asynchronous (written format) discussions, please refer to Table 7.

Table 7. Summary of advantages and disadvantages of asynchronous (written format) discussion compared with synchronous deliberation.

Advantages	Disadvantages
Can be a fairly fast method of generating data (from large samples) (Oringderff, 2004)	Emotions and nonverbal cues cannot be observed.
Facilitates analysis because there is no need for transcription, especially if data are collected electronically, thus reducing transcription errors (Adler and Zarchin, 2002, Oringderff, 2004).	Requires highly motivated participants with strong commitment because participation might distract from everyday life.
Can strongly motivate subjects to participate in a study (Kenny, 2005, Oringderff, 2004, Stewart and Williams, 2005).	Some people are verbally inclined and better express themselves through speaking.
Some anonymity-related ethical problems encountered in synchronous methods can be avoided (Bargh et al., 2002).	Time consuming compared with synchronous focus group discussion.
Subject participation unrestricted by the requirement for a mutually suitable time, eliminating time pressure on participants and allowing detailed responses (Tates et al., 2009).	
Anonymity of asynchronous data collection can motivate participants to take part in a study, especially in research involving sensitive topics (Joinson, 2001, Tates et al., 2009, Oringderff, 2004).	
The possibility of more depth because participants have more time to think about questions and responses (Krueger and Casey, 2014).	

During the synchronous or asynchronous focus groups, participants were asked three main open-ended questions and a closing question. The questions (actual script used in the focus groups) are presented in Table 8.

Table 8. Main questions and prompts for the focus group discussions.

Key question(s)	We are looking to develop a vibro-tactile prototype device that converts sounds into vibro-tactile (haptic) stimulation. *"A haptic (vibro-tactile) device is worn on the skin, on either one or both sides of the body. It picks up sound in the environment and converts it to gentle vibrations on the skin"* 1- What benefit/s (if any) do you anticipate a haptic device could offer CI users? 2- What aspects should be taken into consideration in developing the device? Consider placement, size, cosmetic considerations, cost and funding, candidacy (who might benefit) and other considerations. 3- Are there any challenges/issues that you anticipate might discourage CI users from using the haptic device?
Closing question	Do you have any other thoughts that you would like to share or add?

The asynchronous (written format using Microsoft Teams groups) focus group discussions lasted for a week. Each started with a short introduction to the research topic and the purpose of the research. After this, questions (in Table 8) were posted to give the participants opportunities to answer the questions and review and comment on others' responses. Posting the questions at the same time reduced the risk of losing data if a participant only logged in once. In this asynchronous focus group discussion, the participants were prompted (if required) to sign in daily for at least 10-15 minutes to allow time for reflection and review the contributions of the other participants and enough time to provide thoughtful responses.

The synchronous (live video) focus group discussions were held online and lasted up to an hour. On the day of the session, once all the participants had joined the online meeting, the researcher informed them of what was going to happen and briefly reminded them about the purpose of the study and the ground rules (Appendix O) sent in the invitation email. The discussion questions were presented verbally to the participants and also in the chat function. Additionally, the CI users were instructed on how to activate Microsoft Teams live captioning, and they were advised to keep it enabled during focus groups to increase comprehension and reduce strain.

As with traditional face-to-face focus group discussions, the researcher played certain roles in the live synchronous focus group sessions and with an assistant moderator also present. The researcher's tasks included introducing the topic and ensuring effective engaging exchange, while maintaining a comfortable and relaxed environment and ensuring that ground rules were maintained (Krueger and Casey, 2014). Prompts were used by the researcher where needed to

help participants engage in the discussion and motivate subjects who did not appear to contribute to the discussion. The assistant moderator's role (researcher with experience in focus groups) was to support the researcher, take notes and keep the discussion on time (Krueger and Casey, 2014). Both the researcher and assistant moderator video-recorded the synchronous discussions to reduce the chance of data loss in case of technical issues. For the asynchronous (written format) focus group discussions, a copy of the Microsoft Teams written discussions was saved daily by the researcher into a Microsoft Word file.

6.3.5.4 Stage four

The focus group discussions were followed up with an individual questionnaire (Appendix P) to allow the respondents the opportunity to make any final comments and also to obtain their feedback on the design of an early theoretical EHS prototype shown in images (an example is shown in Figure 32). The questions used in this post-focus group questionnaire are listed in Table 9.

Figure 32. A prototype for a wrist-worn haptic device based on the MosaicOne_C design is being developed by the Electro-Haptics project at the University of Southampton (Fletcher and Verschuur, 2021).

Table 9. The primary questions utilised in the post-focus group questionnaire.

Comments on the focus groups	Is there anything else you would like to add to the focus group discussion topic?
Previous knowledge about haptic devices	Have you attended a presentation or read an article about haptic devices in the past two years?
Key questions about the prototype	1- What do you think about this haptic device? 2- What would you change to improve this device? 3- How likely would CI users be to use this device once it is finished and why?

6.3.6 Development of the Questions in Focus Groups and Questionnaires

Open-ended questions were developed for both the questionnaires and focus groups to encourage participants to share their views. This format guided responses to answer the research questions while being flexible enough to allow thoughts to emerge from participants (Krueger and Casey, 2015). The questionnaires' and focus groups' questions were developed in consultation with the researcher's supervisors, who are experienced CI clinicians and electro-haptic researchers. One of the most fundamental and essential qualities of the questions in questionnaires and focus groups is that they need to be precise and clear to prevent any misinterpretation on the part of the participants (Mathers et al., 1998, Krueger, 1997). The questions were shared with colleagues and CI users known to the supervisors and their feedback was taken into consideration to improve the clarity and content of the questions.

6.3.7 Sample size

The number of participants recommended for traditional face-to-face focus groups is five to eight (Krueger and Casey, 2015). Eight participants are typically recruited, taking into consideration the possible non-attendance of up to 20% of participants (Morgan, 1996). The number of focus groups depends on the point at which saturation is reached, that is, the point at which the deliberation has ceased generating new ideas. In this study, a total of 7 synchronous and 1 asynchronous focus groups were conducted to meet the point of saturation of data.

In the current study, 2-5 participants (on average, 3.5 participants) were included in each synchronous focus group discussion to facilitate communication during the online meeting. Additionally, CI participants are severely deaf and despite their cochlear implants, they experience some degree of communication difficulty. Using 2-5 participants in the online focus groups ensured that everyone's face was visible on the screen at the same time to facilitate lipreading.

Asynchronous (written format) focus group discussions can accommodate more participants. The analysis of 21 asynchronous studies showed that the average number of participants per group is 12 (Williams, 2009). Nevertheless, a smaller group can foster a more convenient environment that promotes self-disclosure (Mann et al., 2000). Thus, the number of participants (n = 6) in this study's asynchronous online discussion can be considered an acceptable and advantageous number for those CI users who do not feel comfortable engaging in synchronous online discussion.

6.3.8 Data transcription and analysis

Initial questionnaire

The initial questionnaire collected two types of information: (1) demographic information about the participants and (2) information about the hearing challenges experienced by CI users, current assistive techniques/technologies to overcome these challenges and any previous experience with haptic devices. The data was analysed using descriptive statistics. The open-ended questions in the second part of the questionnaire were grouped into categories, with the number of responses from participants for each category recorded and calculated as a percentage, following the analysis method used by Lormore and Stephens (1994).

Focus groups and post-focus group questionnaire

The transcriptions of the asynchronous focus groups were already in written format (as added by the participants) and used verbatim. The transcriptions of the synchronous focus groups were also conducted verbatim, using the Microsoft Teams meeting recordings which offer the benefit of both a video recording and captioning. The voice recognition function records and captures the contributions of each participant under their username. This voice-to-text process has the potential to improve accuracy and decrease the time and effort that transcription requires (Shelton and Flint, 2020), but has its own limitations. For example, one limitation is that sentence units are not always accurately captured. A longer pause between words, for example when a speaker is thinking/formulating their thoughts, can be incorrectly captured as the start of a new sentence, resulting in a few disjointed phrases or incomplete sentences. The voice-to-text process was not always accurate in capturing specialised terminology, such as 'Sound Arc', which was captured as 'sound off' or accents, for example 'vain' captured as 'pain', and 'that' as 'dat'. The captioned text was therefore used as the starting point but checked in its entirety to amend inaccuracies. The transcriptions were checked by a second reviewer for accuracy.

Several analytic approaches can be used to analyse qualitative data, but researchers must carefully consider which approaches best suit the research goals and data set before proceeding.

Qualitative content analysis and thematic analysis (TA) are two common approaches for analysing qualitative data (Vaismoradi and Snelgrove, 2019). Both approaches were initially considered for the analysis. Table 10 offers a comparison of these methods. However, TA was ultimately selected for this study as it allowed for a rich and detailed account of the data. TA also ensured thorough coverage of all themes raised by, which is valuable when exploring an under-examined topic or one where opinions are not yet well established (Braun and Clarke, 2006). With TA, themes and sub-themes are highlighted rather than quantified in relation to the research questions. Even themes brought up by only one or two participants can still be crucial and were thus captured in the analysis. This study implemented Braun and Clarke's (2013) well-structured , widely-used six-phase TA process. The six phases are: familiarising oneself with the data, generating initial codes, searching for themes, reviewing the themes, defining and naming the themes, and producing the report.

Table 10. Comparison of qualitative content analysis and thematic analysis (Braun and Clarke, 2020, Vaismoradi and Snelgrove, 2019, Vaismoradi et al., 2013).

<table>
<tr><th>Qualitative Content analysis</th><th>Thematic analysis</th></tr>
<tr><td colspan="2">Similarities</td></tr>
<tr><td colspan="2">• Philosophical backgrounds.
• Immersion in data.
• Focused on both the data analysis description and interpretation.
• Context consideration during analysis.
• Looking for themes in data.
• It can be used for a variety of qualitative data.
• It can be for both deductive and inductive research approaches.</td></tr>
<tr><td colspan="2">Differences</td></tr>
<tr><td>• Risks of missing context of data and also losing some data.
• A quantitative description of qualitative data.
• Selection between manifest and latent contents.</td><td>• Flexible and adaptive method.
• Provide a rich and detailed account of data.
• Purely qualitative.
• Consideration of manifest and latent contents.</td></tr>
</table>

In this study, qualitative analysis software NVivo 12 was used as an aid for thematic analysis of the raw data. The study transcripts were read thoroughly by the researcher to aid familiarisation before the analysis was commenced. Sentences that described a certain idea or opinion were highlighted and notes were made about the common ideas and opinions. Open coding was used in the study, i.e., codes were developed and modified during the coding process rather than using pre-set codes. A list of codes was developed by grouping related responses into categories (or sub-themes). These codes categories were further analysed to form broad themes. This process

was repeated independently by a second reviewer, whereafter the emerging coding hierarchy, themes and sub themes were discussed to determine whether any could be expanded, consolidated or discarded.

To examine the reliability and objectivity of the coding process itself an independent coder was asked to re-code the first focus group transcription using the coding descriptions. Intercoder reliability refers to the extent to which two or more independent coders make the same decisions when applying the same coding scheme to a dataset or a subset of a dataset. The second coder had experience of qualitative research and works in the field of cochlear implants but had not been involved with the present study. Cohen's kappa, κ, is widely recognised as a gold-standard reliability indicator (Fiese and Spagnola, 2005). Cohen's kappa is a measurement of agreement between two coders when the coding is on a categorical scale, taking into account the likelihood of chance agreement (Weber 1990, Rourke et al. 2000).

6.4 Pilot study

Ahead of commencing the formal research, it was decided to conduct a pilot study. The pilot study involved all three phases of the study (initial questionnaire, synchronous focus group, and post-focus group questionnaire) with two CI users and three CI professionals. This primary purpose of piloting was to assess the questions across all the study phases, the effectiveness of the process, and the clarity of the instructions. Also, the participants were asked if they had any recommendations and whether any part of the study would be done differently to improve the quality.

The piloting led to some changes to the questions and arrangements. For instance, it was decided to rephrase only one question about the anticipated benefit of haptic devices in the initial questionnaire due to irrelevant responses to the question's intended aim. The question was *'Could you please explain and justify how a haptic assistive device can provide benefits to CI users?'*, so it changed to *'In what ways do you anticipate a haptic assistive device could offer benefits to CI users?*' Furthermore, since the questionnaire had not included any unique identification for each participant, the researcher could not track which participants had not completed the questionnaire to send reminders. Thus, it was decided to provide each participant with a unique ID before completing the post-focus group questionnaire. That allowed the data to be anonymised but could be linked to the demographic information in Section 1 of the initial questionnaire. The pilot also allowed the researcher to anticipate the time required for a focus group.

Participants were also asked to give their feedback about the study. Firstly, it was recommended that participants should be offered the option to have a British Sign Language interpreter in the focus group. Second, it was advised to keep the focus group discussion questions visible for the participants in the chat function throughout the focus group. In addition, both CI users and professionals indicated that the number of the live focus group should not exceed five participants per session.

As part of piloting, an independent coder was asked to re-code the first focus group transcription using the coding descriptions, to examine intercoder reliability. A high level of agreement was achieved between coders ($\kappa \approx 0.86$).

The suggested changes were implemented, and an amended version of the ethics application was submitted and approved (Ergo 61075.A1, Appendix K).

6.5 Results

6.5.1 Results of the initial questionnaire:

The initial questionnaire aimed to collect two types of information: (1) demographic information about the participants, which is summarised in the previous tables (Table 4 and Table 5) and (2) contextual information about the hearing challenges experienced by CI users, current assistive techniques and technologies to overcome these challenges and any previous experience with haptic devices. Open-ended questions were used for the latter type to allow participants to express their perspectives without limiting them to choices (See Appendix N to review the actual questions). The responses of the participants were analysed using descriptive statistics.

All participants (n=27) completed the initial questionnaire. In the first question, the respondents were asked to indicate listening difficulties reported by CI users. A total of 12 difficulties were obtained. These difficulties are listed and summarised in Table 11. It is worth noting that the most common difficulty reported by both CI professionals and users was listening in noisy environments.

Table 11. CI users' difficulties reported by CI users and CI professionals.

Challenging listening situations and tasks	Number of CI user responses	Number of professional responses	Percentage of total respondents in each group mentioning each situation	
			CI users	Professionals
Presence of competing noise or speech	10	17	100	100
Calling on the phone	5	8	50	47.06
Lack of visual cues	4	7	40	41.18
Localising and tracking sounds	3	6	30	35.29
Unfamiliar accent and content	3	4	30	23.53
Listening to music	2	10	20	58.82
Online meeting and chat	2	3	20	17.65
Watching TV	2	3	20	17.65
Distance from a speaker	1	5	10	29.41
Listening in reverberant environment	1	5	10	29.41
Listening for extended period	1	4	10	23.53
Rapid communication exchange and demand	0	1	0	5.88

Both groups of participants reported that certain strategies and technologies were useful to overcome these challenges. A total of 13 different technologies and strategies were listed by participants in Table 12. The top technologies and methods reported to overcome hearing difficulties were assistive listening devices and listening strategies.

Table 12. Strategies and technologies listed by CI users and CI professionals to overcome hearing difficulties.

Strategies and technologies to overcome challenges	Number of CI user responses	Number of professional responses	Percentage of total respondents in each group mentioning each technology/strategy	
			CI users	Professionals
Assistive listening devices	7	17	70	100
Listening strategies	3	11	30	64.71
Being open about hearing loss	2	8	20	47.06
Processer maps and settings	2	4	20	23.53
Speech to text	2	7	20	41.18
Sign language	1	1	10	5.88
Bimodal hearing	1	1	10	5.88
CI support groups	1	1	10	5.88
Lip reading	1	4	10	23.53
Looking after health and wellbeing	1	2	10	11.76
Auditory training	0	5	0	29.41
Communication partner training	0	4	0	23.53
Listening breaks	0	3	0	17.65

When the respondents were asked to indicate whether haptic devices can be beneficial for CI users, all responses to this question were positive, and the participants listed 6 potential benefits of using EHS devices by CI users. The majority of those who responded to this item felt that these devices could improve the CI users' localisation skills. Other suggested benefits of haptic stimulation are presented in Table 13.

Table 13. Possible benefits of haptic devices listed by CI users and CI professionals.

Possible benefits of a haptic device	Number of CI user responses	Number of professional responses	Percentage of total respondents in each group mentioning each benefit	
			CI users	Professionals
Improving localisation	6	9	60	52.94
Alerting	6	5	60	29.41
Enhancing speech and sound perception	5	7	50	41.18
Music Enjoyment	2	3	20	17.65
Use when CI not being worn	1	1	10	5.88
Limited CI benefit	0	2	0	11.76

The last part of the initial questionnaire included two questions about the respondents' experience with haptic devices. For CI users, the first question asked whether they had personal experience with devices incorporating haptic stimulation. 70% of the CI users surveyed responded "yes", indicating that most had prior exposure to haptic devices.

For professionals, the question asked whether any of their clients had used devices incorporating haptic stimulation before. In response, 47.06% of professionals responded "yes" to this question about their clients' experience with these types of devices.

For the second question, both groups were asked to list specific devices incorporating haptic stimulation they or their clients had used. Table 14 summarises the devices used incorporating haptic stimulation, for each participant group.

Table 14. The listed devices incorporated with haptic stimulation.

Devices that incorporated haptic stimulation	Number of CI user responses	Number of professional responses	Percentage of total respondents in each group mentioning these devices	
			CI user	Professionals
Vibrotactile pagers	5	7	50	41.18
Vibrating alarm clocks	2	7	20	41.18
Smartwatches	2	2	20	11.76
Vibrating phones	0	2	0	11.76
Musical haptic devices	0	1	0	5.88

6.5.2 Results of the focus groups

This section presents the themes and sub-themes identified from the focus group findings, which are accompanied by supportive quotations. The extracted quotations from the data are shown in italics and placed within quotation marks to distinguish them from the other text. In addition, each quotation is marked by participant number and type for easy reference. Table 15 provides a summary of the used markers.

Table 15. The abbreviations used in quotations to describe participants

Pro-Aud	*Indicates the participant is a professional who is working as an Audiologist.*
Pro-EAud	*Indicates the participant is a professional who is working as an Educational Audiologist.*
Pro-SLT	*Indicates the participant is a professional who is working as a Speech and Language Therapist.*
Pro-TD	*Indicates the participant is a professional who is working as a Teacher of the Deaf.*
Pro-Psy	*Indicates the participant is a professional who is working as a Clinical Psychologist.*
CI-Uni	*Indicates the participant is a cochlear implant user who is unilaterally implanted.*
CI-Bi	*Indicates the participant is a cochlear implant user who is bilaterally implanted.*
CI-LinkedHA	*Indicates the participant is a cochlear implant user who is has a linked hearing aid in the non-implanted ear.*
CI-HA	*Indicates the participant is a cochlear implant user who is has a hearing aid in the non-implanted ear.*

The thematic analysis of focus groups transcription, which involved ten CI users and seventeen CI professionals, produced four key themes: (1) possible benefits of electro-haptic device, (2) candidacy, (3) features and aspects to consider, and (4) inhibiting factors influencing users. These four main themes are divided into thirty-four sub-themes shown in Table 16. Each of the main themes and the sub-themes will be explained in the next subsections with the support of the participants' direct quotes.

Table 16. Focus group's emerged themes and subthemes. The last column indicates which group (professionals or users of CI) the subtheme originated from.

Main themes	Sub-themes	Emerged from
1. Possible benefits of haptic device	1.1. Greater access to sounds	Both groups
	1.2. Maximising speech perception	Both groups
	1.3. Pre-CI tool	Professionals only
	1.4. Reducing listening effort	Professionals only
	1.5. Enhancing sound localisation	Both groups
	1.6. Greater music enjoyment	Both groups
	1.7. Alertness or awareness of sound	Both groups
2. Candidacy	2.1. Alternative option to CI	Professionals only
	2.2. Hearing aid users	Both groups
	2.3. Limited CI benefit	Both groups
	2.4. Not in criteria of CI	Both groups
	2.5. Pre-lingual	Both groups
	2.6. Significant additional disability	Both groups
	2.7. Specific CI users	CI users only
	2.8. Sudden hearing loss	Professionals only
	2.9. Unilaterally implanted subjects	Both groups
3. Features and aspects to consider	3.1. Cost	Both groups
	3.2. Design	Both groups
	3.3. Early introduction	Both groups
	3.4. Funder	Both groups
	3.5. body site	Both groups
	3.6. Practicality and ease of use	Both groups
	3.7. Provide meaningful benefit	Both groups
	3.8. Technological recommendations	Both groups
	3.9. Training and instruction	Professionals only
	3.10. Trial period	Both groups
4. Inhibiting factors influencing users	4.1. Acclimatisation	Both groups
	4.2. Age	Professionals only
	4.3. Complexity of use	Both groups
	4.4. Cosmetics concerns	Both groups
	4.5. Cost if self-funded	Both groups
	4.6. Late introduction of the device	Professionals only
	4.7. Limited benefit	Both groups
	4.8. Sensory overloading	Professionals only

Theme 1: Possible benefits of electro-haptic device

The focus group participants were asked to discuss the potential benefits of the haptic device for CI users. In particular, they addressed seven major aspects described in the following sub-themes: greater access to sounds, maximising speech perception, pre-CI tool, reducing listening effort, enhancing sound localisation, greater music enjoyment, and alert & safety.

Sub-theme 1.1. Greater to access to sounds: During a discussion on the benefits of electro-haptic devices for individuals with CI, both professionals and CI users highlighted that these devices may provide greater access to sound.

'…there's perhaps a chance of picking up some of that information which is actually lacking in the cochlear implant.' Pro-Aud(04)

They believe that this information, in conjunction with other useful information such as lip-reading, can assist individuals with cochlear implants to fill in the gaps of the missing CI information.

"The cochlear implant will give you so much in terms of that sound, but you'll also be needing to use your lipreading and putting it together as if you were putting together a jigsaw puzzle, to work out perhaps what's being said or what sound you can hear. When I was thinking about the haptic device, I think of it, maybe, in those sorts of terms, like it's another piece of the jigsaw puzzle... to give people more of a picture. You're filling in the gaps that cochlear processing on its own gives or bypassing a damaged cochlear" Pro-Psy(1)

Some participants provided specific details about poorly delivered signals by CI. The most common poorly delivered signals mentioned by the participants were low-frequency sounds. Therefore, they believed that the use of electro-haptic devices to transmit these signals could enhance the CI hearing experience.

'The other thing is perhaps to help more with deeper, low frequencies which is something I don't get a lot of from the cochlear implant. High frequencies are brilliant but low frequencies are a bit dampened…would it help with that?' CI-Uni (2)

Others considered the possibility of employing electro-haptic devices to convey particular aspects of speech, such as intonation.

'I don't know if there's different strengths of vibration, but could that be linked to different parts of speech, different functions, someone's intonation' Pro-SLT(3)

Sub-theme 1.2 Maximising speech perception: Several respondents stated that CI users function well in quiet environments. Participants therefore investigated a range of challenging situations in which speech perception becomes a difficult challenge for CI users. So, they thought it would be very helpful if the electro-haptic device could make speech more comprehensible in these challenging situations.

The responses from the initial questionnaire were consistent with the focus group discussion. The majority of CI professionals and users reported that listening to speech in the presence of background noise or multiple speakers were the most significant challenges faced by CI users, as well as listening from a distance away. Hence, they thought that would be beneficial if the haptic devices can aid their hearing in these situations.

'such as is background noise or distance from a speaker' Pro-Aud(7)

Participants were unsure of how this technology might enhance the CI users' ability to perceive speech in such challenging circumstances. Nevertheless, they expressed interest and the believed that any further information may be useful.

'…I don't know how the device would help, but that is one issue on the day out.' Pro-Aud(1)

Sub-theme 1.3 Pre-CI tool: Interestingly, only a few CI professional participants suggested that a electro-haptic device could be a useful tool before implantation, where it is used for CI candidates before/during assessment process. Using an electro-haptic device could also indicate the candidates' dedication to the CI training programme.

'Okay, it might be helpful for us to be able to use it in the assessment process and in the waiting for an implant process who may be going through. Some exercises and get an idea of whether somebody will stick with a training programme' Pro-Aud(2)

Mentioning such a benefit of the electro-haptic device was unexpected. Therefore, the participants were asked to elaborate more on this. A professional expanded that most CI candidates have limited knowledge about the aural rehabilitation programme after the implantation. She further noted that the training procedure for old tactile aids (explained in Section 2.3.2) was similar to the CI training programme and some aspects such as rhythm, pitch, and loudness could be introduced with an electro-haptic device before implantation. It is noteworthy that this professional was one of the professionals who had previously worked with tactile aid users.

'Well, mostly when people come to see us, they won't have an idea of how much effort it will take to learn to work with their implant and a similar kind of programme can be used with vibrotactile aids, and it might be helpful to demonstrate to them the kinds of exercises that it will be useful. Maybe introducing the ideas of things like rhythm and loudness and pitch change and so and so. Introducing a vocabulary to talk about and so they're kind of hitting the ground running by the time they get around to having an implant' Pro-Aud(2).

Another professional suggested electro-haptic devices could be used to provide access to sounds for cases of sudden deafness who are still on the prolonged waiting list for implantation. This could help alleviate the adverse effects of being without access to sound for an extended period.

'People who go suddenly deaf. Particularly now with COVID, if they go a long, long wait to their operation, they can be absolutely in a desperate position. If they could loan for a year or for however long until they get sound, this could be an interim gadget to tide them over.' Pro-SLT(2)

The interim period before the implantation could also be serve a trial period for these potential CI users, who may continue to use the electro-haptic device with their CI in the future.

'It could potentially be used as a trial period pre-cochlear implant to see if they get any benefit and then also get a sense of whether that is a sensation they like and would like to consider in their hearing journey post-implant, so a two-pronged approach.' Pro-Psy(2)

Sub-theme 1.4 Reducing listening effort: Recently, listening effort has become an aspect that attracts hearing rehabilitationists (McGarrigle et al., 2014). Pro-Aud(06) thought that listening effort is not routinely measured in clinics, which is not ideal because such an aspect is important. Two professional participants pointed out that it is possible that using multi-sensory stimulation could potentially minimise the listening effort in certain conditions among CI users, which may be of significant benefit for CI users.

'I think also the other thing it might help with is listening effort. We don't always really measure that. When we measure how somebody does with an implant, we use control tests so that we test in the same situation so that we can see if a person's still doing as well as they were. It is quite difficult to do tests which involve listening effort…that does affect a lot of people with a hearing loss. If the haptic device can reduce in combination with an implant their listening effort, that will probably be a big benefit to them. Even if it's not in every situation, even if it's in just certain situations.' Pro-Aud(6)

However, one participant felt that although multisensory inputs such as auditory and vibrotactile stimulation might not improve test results, they would be beneficial if they reduced listening effort. Furthermore, she did not anticipate that the electro-haptic device's benefits would be comparable to those of bilateral implants. Pro-Aud(3) elaborated on this:

'multiple sensory sources of information can be combined. Maybe not give improved test results, although that does happen but certainly to reduce effort, and it may be something we've been talking about difficult listening conditions. If there's any possibility of reducing listening effort, then that would be a big help there…. the skin doesn't allow as good discrimination maybe for

pitch. For example, so the amount of extrasensory information coming in isn't like having a bilateral implants for example,' Pro-Aud(2)

Sub-theme 1.5 Enhancing sound localisation There was also agreement by both professionals and CI users that the localisation of sound is another issue that CIs struggle with to varying degrees. This issue is more prominent for unilateral CI users. This could potentially be improved with the use of a haptic device. CI-Uni001 expressed difficulties with localisation as a unilateral user and believed that improving this issue might persuade her to obtain the electro-haptic device.

'…definitely localisation because just the one processor. I really have a lot of problems with localisation and that for me would be a quite selling point' CI-Uni(1)

Pro-Aud001 expanded on this issue, and she was wondering whether having a device on both sides of the body can be used for improving localisation.

'if you're wearing two devices, one on each side, for example, I don't know whether that would help with localisation' Pro-Aud(1)

Sub-theme 1.6 Greater music enjoyment: Many CI users reported poor appreciation of music. However, the level of music enjoyment varied among CI users.

'So, a number of our functions that we see struggle quite a bit with music appreciation. For music, some of them do not enjoy it at all, while some of them enjoy all kinds of music.' Pro-Aud(1)

Participants thought that delivering additional information and accessing unheard components of music through skin could improve the musical experience of CI users.

'…. I was thinking about music because of those low pitches I wonder whether it gives some more temporal information depending on the equipment ...' Pro-Aud(1)

During focus group discussions, the potential benefit of using haptic stimulation to enhance music enjoyment for CI users was suggested by a CI user. This participant noted that some pre-lingual patients experience better enjoyment from music by feeling the vibrations.

'… we were saying about music and being able to feel. I'm just thinking like a lot of our prelingual patients that they are saying when they listen to music by vibration and whatever. Anyway, that's how they get the enjoyment. So, it may be more for born deaf patients …' CI-Uni(1)

Sub-theme 1.7 Alertness or awareness of sound: Although many participants indicated that CI had improved users' awareness of sound, they assumed that having electro-haptic devices on top of CI could further enhance users' awareness of sounds, as a result, increase their safety.

'Yes, for safety at home if someone's at the front door or alerting them to any unusual noises or something like that, so they feel a bit more safe in their own home.' Pro-SLT(04)

Their responses about alerting them to sounds and safety ranged from general situations like: *'It could help with alerts to sounds like alarms and doorbell, baby monitors etc.' CI-HA(1)* to more specific like *'Cooking is another one, isn't it? The timer, I can't always hear the timer on the cooker…. To alert you to things like that, that would be good and the smoke alarm, I don't hear the smoke alarm at home either.' CI-Uni(4)*

Other participants from both groups suggested that electro-haptic devices might be able to alert them or reduce the risks at situations when CI are not being worn or cannot be worn.

'You could have it on while you're in the bath or the shower as well as an alert device.' CI-Uni(2)

'I was thinking about safety in terms of at night because they'd have to take the processor off, so they could have that still on wherever it is on their body. If there was a sound in the night that would vibrate, alert them for safety reasons.' Pro-SLT(4). A further example from one of the CI users is*: '' Yes because you'd hear the baby cry in the night, yes that's great' CI-Uni(4)*

Additionally, it was also pointed out that electro-haptic devices may be beneficial for the safety of unilateral CI users who might have difficulty locating sounds, which could endanger them in some circumstances.

'I think it will benefit particularly people who only got a unilateral implant because it might give them some spatial awareness of where the sound is coming from…It helps them with telling where traffic is coming from that sort of thing' Pro-Aud(07)

Theme 2: Candidacy

In the focus groups, participants discussed potential candidates for haptic devices. These candidates were represented by the following subthemes: alternative option to CI, hearing aid users, limited CI benefit, not in CI criteria, pre-lingual deaf, significant additional disability, specific CI users, sudden hearing loss, and unilaterally implanted subjects.

Sub-theme 2.1 Alternative option to CI: A discussion was held about the possibility of using haptic devices instead of CIs, either because surgery was not an option or because the current implant had failed.

'People who can't or don't want to go through a general anaesthetic and an operation might be (interested). It might be another option to offer instead of an implant.' Pro-Aud(2)

'I think it would be helpful for someone that we've recently had whose processor has stopped working completely... If there's something like this in the between time while they're waiting maybe to have reimplant surgery again, that could be useful.' Pro-SLT(4)

Sub-theme 2.2 Hearing aid users: Participants in the study believed the use of haptic devices should not be limited to CI users, but should also be applicable to all hearing-impaired individuals, including those using hearing aids.

'If it did include, I don't know, alerts at night-time when you're not wearing your hearing aids it would potentially be equally viable for a lot of hearing aid users. Then there are more hearing aid users in the world than there are cochlear implant users.' Pro-EAUD(2)

Sub-theme 2.3 Limited CI benefit: Many participants indicated that haptic devices '*may help people who don't get as much benefit from their implant' CI-Uni(6)*. Some professionals, in different focus groups, provided more details about these types of candidates. For example, *'For users where their implant doesn't give them great outcomes for various reasons… maybe they've got poor auditory nerves, maybe there are problems with the cochlea, maybe they're using split arrays for meningitis…. so things that affect outcomes even in quiet. They may only get some information, or maybe a patient who, for various reasons, has had to have a lot of electrodes turned off, or maybe something's gone wrong with their implant, it's not working well, but there's some medical reason or other why they can't have a faulty implant removed and another one put in. It's a small number of people, but different things come up for different patients. Whether for these types of patients a haptic device, could help by helping filling gaps if you like, or provide additional information that maybe they can't get from their implant in the way that maybe most users hopefully can.' Pro-EAud(2)*

Sub-theme 2.4 Not in CI criteria: The participants considered individuals *'who don't fit into … (CI) criteria' Pro-SLT (04)* as potential candidates for haptic devices. These candidates might permanently not fit the criteria of CI due to congenital disorders such as: *'compromised nerves' Pro-TD (01), 'ANSD (auditory neuropathy spectrum disorder) cases', 'absent auditory nerves or no cochlear' Pro-SLT (02).* On the other hand, the participants also discussed the candidacy of subjects who are temporarily ineligible for CI due to their degree of their hearing loss. An example of this is: *'A group of patients we don't see in clinic as much because essentially their hearing loss is too bad for bone conduction hearing aids or a middle ear implant, but they're not quite bad enough (if that's the right word) for a cochlear implant. So, they're a bit in no man's land. Typically, they will have, you know, well a number of them will have a progressive loss - so, they will eventually get to CI, but they will be that period in life where they are neither here nor there. Is*

it something that you might want to consider looking into to see you know (if they might benefit)?' Pro-AUD(1)

Sub-theme 2.5 Pre-lingually deaf individuals: In several focus groups, participants highlighted the consideration of prelingually deaf sign language users for haptic device. An example of the professional comments within this sub-theme: *'I'm thinking particularly for some of the children that are sign language users and we're not expecting them necessarily to get speech that it might help them to be quicker to turn to see who's signing. People aren't very good at getting the information-- alerting people. You'd hope that if there were signers, they'd be a bit beyond that and that people that were signing to them would make sure they got their attention first' Pro-TD (01).* The possible reason of the haptic stimulation benefit for this category of candidates is due to *'relying on additional sensory information' CI-Bi (1*)

Sub-theme 2.6 Significant additional disability: Participants indicated that individuals with additional disabilities in addition to their hearing disability might be candidates for the haptic devices. A number of disabilities were mentioned during the focus groups, including sensory, physical, and learning disabilities.

The most frequently mentioned category of people with disabilities by both CI users and rehabilitationists was '*people with a visual loss' CI-Bi(1*). An example of this category was one of the focus groups participants who is a CI user with visual impairment. She said *'I think for people like me who would benefit more from me being alerted to something that you might not hear because it's too low or too high or whatever. You're warned that there is something coming or someone shouting at you, a noise, would be good' CI-Uni(4).* Generally, the participants indicated that haptic devices could help 'people that don't have as much (sensory) access… to get additional information' CI-Bi(1). Age-related sensory impairment affects everyone, so some participants think '*elderly people would benefit from it haptic devices because even though they've got a cochlear implant, everything else starts to become a little frail, doesn't it, as we get older? Maybe it would be something that retired people, should I say retired folk might get benefit' CI-Uni(5).*

Another professional suggested using haptic devices for individuals with physical disabilities.

'I was thinking of children with quite significant additional disabilities physical disabilities who again with rely on every sense that they have to make sense. You know to be able to be aware of sounds obviously in that situation safety is even bigger Paramount than adults so something. I kind of met, you know, we've had a number of patients where they will not respond to an auditory sound, but then you put some you know, the sound with the feel you see a better reaction, and we're seeing those type of patients more and more.' Pro-Aud(1)

Another professional suggested extending the candidacy of haptic devices to include individual with mental disabilities:

'Adults with learning difficulties, we do have adults with multi-sensory impairments. Also, autistic children, I think would get a good response from it, in my experience. Sorry, it's very broad but yes, kind of looking at additional needs. I think it would be really useful.' Pro-TD(02)

Sub-theme 2.7 Specific CI users: Many users of CI are physically active, so they require greater access sound in order to be able to perform their activities. Consequently, haptic devices would assist them during their activities by maximising their access to sounds.

'Young people may, if they're sports people they may, I don't know.' CI-Uni(4)

Sub-theme 2.8 Sudden hearing loss: Some participants felt that *'patient who has had sudden deafness onset' Pro-SLT(03)* can benefit from haptic devices. Especially with the *'long wait to their operation' Pro-SLT(2),* these candidates *'can be absolutely in a desperate position' Pro-SLT(2).* So, this professional thought *'If they could loan (EHS device) for a year or for however long until they get sound, this could be an interim gadget to tide them over' Pro-SLT(2).* Another professional in a separate focus group suggested '*It might possibly help pre-implant, when people are really struggling, particularly those that maybe have lost their hearing very quickly, so don't just lip-reading skills or other coping mechanisms that might have been developed with more of a progressive loss' Pro-Psy(2)*

Theme 3: Features and aspects to consider

The participants discussed many factors relating to the haptic device's characteristics, and these were seen as necessary for the acceptance and ultimate use of the potential device. The participants focused on ten aspects presented in the following sub-themes: cost, design, early introduction, funder, body site, practicality and ease of use, provide meaningful benefit, technological recommendations, training & instruction, and trial period (see Figure 33 for details about sub-subthemes).

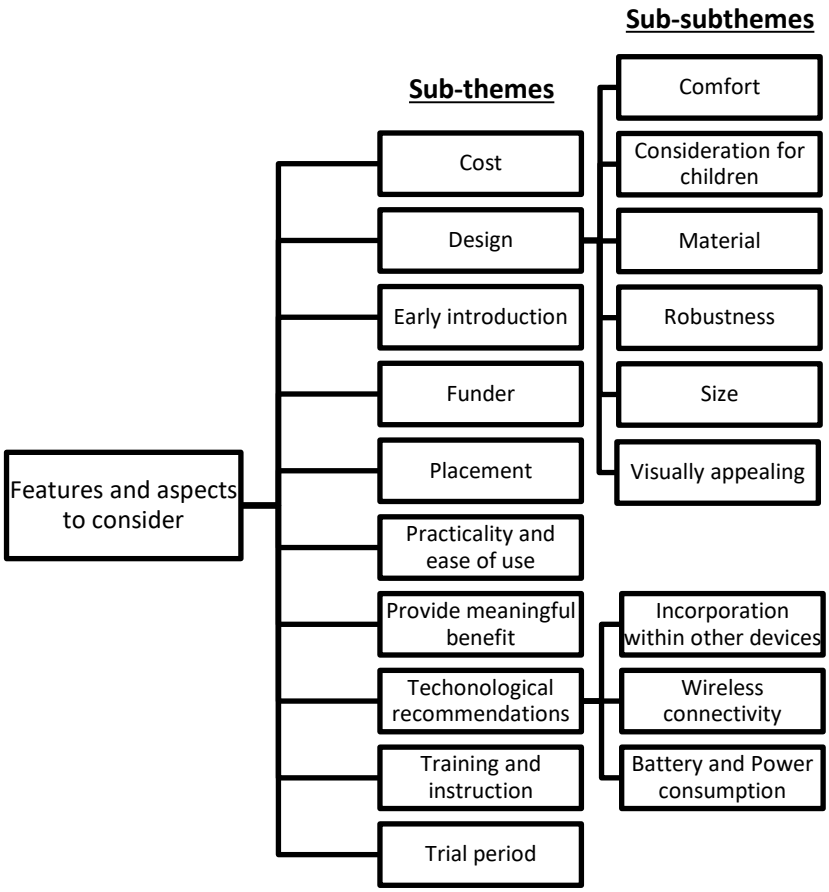

Figure 33. Theme 3 Features and aspects to consider in electro-haptic devices and its subthemes and sub-subthemes.

Subtheme 3.1 Cost: Cost is one of the main concerns with the potential haptic devices. Several participants stressed the affordability of the potential devices when determining the price of the device. The aim is to make the device reasonably priced and accessible to those who need it while still covering the cost of research and production.

'to do it at a reasonable price where you'll cover your costs and the idea is to make some profit, isn't it, to put back into research' CI-Uni(4), 'you wouldn't want it to be a point that only people that can afford it can benefit, if there is a real added addition to the CI users' Pro-Psy (2)

Despite the focus on affordability, participants believe that if the device can offer significant benefits and additional functions as other awareness vibrotactile devices on the market, the price should be within a similar range. This balance between affordability and added value is important in order to provide value for money to user.

'A similar cost to what you would pay for your pager and your environmental aid. People would embrace it as an environmental aid added to their cochlear implant or hearing aid. If it were a similar price, that'd be fantastic' Pro-SLT (02)

Another professional proposed the idea of offering the haptic devices as a complimentary accessory with the cochlear implant kit. This approach would increase the adoption of the technology as more individuals become willing and able to take advantage of its benefits. Additionally, users who receive the haptic device for free as a "one-off" opportunity may become reliant on its functionality, so they might feel compelled to purchase a replacement if it were to break after a period of use.

'It could come as a freebie included with their kits. Then it is a sales pitch really. It draws them in, and then they can't live without it. Then when it breaks after a year because that's when the warranty runs out, then they'll have to buy their own. [laughs]' Pro-TD (01)

Sub-theme 3.2 Design: The design of a haptic device for individuals with hearing impairments can be critical to its usability. Therefore, this sub-theme will discuss the participants feedback related to the design of the haptic device. During focus groups, participants covered several design dimensions such as appearance, comfort, robustness, and material.

Visually appealing and discreet designs are important aspects that were advised to consider when designing haptic device. In order to be visually appealing, a device must have a stylish appearance and be aesthetically pleasing. This can encourage users to use the device regularly and make it more desirable to potential users. Broad examples of this are*: 'I'd like it to be attractive' CI-uni (6), 'to be small and look nice' CI-uni (5), 'to look cosmetically good… to be small and discreet' CI-LinkedHA (1), 'to be small/discreet, not attract attention' CI-Bi (2), 'not too visible' CI-uni (2).* On the other hand, the discreetness of the design was also an important aspect that was discussed by both groups of participants because it might allow users to wear the device comfortably and discreetly without it drawing attention to itself. A way to achieve that is by using subtle colours that do not stand out. Alternatively, many participants were inclined to make the device look like something that other people wear. This can be particularly useful for users who are self-conscious about their hearing loss or who prefer to wear the device in settings where they do not want it to be visible.

'It is the stigma sometimes if you do something that actually looks like it's for a particular disability, people are inclined not to use it or wear it. If it was like a Fitbit, quite modern looking and so you could change the strap to whatever colour you wanted coming into then that would be good. I think that would be very popular.' CI-Uni (04)

‘I suppose it depends on how visible it is. A lot of the hearing aids and cochlear implants are made in the different skin tones. Then if they wanted colour, you can get covers or some of the devices are made in contrasting colours or they are made in hair colour tones so that they are a bit more inconspicuous. I suppose some colour choices might be required’ Pro-TD (01)

‘If it were something like a Fitbit type of thing where you've got your adjustable band and it comes in different colours that probably would be quite good because people would be happy to wear it. It's not an eyesore, it blends in. It looks just like another device. It doesn't stand out and say, "I'm a deaf person" which I think a lot of people worry about’ CI-Uni(04)

The participants were concerned about design comfort, and they thought that it is a crucial element in the design of a haptic device for cochlear implant users. A comfortable design might increase the likelihood that users will wear the device regularly and derive the full benefits of the technology. Ideally, a well-designed device should be comfortable to wear for long periods, including during sleep, when the user needs to be alerted to environmental sounds.

‘Is it going to be comfortable to have on your arm all day long’ Pro-Aud(04)

‘The device could still be worn when they're sleeping it would pick up environment sound maybe, and that would be a comfort if someone called you in the night or something’ Pro-Aud(05)

The importance of comfort can be even greater for individuals who engage in physical activities or fine motor skills, such as sports or writing.

‘I guess the comfort of something on your wrist if you're writing because I suppose a lot of people tend to wear something on their, maybe non-writing arm, potentially maybe their watch. Something that's comfortable enough if you're writing, soft enough to be comfortable but robust enough that it doesn't break’ Pro-Psy(02)

‘I play a lot of sport so would want it to be comfortable and robust’ CI-Bi(2)

I'm thinking about my Fitbit actually. I don't know how you will attach the haptic device, but thinking ‘about the material of the band, if you do a lot of exercise, is it splashproof, waterproof, that kind of thing, safety, what happens if it gets dropped, would that damage it or even if it gets flushed down the toilet. These are things we see often happening with processors’ Pro-SLT(04)

From the previous comments, it is possible to infer that participants expressed interest that a device should be robust, waterproof, and made of a soft material. It is also noteworthy that the reaction of different skin types to the device and materials must be taken into account.

‘I would say it needs to be comfortable to wear. If there's anything uncomfortable or if there's

anything anybody is allergic to, that sort of thing needs to be considered' CI-Uni(02)

'I was thinking about with older people, would you have to consider their skin health as well in a way? Like we do get with the speech processor magnet where it can get sore. You'd maybe have to monitor it. If it is too tight on their wrist, if they're putting it in the same place, or maybe there's instructions about varying it or adjusting it if it's got an adjustable band to put it in a different place the next day or something' Pro-SLT(04)

'Just thinking about skin sensitivity. When patients have allergies, so just thinking about what it's made of is quite important, and whether you have the 'stickies' that stick over if they've got a skin allergy something like that' Pro-SLT(01)

'I get eczema so the material it is made of is important to me' CI-Uni(06)

Sub-theme 3.3 Early introduction: A few participants expressed that it would be advantageous to introduce the haptic device at an earlier stage in the rehabilitation process. Consequently, the user of CI will get a more in-depth grasp of how to use it and become increasingly reliant on the EHS device.

'I think, thinking again about when to introduce the device, if it's something that is introduced from day one, even as being a simple thing… If it's introduced early on it might be taken on as this part this is the core. If you introduce it much later, it just becomes ... well, I'm used to what I'm hearing now. So, we've been thinking about the (other)accessories, we've actually even brought that forward. We used to introduce them at three and even six months at one stage and then there wasn't really a big uptake because patients would have gotten use to functioning with (just) the implant. We've now brought it forward were with some patients even at one week (into tuning) will be already using something. So it's about making it a core, rather than additional' Pro-Aud(01)

A CI user advised that young children with hearing impairments be provided with a haptic device so they can learn to maximise their benefits. It is, however, crucial that the device designer consider how parents can secure EHS devices to prevent them from being lost.

'Children, I'm in two minds about, because the younger you start them, the better. They will learn quickly and they'll grow up with it, but it's how do you get them to wear it, how do you get them to not lose it' CI-Uni(2)

One professional also mentioned including the haptic device into their CI kit. In this way, the user develops some sort of attachment to the device from the beginning.

'It could come as a freebie included with their kits. Then it is a sales pitch really. It draws them in, and then they can't live without it. Then when it breaks after a year, because that's when the warranty runs out, then they'll have to buy their own. [laughs]' Pro-TD(01)

Sub-theme 3.4 Funder: The majority of CI professionals and users who took part thought that government agencies like the National Health Service (NHS) should fund the EHS devices. There are differing opinions about the funding, with some individuals believing that the EHS technology should be funded by the NHS, while others suggest that EHS devices should be funded by local support services, their employers, or be self-funded.

The group that wanted the NHS to fund the device wanted that because they wanted many CI users to benefit from these devices, not just f users who can afford it. Furthermore, they thought it could be selected optionally from the free offered accessories in the CI package.

'I think if it's proven to be clinically cost-effective, then the NHS just might decide it would pick up the cost as a new technology, but you'd have to have the hard evidence of cost-benefit' Pro-Aud(03)

'The NHS should pay for it. It should be part of the kit and the accessories that come with it. It should be funded by the NHS I think' CI-HA(1)

Other participants believe that the device should be supported by local support services or their employers if it is not funded by the government.

'This is a security thing, a safety thing. There is social services, isn't there? Local support services that get involved (help with funding)' Pro-SLT(04)

Interestingly, a few participants suggested that CI users should fund the EHS device themselves, as is the case with other assistive listening devices, as the funding process may take some time.

'Yes, definitely. It should be self-funded. It shouldn't go through the NHS. If we can get a company to cover it, great. If we could get it at cost; better, but it depends what profit they want to make in the company' CI-Uni (2)

'You can buy accessories, so it could be in there as well, couldn't it? The general public could buy it that way' Pro-SLT(03)

Sub-theme 3.5 Body site: There are a variety of reasons why a wearable device may be positioned on one part of the body rather than another. Among the main discussions concerning the design of the haptic device is where on the body it should be worn.

The comments indicate that the ideal location for the EHS device depends on the specific

requirements of the device, such as the level of sensitivity required, device size and the type of information to be delivered.

'So, you might want to think about the whereabouts in the body you would get that spatial separation if you wanted to use a similar sort of delivery for that' Pro-Aud(2)

'it's which bits of the body are better for feeling vibrations?... Different bits of you are going to be able to get more information than others, depending on what it is we want the device to be able to do… if you're trying to capture more sound information to allow, help with recognising different environmental sounds, or certainly for anything linked to speech, then you'd need a much more finer ability sensitivity wise, to be able to pick up that information' Pro-EAud(2)

'In terms of the size, again, with people with different sensory tolerances, it might be worth having a varied size plate, so to speak. The bit that's actually touching the skin might be more beneficial to be a larger surface area for some and a smaller surface area for others' Pro-TD(1)

'So, if you just want localisation, and you just want to know left and right, then it doesn't really matter. Probably could have something on either side of the body that vibrates to tell you which side the sound is coming from, it can be pretty basic.' Pro-EAud(2)

The participants suggested a range of body sites for the device. The most common placements proposed for EHS devices were arms, wrists, necks, heads, fingers, and chests.

Arms were one of the most popular proposed body sites. The popularity of arms placement for haptic devices can be attributed to two reasons. First, *'would work under clothing and then you just put it on and that's it, isn't it? It's not interfering with the watch. It's not interfering with rings or bracelets or anything else' CI-Uni(4). Second, 'You could have two little armbands or something and it will tell you which way to look' Pro-Aud(3)*

Similarly, wrist placement was also another popular choice among participants. This placement allows the device to be worn on either side. Moreover, participants remarked that many individuals are familiar to wearing watches and other types of bands, which could make a wrist-worn haptic device more comfortable and familiar body site. Lastly, the participants assumed wrists to be more sensitive site for haptic stimulation than other places in the arms to transmit haptic stimulation effectively.

'My imagination would be something on the left wrist and the right wrist' Pro-EAud(1)

'I think the wrist option… I suppose the wrist would be possibly be something that adults would like, perhaps, teenagers would like' Pro-TD(2)

'We just sort of assumed it's going to be wrist because of sensitivity… being worn somewhere else that was less obvious that people might feel happier about wearing it' CI-Uni(1)

During the focus group discussions regarding the placement of haptic devices, the fingers were mentioned as a feasible location due to the good sensitivity. The participants advocated a ring-like device as a solution to the issue of practicality in situations where the fingers can be used for other tasks.

'Sensitivity might be good in fingertips, but from a practical point of view, that would be absolutely hopeless in everyday life, I think' Pro-Aud(2). Then several participants mentioned about a device *'like a ring (pointing to finger)' Pro-Aud(5)* to free the fingers for other tasks.

The chest area was another suggested placement to be used for haptic stimulation. The chest area is not a novel place to be used for haptic stimulation since the breastbone was previously used for tactile aids. Participants thought that making a haptic vest that could be worn on the body would be better than strapping it to the breastbone, especially for children.

'Previously we've tried on the spine and on the breastbone. One of the previous devices had seven different buttons, and each corresponded to a frequency range' Pro-Aud(2)

'I suppose you could have a body-worn vest' Pro-019. However another participant *'don't think an adult would wear a vest type thing' Pro-Aud(7)*

In some focus groups, participants recommended placing haptic devices closer to the ears, such as on the head, ears, or neck. Providing haptic stimulation from these sites is thought to be more intuitive and natural than receiving haptic stimulation from other body sites, as haptic feedback corresponds to the sounds occurring in the same area as the organ of hearing.

'When you get bone conduction aids… people have like bone conduction headphones, obviously, that's to do with hearing, because it sends vibrations through the bone to the ear, but I don't know if there's something haptic wise, that could make use so that you could wear around your head or your neck or something that would give you vibration stuff that went with what you were hearing rather than listen from your wrist' Pro-EAud(2)

'What about something like you the "Adhear" device that they got for bone conduction hearing instruments… something like that just sticks on each side (pointing to left and right mastoid). Would that give you something discreet just behind the ear, and really small, that would take the place really of the ear, the pinnas, or just behind? I don't know whether that would be feasible to get it small enough to be there because that would make more sense than being on the arms, really, wouldn't it? Then you got the issue of clothes and sleeves and stuff if it's on the arms, and

it's not really where hearing is designed to be. It's not designed to be on the head' Pro-SLT(2)

Others suggested that the device could also be placed in a more discreet area near the ears. For example, it is possible to deliver haptic stimulation to the mastoid through the sleeves in the battery compartment for CIs or hearing aids. Another participant suggested the use of haptic earbud devices inside the ear canal but questioned whether users would be bothered by this.

'If you're talking about cochlear implant users or hearing aid users, if you could add it on the inside on the sleeve of the battery compartment or something, so it's just touching the mastoid but very, very discreet and it's just on the battery sleeve' Pro-SLT(2)

'Oh, that makes you think about wireless earbuds even and whether-- I don't know whether it-- Or that would drive you absolutely potty wouldn't it? I mean it's vibrating in your ear canal' Pro-Aud(3)

Sub-theme 3.6 Practicality and ease of use: The participants agreed that the haptic device must be functional and easy to use for it to be adopted by users. Otherwise, it will be left unused due to its complexity, as is the case with many other devices they received with the CI package.

'Yeah, that's fine. I was only gonna really say the same thing Pro-Aud(2) was saying about the technology. People you know, they just say [sigh] I can't open all those boxes and wherever they're in my kit and whatever, there's just too much. You know, you ask people, well, have you used your mini mic. Did you get that certain goal? I don't know. I've not looked in the kit. So yeah, if it's too technical, a lot of people won't want to know, just fear. I'm frightened of it all. Yeah.' CI-Uni(1)

Although some of the owned devices were straightforward to use, participants thought that the lack of instruction or training may have contributed to their non-usage. Therefore, it was suggested that a proper demonstration should be conducted to illustrate the simplicity of use to the user.

'I think it comes back to the ease of use really, doesn't it? If people can be reassured that it's easy to use and by that, I don't mean people saying, "Oh, here's this new technology. It's very easy to use." Because a lot of people will say, "Well, you're saying that, but I don't know if that's really the case." It really means demonstrating that it's easy to use rather than just telling people it's easy to use' Pro-Aud(06)

Other participants, however, held the view that technological complexity should be an available option to some users, as certain individuals are proficient with technology and may appreciate using a more advanced settings when operating the device.

'It might be a lot to take on board and I guess making it like we were saying, maybe as simple as possible for some, but the opportunity to have other features later down the line, or if somebody is particularly technical' Pro-Psy(2)

One participant gave an example of old tactile aids and that they were too complicated for many users, resulting in large usage rates. Thus, ease of use is a crucial aspect to consider in the development of any potential haptic device.

'Previously with previous commercially available devices. that was hard connection… about 20% used it for most of the day' Pro-Aud(2)

Sub-theme 3.7 Provide meaningful benefit: It was indicated that device's benefits are the most convincing aspect when it comes to persuading CI users to justify the inconvenience of wearing an additional device. So, the device has *'Got to get good benefit. Otherwise life's too busy' Pro-SLT(1)*

'I think the biggest thing would be how what benefit do they get? if you get big benefits, the downsides of how to wear it where to wear it the cumbersome aspect of something else goes down is the out if the impact is not as big then. they're going to think or do I really want to be wearing this for such a small benefit. So personally, I think the benefit is the biggest thing. was even if it was the smallest thing in the world if you don't really get much benefit you will forget about it.' Pro-Aud(1)

'…you know a big benefit from this to have to wear... It's got to have a really obvious benefit, and it's got to be something to me…' CI-Uni(1)

Pro-Aud(2) had experience with tactile aid users, and observed that only a low percentage of them used the device for most of the day due to the lack of the perceived benefits. Thus, it is imperative to make sure the new haptic device provides tangible benefits to the user so that consistent use is likely to occur.

'I've worked with people who've used vibrotactile aids when we had to look at commercially available devices. Of that group, about 20% used it for most of the day. So, for somebody who liked it and was getting information from it that was useful to them and it was too much of a faff' Pro-Aud(2)

Sub-theme 3.8 Technical recommendations: Specifically, this sub-theme examines technological advancements that may enhance the adoption of devices, and it is divided into five sub-subthemes. The five sub-subthemes are integrated devices, wireless connectivity, power consumption, number of channels, and tuneable vibration.

The majority of participants were concerned about wearing a variety of devices at the same time. Therefore, they strongly advised that incorporating the haptic device within other devices might be more convenient than having each device standalone. Participants believe that this would make the device more appealing to users and increase its use, as it would no longer require the user to wear an additional item. Many participants favoured the integration of a haptic device into smartwatches.

'I think, given the fact that we're heading down that route of having multifunction devices, if you had one that additionally was able to give you vibrotactile stimulation in order to perceive a sound signal, that you otherwise wouldn't be able to access, I think it would be great to incorporate it in one of those rather than having to have a second device because I suspect that for a lot of people actually, what they're wearing on their wrist is quite important to them and they wouldn't necessarily want to give that up. They also, I think, would probably find it too difficult to wear two devices on one wrist' Pro-Aud(4)

However, few participants suggested including the device within the CI processer in order to eliminate the need for carrying any additional devices.

'It would like be nice if it is part of the speech processor - then it's not another thing to wear' CI-Uni(5)

'I think in an Ideal world nearly either Incorporated in watch of some sort or even better incorporated within attached to, um, the processor or Itself, so you're not limiting whether someone has extra, you know the watch what type of watch it is. That's yeah, I think you should think about' Pro-Aud(1)

Mentioning this expanded the discussion to include the connection of haptic devices with other devices such as CIs, alert systems, mobile phones, etc. This connection could be used to access other components of devices or access other information. However, the CI manufacturer may have some regulations that prevent the haptic devices from being linked to the CI components unless the haptic devices were sponsored by the CI manufacturer. Besides this, participants proposed controlling the EHS device with other devices, such as a smartphone or remote control, in order to facilitate its use.

'There's already that connection between the phone, a watch, and the processor. It's just seeing whether the haptic part of that can go in. That's a very expensive route to take…You want to have some communication, near-field communication between the two, the hearing device and the haptic device because you're not talking about having a microphone on you, as the microphone is the ear. That's capturing the signal, and then that's processed by the implant processor. Then that

initial capture signal may also be processed by the haptic device that's giving those additional cues, whether it's localisation, or the speech envelope or those transitions that I talked about earlier' Pro-EAud(1)

'I suppose the issue as well is going to be what happens with the microphone? Because I can't see any of the cochlear implant manufacturers changing the design of their processors given all the regulation hoops that they have to jump through to allow something else to be linking up with it in terms of the microphone going to something else. They will do it with things Link and CROS aids, so there is some linkage but it's an interesting one in terms of how that would work… Like your microphone on your phone could be used in some situations particularly for environmental sound to alert to Haptic advice. I mean you could do that at night, your phone's plugged in, it hears something goes off and it sends a message to your haptic device.' Pro-EAud(2)

'They're linked up to another alerting system, aren't they?' Pro-Aud(5)

Participants agreed that wireless communication between devices should be used because it allows for the easy transfer of information and data between devices. As a result, this can improve the users' experience with the device, as it reduces the hassle of connecting devices and constrains movement.

'Let's say it's behind the ear, then that sound that's being captured by the hearing devices has then got to talk to the haptic device to say, "Well, this is the signal that I've processed," and give those additional cues and things like that. You've got to get how one talks to the other because you're not going to want to wear it as a wired device. You're not going to want to put a whole coat on, that's going to be haptic stimulation. You want to have some communication, near-field communication between the two, the hearing device and the haptic device because you're not talking about having a microphone on you, as the microphone is the ear' Pro-EAud(1)

The device was again contrasted with the old tactile aids, which had inconvenient hard wire connections. As result, participants stressed the necessity of avoiding such troublesome wiring in the new haptic devices.

'Previously with previous commercially available devices. that was hard connection and I'm presuming that it will be wireless this time and that will make it a huge wearing difference I think to it.' Pro-Aud(2)

The participants thought battery life, type, and consumption of the haptic device were other technical aspects that were equally important. They preferred a long-lasting rechargeable battery that could be charged wirelessly as the device will be used for prolonged periods of time. They

also noted that CI users are already recharging multiple devices daily, including their CI processors and phones, so adding another device could be inconvenient. It is therefore desirable to have a battery with a long lifespan for the device, so that battery charging is not required as frequently.

'if you have something that is switch on and go and that will last for a sensible amount of time before you have to recharge it and so on…' Pro-Aud(2)

'I think that would make it more user friendly than something that you have to charge every night. When you've got your phone plugged in, and you've got your cochlear implant plugged in and then you're going to have to plug something else in and it's all flashing all night [chuckles]. I think if you could make user friendly that way that would be good. I don't know how you were going to power it' CI-Uni(4)

During the discussion, some aspects of the battery and design were suggested for specific age groups, such as very young children and elderly people.

'Whereas I suppose like we have the charging mats, don't we, for phones and things now? We can have something like that for it. I suppose for older people, as well, you know like with the adults who-- I don't know how they do it, I think they're amazing. With their processors are really fiddly, like trying to change microphone covers and batteries, and especially people who've got limited function, hand-wise, and visually too if it can be really…' Pro-TD(2)

'I was just thinking about the power source and how maybe something like disposable batteries, if we're going to give them to children, they have to have a lockable battery drawer. In a way, having something that has maybe a rechargeable battery might just eliminate that being an issue, having to have separate parts and stuff. The idea of having even wireless charging is really cool, but maybe that bumps the price up a bit. I think just the power source is something to consider and how it affects who it's available for because I think for the ADHEAR, for example, the bone conduction one, we can't offer it to very young children or people who would need a lockable battery drawer because it doesn't offer that' Pro-Aud(05)

Sub-theme 3.9 Training and instruction: Participants expected that the brain might need time to learn how to synthesise inputs from the haptic device with the CI processor signal in order to gain benefit from the new haptic signal. They came to this conclusion based on their experience with CI and hearing aid users who needed some time to acclimate to their newly acquired devices. They also thought that a proper guidance program can make it easier and quicker for users to learn how to synthesise this type of input signal.

'You're wanting to give the device with some guidance, a few visual descriptions and notes that

basically say, "Look, here are some things that you're going to need to experience, try these different environments." Because people don't want to go away with a box and something that they slap on the wrist and that's it. They'll need some guidance with it to say, "Use it in these different situations. Try it out when you're picking up your children from school, when you're listening to the radio, when you're in a noisy environment, when you're in a café, when you're going dancing or something like that."…People are going to need to know that because it is about training your brain in a new way of dealing with these signals and synthesising the brain's response from the touch and the electrical sensation of hearing, that it's going to need some work, you're going to have to bring something to the party. It's not just a case of putting it on your wrist and it'll work' Pro-EAud(1)

Sub-theme 3.10 Trial period: In the previous subtheme, it was mentioned that learning this new input signal would take some time. In light of this, participants believe a trial period may be necessary for CI users, especially if the device is self-funded. This is to find out if the haptic device could be beneficial for them and if they could tolerate the haptic signals or not.

'I think a trial is necessary for the cosmetic considerations, knowing if they like the tactile feeling, understanding how it works. I think all of those things - you need to experience or try it to kind of see if it is something that you might find useful. I think that would be quite important with any kind of marketing going forward, that there is a 'try before you buy' sort of option' Pro-Psy(2)

Theme 4: Inhibiting factors influencing users

As part of this theme, participants revealed eight sub-themes related to the barriers to the adoption of potential haptic devices among CI users.

Sub-theme 4.1 Acclimatisation: The participants discussed that haptic users might have high expectations about the devices and expect instant benefit. In such a situation, the device might be rejected by users. Therefore, participants suggested some of the previous aspects to be considered such as proper training, instructions and trial periods to avoid this issue acclimatising to the device.

'If you don't prepare people for that, then they could then decide, "Oh well, I've tried it for a couple of days, I didn't see much benefit. I can't see the point of wearing it." Whereas if you say, "You need to wear this for at least a month before… just for example, before you make your decision as to whether it's beneficial or not"' Pro-Aud(06)

Sub-theme 4.2 Age: The age factor could also hinder the acceptance of haptic devices. Participants specifically mentioned two categories of age groups: young children and teenagers.

Thus, it is important to consider the users' age and social context when developing the haptic devices.

'I think like you say, particularly for teenagers, it might be another thing that stands out from their peers, kind of at the time where you just want to be part of the group' Pro-Psy(2)

'Children having more things for them to wear and to tolerate might be quite a lot for young children. I'm thinking of parents who have to keep processors on, keep haptic devices on, keep everything on, not being lost and charged, and whether actually, it might be more useful to start with the adults or older children' Pro-Psy(2)

Sub-theme 4.3 complexity of use:

A haptic device's complexity may deter some users from purchasing it. Both group of participants in the focus groups indicated that the difficulty of use and complexity were also important factors preventing adoption of the device; *'just the ease of use, particularly for people who are not very tech-savvy. Something that will just work from the time you switch it on would be ideal really' Pro-Aud(1).* Another participant stated *'if it's too technical, a lot of people won't want to know just fear. I'm frightened of it all' CI-Uni(1)*. As a result, both CI users and professionals stressed the need for simplicity and ease-of-use of the haptic device as we discussed in the practicality and ease of use subtheme; otherwise, users might refrain users from having it.

Sub-theme 4.4 Cosmetics concerns: The aesthetics of the haptic device was reported to play a significant role in its wearability. There was a consensus among both group of participants that the design aesthetics of the haptic device are influential factors in determining the adoption of the device; *'it would have to look cosmetically good' CI-Linked HA*. Furthermore, the wearer may also be reluctant to use a haptic device if it stands out and appears to be designed for a hearing-impaired individual; '*It is the stigma sometimes if you do something that actually looks like it's for a particular disability, people are inclined not to use it or wear it' CI-Uni(4).* Also, a few participants from both the professionals and the CI users groups indicated that CI users already wear other accessories on their body such as watches, bracelets that they may not want to replace them with haptic device; *'I suspect that for a lot of people actually, what they're wearing on their wrist is quite important to them and they wouldn't necessarily want to give that up. They also, I think, would probably find it too difficult to wear two devices on one wrist' Pro-Aud(4).*

As a result, the majority of participants from both groups were in favour of discreet designs or haptic devices that can be incorporated into other commonly used devices; *'if there was any possibility of it being worn somewhere else that is less obvious, that people might feel happier about wearing it' CI-Uni(1)*

Sub-theme 4.5 Cost if self-funded: The cost of haptic devices was a concern for both groups of participants if the devices were self-funded; *'If we have to buy it then it must not be expensive 'CI-HA*. Participants compared the price of the haptic device to the existing commercial CI accessories. So, they think the users might buy it because of the benefit based on their financial power, but if the price is exaggerated, they might not be willing to purchase the device.

'if I think about the accessories that companies have had out. XXXXX (CI company) have their accessories at one point around a hundred and eighty pounds and that's a lot for some people that rights them out completely, (Pro-Aud(1) and Pro-Aud(2) nodding heads) but it was affordable for some and they would save up the XXXXX (Another CI company) was between five and eight hundred pound and people were just no. That helps you know it was very few people can say I've got eight hundred pounds to spend on accessory.' Pro-SLT(1).

In addition, the device should be trialed for a period so that the user can experience its benefits. This might motivate the user to buy it rather than paying for something you do not know.

'I would be interested in purchasing it if there was a free period but like with hearing aids. Like to try it and then decide whether to buy it or not unless it was I don't know up to 50 pounds. I wouldn't really be spending more on something. I don't know whether it will work' Pro-Aud(1).

Sub-theme 4.6 Late introduction of the device: According to the professionals, the timing of the device's introduction to the user could impact their adoption; *'If it's introduced early on it might be taken on as this part this is the core. If you introduce it much later, it just becomes ... well, I'm used to what I'm hearing now' Pro-Aud(1).* Other professionals suggested that the device should be introduced even before CI because *'it could be a challenge to get lots of information about their (CI users) processors and a haptic device at the same time' Pro-Psy(2)*

Sub-theme 4.7 Limited benefit: Participants from both groups in the study agreed that the device's lack of benefit is one of the main factors inhibiting adoption. They emphasised that the main motivation for CI users to purchase the device is to receive benefits, otherwise they would not spend money on unnecessary items. A CI participant stated, '*I'm not sure … weather I would wear an additional piece of kit to give me some information which I'm not going to particularly find useful' CI-Bi(1).* In addition, some professionals believe that haptic devices would not be utilised if they did not provide equivalent or superior benefits to other assistive listening technologies; *'it's worthwhile enough to use the second device, that it's got to give them something more than just using the first device on its own. It's got to be really clear to the individual that it is going to give them something above and beyond what they've already got' Pro-Aud(4)*

Sub-theme 4.8 Sensory overloading: CI professionals cautioned that the use of haptic stimulation

may not be suitable for individuals with certain sensory disorders. Several professionals in different focus groups expressed concerns about how other users with neurodevelopmental disorders would react to the device's haptic stimulation such as cerebral palsy and autism cases. *'I'm thinking that children with cerebral palsy, and things like that, and sensory integration problems, and how they would actually tolerate the signal?'* Pro-TD(01). Also, there was some discussion among therapists regarding the possibility that haptic stimulation may not be successful for autistic children due to their increased sensitivity to vibration; *'we have some children, say who are severely autistic and it's just too much. Adding a haptic device isn't going to help in terms of engaging their sensory overload' Pro-EAud(2)*

6.5.3 Results of the post-focus group questionnaire

The main purposes of this post-focus group questionnaire were to allow the respondents the opportunity to make any final comments on the focus groups and to obtain their feedback on an early theoretical EHS device prototype. Data from the questionnaire revealed a wide range of insightful thoughts, suggestions, and recommendations related to the proposed haptic device. Based on the thematic analysis of responses, three key themes emerged: (1) Feedback on the current prototype, (2) aspects to consider in further development, and (3) factors likely to influence uptake. These three main themes are broken down into twenty-six subthemes (Table 17). The following subsections will provide detailed descriptions of the main themes and subthemes based on direct quotes from the participants.

Table 17. The list of themes and subthemes identified in the post-focus group questionnaire. The last column indicates which group (professionals or users of CI) the subtheme originated from.

Main themes	Sub-themes	Emerged from
1. Feedback on the prototype	1.1. Comfort	Both groups
	1.2. Design and cosmetic aspects	Both groups
	1.3. body site	Professionals only
2. Aspects to consider in further development	2.1. Adjustable fitting	Professionals only
	2.2. Batteries	Both groups
	2.3. Control buttons	Both groups
	2.4. Incorporate with other devices	Both groups
	2.5. Material	Both groups
	2.6. Microphone placement	Both groups
	2.7. Safety	Professionals only
	2.8. Visually appealing	Both groups
	2.9. Waterproof or resistant	Both groups
	2.10. Wireless	Professionals only
3. Factors likely to influence uptake	3.1. Benefit	Both groups
	3.2. Clear instruction and training	Professionals only
	3.3. Comfort	Both groups
	3.4. Cost and funder	Both groups
	3.5. Limited CI benefit	Both groups
	3.6. Personality	Professionals only
	3.7. Practicality and ease of use	Both groups
	3.8. Training and instruction	Professionals only
	3.9. Trial period	Both groups
	3.10. Additional needs	Both groups

Theme 1: Feedback on the prototype

The participants focused primarily on four aspects of the proposed prototype, as described in the following sub-themes: comfort, design and cosmetic aspects, and placements.

Sub-theme 1.1 comfort: The feedback gathered about the prototype's comfort was overall positive. The participants found the device to be comfortable due to its size adjustability, light weight, thinness, ventilation holes integrated into the design, and the materials employed in producing the device.

'Good that there are air holes for ventilation' Pro-Aud(6)

'Seems light' Pro-Aud(5); 'it looks thin and comfortable' CI-LinkedHA

'Expandable is good for comfort' pro-Aud(2)

However, many participants were concerned about the comfort of the inner side of the metal buckle, and they thought it was a bit raised which could be uncomfortable and it could irritate the users' skin. Thus, some participants believed that the metal buckle should be smoothed, replaced by a more comfortable material or at least redesigned to avoid discomfort.

'I think the buckle might need to be smooth on the inside, it looks like the underside of the buckle would dig in and feel uncomfortable' Pro-TD(1)

There was one participant who felt that the shape of the shakers could cause pressure points on the skin, especially if worn long-term, which could lead to discomfort over time. Due to this, the pressure and place of vibration applied to the skin by the haptic device need to be adjusted from time to time to avoid having it always vibrate against the same place on the skin. This professional's opinion was based on her experience with bone conduction hearing aids, where the soft band needs to be adjusted from time to time to make the user feel comfortable.

'The shape looks like it might create pressure points on the skin that could become uncomfortable after a while… the band would need to be able to adjust quite a lot… With bone conduction devices that are worn on the head using a softband, users sometimes need to move the softband round slightly so that the device is not always vibrating against the same bit of skin otherwise soreness can develop' Pro-EAud(2)

Sub-theme 1.2 Design and cosmetic aspects: Several attributes were mentioned in participants' responses regarding the prototype's design and aesthetics. A variety of comments appreciated the gender-neutral design look and they considered it visually appealing. Also, participants thought that the device's small and modern design was similar to well-known health trackers, which might not draw others attention to the users' hearing loss. In this way, the haptic device could be easily accepted by users.

'Overall the design looks quite 'futuristic' and not obvious a hearing device so might be quite acceptable to patients who are used to seeing fitbits etc as it wouldn't stick out too much' Pro-Aud(3)

CI-HA, however, finds the design *'not very visually appealing'.* She also believes it would be better if the device was *'incorporated into a watch or piece of jewellery or... worn more discreetly'.*

Sub-theme 1.3 body site: One participant highlighted that the placement of the prototype on the wrist *'seems quite practical and acceptable' Pro-Aud(3)*

Theme 2 Aspects to consider in further development

Participants provided various suggestions for further developing the prototype as part of the feedback process. A total of twelve subthemes were proposed to improve the prototype including: adjustability, batteries, control buttons, integration with other devices, material, microphone placement, pricing, safety, visual appeal, waterproofness or resistance, wearability, and type of connectivity.

Sub-theme 2.1 Adjustability: On multiple occasions in this study, participants stressed the importance of adjustability, although the prototype was adjustable; *'It would be important that the device could be tightened so it fits close to the skin (or more loosely as desired if this wouldn't interfere with the functioning of the device)' Pro-Psy(1)*

Sub-theme 2.2 Batteries: Among the most important considerations for participants of the future device are the battery life and type of battery (disposable or rechargeable). The participants posed questions.

'How is the device going to be powered and how long would it be able to go between charges?' Pro-Eaud(2)

'Are the batteries rechargeable or disposable?' Pro-AUD(05)

Sub-theme 2.3 Control buttons: There were differing opinions regarding the inclusion of a control button. Two participants thought the inclusion of a button necessary for controlling the device and turning it on and off; *'There appear to be no controls on the device to adjust settings or turn on and off. It would be good to know what user controls there will be' Pro-Aud(6).* On the other hand, another participant appreciated the absence of buttons on the device; *'The device does not appear to have any buttons on it, which is good because some elderly patients can really struggle with fiddly buttons. Also, this would avoid any buttons or settings accidentally being knocked and changed' Pro-Aud(5)*

Sub-theme 2.4 Incorporate with other devices: Similar to the focus groups, this subtheme also featured on the post-focus group questionnaire for further development. Several participants recommended *'incorporating it into a watch, a piece of jewellery, or a device that can be worn more discreetly' CI-Uni(1).* Otherwise, the haptic device will prevent users from wearing their important items alongside the haptic device; *'Some people may be concerned that they will not be able to wear other wrist devices or may limit the use of the haptic device so they can use other wrist devices' Pro-Aud(6).* There was also a suggestion that the haptic device should incorporate

features of other devices that may be worn in the same location; *'if it incorporated a step count and heart rate monitor I think it might catch on!' CI-Bi(1).*

Sub-theme 2.5 Material: The participants provided some key aspects of the materials intended for the haptic device. Therefore, many respondents emphasised the necessity of using durable, flexible, easy-to-clean, recyclable, and waterproof materials.

Sub-theme 2.6 Microphone placement: Several respondents expressed concern regarding the location of the microphone, as if it was integrated with the haptic device. This may lead to problems in picking up sound, especially when moving the hand for daily tasks or when wearing a long sleeve; *'If the microphone is built into the device then that won't work if it's up someone's sleeve' CI-Uni(2). In order to avoid this, 'presumably there has to be some sort of external microphone somewhere so how are signals picked up and routed to the device? It would need to be wireless transmission' Pro-EAud(2)*

Sub-theme 2.7 Safety: '*May need to consider lockable fixtures if the batteries are disposable as batteries can be fatal if swallowed - a consideration for patients who are around young children' Pro-Aud(5).*

Sub-theme 2.8 Visually appealing: Several suggestions were made to make the device more visually appealing. A few respondents preferred a more discreet device. This could be achieved by *'incorporating into a watch or piece of jewellery' CI-Uni(1)*, making the device *"smaller and invisible' CI-Uni(2)*, or *'choosing colours that blend with their skin tones' Pro-SLT(3)*.

Sub-theme 2.9 Waterproof or resistant: Many participants expressed a desire for a waterproof device in their responses to the questionnaire; *'Will the device be waterproof so that the user will not have to remove it to wash their hands for example? This may be especially important if the user works in health care or food preparation and has to wash their hands frequently' Pro-09.* Another participant stated: *'I wondered if I could swim with it. I do a lot of sports, and it's a pain needing to take things off' CI-Bi(2)*

Sub-theme 2.10 Wireless: In this study, there was a clear desire for a wireless device, which was also noted in the post-focus group questionnaire as a further development suggestion.

Theme 3 Factors likely to influence uptake

The responses of the participants revealed some of the elements that may influence the adoption of haptic devices. Ten subthemes emerged from these responses: benefit, clear instructions, comfort, cost and funder, limited CI benefit, personality, practicality and ease of use, training, trial period, and other additional needs.

Sub-theme 3.1 Benefit: One of the main factors influencing the adoption of a device is the benefit it offers CI users. Most of the participants once again stressed that without adequate benefits, the device might be left unused; *'I think that if it added a significant benefit on top of their CI then they would be likely to wear it.' Pro-Psy(2)*

Sub-theme 3.2 Clear instruction and training: The professional participants proposed providing the device's users with clear instructions, proper training, and proper support in order to enhance the device's adoption; *'They would need to be clear about the benefits and limitations and maybe have some training to understand these in practice' Pro-SLT(2)*. In addition, this process should continue until the users are able to adequately utilise the device; *'Support during the 'getting used to it' phase is important' Pro-Aud(2)*

Sub-theme 3.3 Comfort: Users and professionals agreed that physical comfort is crucial for the device's acceptability. Considering the device will be worn during sleep, one participant believed it should not only be comfortable during the day but also at night; *'I can imagine patients being interested in alerting to environmental sounds at night, but not sure how comfortable it would be to wear at night' Pro-Aud(3)*

Sub-theme 3.4 Cost and funder: The post-focus group questionnaire responses also pointed out that the cost and funding sources of haptic devices could affect users' adoption. The participants believed that if the device were funded by the NHS, it would be more likely to be adopted. Alternatively, the low cost may motivate CI users to purchase the device.

Sub-theme 3.5 Limited CI benefit: Individuals with limited CI benefit may be more likely to adopt the haptic device than those with greater CI benefits because it might help them locate sounds and become aware of ambient sounds. The participants specifically mentioned two types of CI users with limited benefits; *'I think this would appeal to adult patients who are unilaterally implanted as it may improve their localisation ability. This may also be of benefit to newly-implanted patients as they are adapting to the sound of their CI' Pro-AUD(5)*

Sub-theme 3.6 Personality: The personalities and thinking styles of individuals differ by nature. Thus, the participants believed that the haptic device might be accepted more readily if the CI user has a certain personality. For instance, there are those users who can readily adapt to change; *'I think CI users would give it a try, they are already the type of people who have dealt with* change' *Pro-TD(1).* Furthermore, it is how CI users perceive themselves and their lifestyles varies, which impacts the adoption of the haptic device; *'I would think that there would be a variety of responses which would reflect the individual, their personality and how they view themselves and what they would want to have to assist them with their hearing loss' Pro-SLT(4)*.

Sub-theme 3.7 Practicality and ease of use: Practicality and usability were also emphasised in the questionnaire by the respondents. It was believed that the device's ease of use and practicality would have a significant impact on its adoption. Among the practical difficulties that were explored by a number of experts was the issue of senior users who may find it difficult to use complex technical devices; *'One thing to consider is how easy it is to put on - in particular, elderly people can struggle with fiddly devices and often live alone so need to be able to operate a device independently' Pro-Aud(5)*

Sub-theme 3.8 Trial period: Several respondents mentioned the possibility of trying out a haptic device before making a purchase as a factor in increasing device adoption. This is due to the fact that users want to know how much benefit they will receive from the device before purchasing it; *' A trial period with such a device, I'm sure, would help people to consider whether it would be worth them purchasing/wearing, as otherwise, it may be difficult to know how much it could benefit them over and above their CI, for example' Pro-Psy(1)*

Sub-theme 3.8 Additional needs: The need for additional hearing assistance might be greater for individuals with multiple sensory loss. As a result, the device may gain popularity among these individuals because it may enhance their hearing and safety. Several participants mentioned in the questionnaire that people with dual sensory loss would be good candidates for the new haptic device; *'Would depend on how much extra sensory information they needed - so CI users with a dual sensory loss or users who want an extra sensory dimension' CI-Bi(2)*

6.6 Discussion

The aim of this multi-method study was to explore CI users' and professionals' perspectives and recommendations regarding electro-haptic devices and to obtain their feedback on an early hypothetical EHS prototype. The study consists of three phases, and each phase aimed to capture specific information from the participants. In phase 1, information was collected about cochlear implant users' hearing challenges and the assistive devices used to overcome them. As part of phase 2, feedback from CI professionals and users was gathered in order to inform the development of electro-haptic device that might more effectively address some of these challenges. Lastly phase 3 obtained participants feedback on theoretical EHS device prototype. To the best of the researcher's knowledge, this study represents the first qualitative investigation of CI users' and professionals' perspectives on EHS devices.

6.6.1 Phase 1

This phase's objective was to collect information regarding cochlear implant users' hearing difficulties and the assistive devices used to overcome them. Information was gathered via an open-ended questionnaire. Using this type of questionnaire has been helpful in identifying the problems and challenges faced by those with hearing loss, as well as the strategies for overcoming these challenges (Barcham and Stephens, 1980, Hallberg and Carlsson, 1991, Hallberg and Carlsson, 1993, Hétu et al., 1988, Lormore and Stephens, 1994, Scarinci et al., 2008).

Both professionals and users of CI listed a wide range of challenging listening situations and tasks in the questionnaire. Among these challenges are difficulties associated with live speech, electronically generated speech (e.g., phone, radio, and TV), and other issues listed in Table 11. The reported challenges are in line with other challenges reported in other literature about difficulties related to CI users (Zhao et al., 1997, Chundu et al., 2014, Stephens et al., 2008, Hunniford et al., 2023). The most commonly listed challenging task faced by CI users in this study, as listed by both groups of participants, was the difficulty in understanding speech in noisy environments or with competing speech. Similarly in Hunniford et al. (2023), Stephens et al. (2008) , and Zhao et al. (1997), CI users also listed hearing in a noisy surroundings as the most significant acoustic and practical limitation of CI. Following listening to speech in noise or competing speech, CI users in this study reported calling on the phone, not having visual cues, and localising and tracking sounds as challenging tasks. Several studies have also shown that listening to electronic speech, such as the telephone and television, is a common difficult task among hearing-impaired people and CI users (Lormore and Stephens, 1994, Zhao et al., 1997, Bai and Stephens, 2005, Anderson et al., 2006).

As part of the questionnaire, CI users and professionals described how the CI users cope with difficulties using a variety of techniques, trainings, programmes on the processor and devices. For both groups of participants, ALDs such as remote microphones, wireless streaming, and other similar devices were discussed were the most frequently listed methods for overcoming hearing difficulties. ALDs are widely known to improve communication for CI users (Anderson et al., 2006, Duke et al., 2016, Harkins and Tucker, 2007, Kim and Kim, 2014, Mehrkian et al., 2019, Nelson et al., 2013, Razza et al., 2017, Schafer Erin et al., 2013), which explains their popularity. Furthermore, listening in noisy environments is one of the most common situations in which hearing aid and implant complained as explained in this section. Some of these studies indicated that the ALDs made speech somewhat or significantly easier in these situations based on the respondents' feedback (Mehrkian et al., 2019, Razza et al., 2017, Schafer Erin et al., 2013). On the other hand, several studies have evaluated the speech-in-noise improvement with remote

microphones, and they showed that remote microphones significantly improved speech-in-noise performance of CI users compared to the CI alone (De Ceulaer et al., 2017, Fitzpatrick et al., 2009, Mehrkian et al., 2019, Razza et al., 2017). This could be one of the main reasons of their popularity for CI users.

The last part of the questionnaire asked participants whether they had used any form of haptic stimulation to reduce the symptoms of hearing impairment in the past. 70% of CI users and 47% of professionals indicated that either themselves (CI users) or their CI clients (CI professionals) have used a device that uses haptic stimulation in some form, including Vibrotactile pagers, smart watches, and mobile phones. Together, this may suggest that CI users were found to have prior experience with haptic devices, although not necessarily with electro-haptic devices specifically. This may suggest that if electro-haptic devices were available, they could potentially be used.

6.6.2 Phase 2

In this phase of the study, CI professionals and users' perspectives about the electro-haptic devices were explored through focus group discussions whereafter thematic analysis was done (as outlined under section 6.3.8). Four main themes emerged from the discussions: potential benefits of electro-haptic devices, their candidacy, important features and aspects, and factors that may inhibit their use. These themes gave rise to a total of thirty-four subthemes, which were outlined in Table 16.

A closer examination of the subthemes revealed several areas of agreement as well as some nuanced differences between the two groups. Both professionals and users recognised similar potential benefits like greater access to sounds, enhanced speech perception, music enjoyment and sound localisation. This alignment indicates both groups see significant potential for haptic devices to improve outcomes. However, professionals emphasised capabilities from a clinical standpoint, while users focused more on practical improvements in their daily lives. This suggests that while the goals are aligned, the perspectives differ based on priorities.

Regarding candidacy, both groups agreed on benefits for hearing aid users and limited CI users. However, professionals considered more niche physiological factors, while users focused on candidacy based on lifestyle needs.

On features, both groups agreed on factors like cost, ease of use, and trial period. However, professionals uniquely emphasised training needs, illuminating a gap between clinical recommendations and users.

With inhibiting factors, both groups recognised challenges like acclimatisation and cosmetic concerns. However, professionals focused more on physiological factors, while users did not. This highlighted divergent clinical versus practical outlooks.

Overall, while there was agreement on the core themes, professionals and users offer complementary perspectives stemming from their distinct viewpoints. Professionals provide specialised expertise on clinical candidacy, appropriate intervention and technical optimisation. Users share crucial experiential insights on practical adoption and quality of life enhancement. A holistic understanding requires integrating both viewpoints.

The four main themes provide a useful framework to discuss the perspectives. The following sections will discuss each theme.

6.6.2.1 Potential benefits of haptic devices

The potential benefits of electro-haptic devices, as identified by participants, have been classified into seven subthemes. These subthemes included: greater access to sounds, maximising speech perception, pre-CI tool, reducing listening effort, enhancing sound localisation, greater music enjoyment, and alertness or awareness of sound.

In review of evidence about CI signals, it has been found that signals can become highly degraded due to limitations in frequency resolution, pitch perception, and dynamic range (Bento et al., 2005, O'Neill et al., 2019, Dincer D'Alessandro and Mancini, 2019). These limitations are the main reason behind issues faced by the CI users. Thus, a growing body of evidence suggested that delivering a variety of poorly transmitted CI signals through haptic stimulation to the skin of CI users can enhance their speech-in-noise performance, sound localisation and music perception. For instance, researchers have shown that haptic stimulation of the amplitude envelope (Fletcher et al., 2020a, Fletcher et al., 2019) or F0 (Ciesla et al., 2019, Huang et al., 2017) information can significantly improve speech-in-noise recognition for CI users. The results of another series of experiments indicate that electro-haptic stimulation may also be used to improve CI users' perception of music (Fletcher et al., 2020c, Huang et al., 2020). In Huang et al. (2020), haptic stimulation of the low-frequency portions of sound to the fingertips was found to significantly improve the melody recognition of CI users. On the other hand, Fletcher et al. (2020c) showed that delivering haptic cues, corresponding to the intensity and frequency of the sound, to different locations along the forearm can improve the reception of pitch in music. Besides the positive effects of haptic stimulation on improving speech-in-noise and music perception, few studies have shown that this haptic can improve the sound localisation for CI users (Fletcher et al., 2020b, Fletcher et al., 2021a).

The haptic stimulation benefits subthemes identified in the current study, which aligns with the findings of previous studies that found that electro-haptic stimulation could improve speech perception (Ciesla et al., 2022, Fletcher et al., 2018, Fletcher et al., 2020a, Fletcher et al., 2019, Huang et al., 2017), music perception (Fletcher et al., 2020c), and sound localisation (Fletcher et al., 2020b). However, the current study has also uncovered additional benefits of haptic stimulation that were not previously reported or evaluated. These additional benefits could contribute to broadening the use of electro-haptic devices. The following paragraphs will explore some of these new insights in more detail, highlighting their significance and potential implications for future research that can be gained from haptic stimulation.

The potential benefits of using electro-haptic devices as a pre-CI tool were only raised by professional participants due to their expertise and understanding of the CI process. These professionals believed that electro-haptic devices can offer two significant advantages for CI candidates. Firstly, the electro-haptic device can serve as a valuable tool in cases of sudden deafness where patients are still waiting for the implantation process or prior to processor activation. In such cases, a electro-haptic device can provide a temporary solution for accessing sound rather than being completely isolated from sound. Particularly during COVID-19, many elective surgical operations were postponed, including CI surgeries (COVIDSurg Collaborative, 2020), leaving many CI candidates without access to sound. As a result, the well-being of those candidates has been severely impacted, and most of these candidates were unable to adapt to changes such as telecommunications and social distancing (Abrar et al., 2021). Furthermore, the interim period may be taken as a trial period for the device, and if the device is found satisfactory, the user may choose to continue using it after implantation. Secondly, haptic devices can also be used as a useful tool to prepare CI candidates for the auditory training process and possibly reveal their rededication to the aural rehabilitation process after implantation. These potential benefits appear logical if similar training patterns, such as those used for the old tactile aids, are followed. The old training methods began with simple sound detections and progressing to increasingly complex discrimination tasks, like those used in current CI aural rehabilitation (Plant, 1995a). Considering the aforementioned benefits, haptic devices may be a valuable tool in the pre-implantation phase.

The use of haptic devices to reduce listening effort was another advantage raised only by professionals. The listening effort has recently received attention from hearing rehabilitationists (McGarrigle et al., 2014). Despite participants believing that the haptic device could potentially reduce listening effort, this is not directly supported by any known evidence. However, studies of multi-sensory integration on normal hearing have shown that audio-visual stimulation can enhance the speech-in-noise performance and reduce listening effort (Fraser et al., 2010, Mishra

et al., 2013, Moradi et al., 2013, Brown et al., 2021). Similarly, a study evaluated the speech intelligibility of 37 CI users and ten normal hearing subjects during COVID-19 and found that the reduction in speech reception threshold due to the loss of visual cues from wearing masks was approximately 5 dB (Sönnichsen et al., 2022). The effect of masking was significantly greater for CI users who rely solely on their CI compared to normal hearing subjects (Sönnichsen et al., 2022). Furthermore, another study investigated the benefit of using multi-sensory stimulation amplitude cues (audiovisual, audio-tactile, and audio-visual-tactile) on speech-in-noise performance at different fixed signal-to-noise ratios for normal hearing subjects, and the results showed that adding any multimodal cues significantly improved speech recognition score compared to audio-only condition, particularly at low SNR (Oh et al., 2022). Additionally, the effects on performance in this study with audio-tactile and audio-visual cues were quite similar. Together these studies could demonstrate a potential effectiveness of haptic device to reduce listening effort as raised in the focus group. However, further studies on the listening efforts required for haptic stimulation for CI users are required to understand its benefit.

Another benefit mentioned by both groups of participants is the ability to be alerted and aware of surrounding sounds with EHS devices. While there are already several devices made for this function the inclusion of this feature in the potential haptic device can be a valuable addition. Furthermore, as CI users may not wear their implants all the time (sleeping, showring, etc.), the haptic device can be used to provide complementary solution for sound awareness while the CI or hearing aids is not in use. Thus, it was helpful to point out that a haptic device can be used for this purpose.

This theme concluded that some of the identified benefits of employing haptic devices for CI users, such as enhancing speech perception in adverse environments, improving sound localisation, and increasing music enjoyment, are consistent with earlier reported research. However, this study also suggested several additional benefits, including using the device as a pre-CI tool, reducing listening effort, and enhancing sound awareness. Those findings can help guide future research directions for haptic devices by reviewing these aspects and designing devices that could be used for these purposes.

6.6.2.2 Candidacy

Participants in focus groups discussed who might benefit from the device. The focus group of end-users identified the types of individuals who may gain more from the use of the haptic device or be attracted by the device. This information could be very valuable so that future research can focus more on these categories of users as potential users for haptic devices and to consider their actual requirements and needs in the design. The majority of those mentioned as potential

candidates for the haptic device were those who were not eligible for CI, had unilateral CI, had limited benefit from CI, or had other disabilities that limited the benefits of CI. In these candidates, any additional information regarding auditory signals would be needed to help improve their hearing.

6.6.2.3 Features and factors influencing the adoption

A crucial step in developing successful new products is determining the features and influential factors of stakeholder. Thus, a better understanding of the potential facilitators, barriers, and preferences that end-users might experience while using the haptic device is important in order to develop a successful device that meets their specific requirements. Based on the focus groups, several related themes and subthemes were identified, and they are listed on Table 16.

Haptic device adoption can be dependent on two main factors: perceived benefits and ease of use. In several studies, perceived usefulness and ease of use have been identified as the most powerful factors for technology adoption (Chuah et al., 2016, Gao et al., 2015, Li et al., 2022). In this study, the majority of participants similarly indicated that perceived usefulness and ease of use could be the primary motivators for increased willingness to utilise the device. In order to ensure the device's benefits, a trial period was recommended to raise awareness of its perceived benefits. Introducing the device early and providing clear instructions can ensure its ease of use.

The focus group discussions in this study revealed that the design of the haptic device is another critical aspect that should be carefully looked at to ensure its acceptance and utilisation. This is consistent with the findings of other studies evaluating other wearable devices, such as smartwatches which have also demonstrated the significance of design as one of the main driver of device adoption and a crucial factor in market success (Hsiao, 2017). To a certain extent, the users should be encouraged to take part throughout the product design process (Morcillo et al., 2020). During the focus group discussions in this study with the end-users, several attributes related to the device’s design were remarked including placements, aesthetic, comfort, size, material and robustness.

It was suggested that the device could be located on the arm, wrist, neck, head, finger, or chest. However, deciding the best location was challenging as it is a subjective aspect and individuals have different preferences. The arms and wrists were one of the mostly mentioned due to their practicality which is consistent with the preferred location of wearable body sensors (Bergmann et al., 2012). Although the majority of participants were not opposed to a visible placement, some participants preferred a more discreet placement due to self-consciousness. Furthermore, gender

may also play a role in placement preferences as female participants expressed concern about wearing the device on wrists where they prefer to wear other accessories.

To address some of these concerns, some participants suggested incorporating the haptic device into other commonly used devices or accessories such as a CI processor, fitness tracker, watch, jewellery etc. to make the device more visually appealing. Additionally, some participants expressed frustration with having to manage multiple devices such as a CI processor, smartwatch, mobile phone. Thus, integrating the haptic device into another device is not only for aesthetic purposes but also can reduce the hassle to manage an extra device. On the other hand, if the device is not integrated, participants preferred an aesthetically appealing design that blends in and does not draw the attention to their hearing impairment. This finding is aligns with prior studies showing that aesthetics and product design are important factors for adoption (Chuah et al., 2016).

The wearing comfort was one of the most mentioned aspects related to the design, as the device might be worn for prolonged periods, and during other daily activities. Research suggests that wearable devices need to be comfortable and they should not interfere with daily activities. (Keogh et al., 2020). Therefore, the size, weight, and materials should be chosen carefully because it could affect comfort of the device.

Accordingly, there is no optimal design body placement nor design due to individual subjectivity, but the designers should strive to create a device that is comfortable and aesthetically appealing to the potential users to improve the adoption of the device.

The focus group’s discussion also offered a variety of technological recommendations. One of these recommendations was the compatibility of the haptic device with other devices such as CI processer or mobile phones to enhance support and functionality. In this way, these devices can complement each other. For instance, the haptic device could exploit components of other devices like microphones, buttons, or use the installed application to control the device. As a study on smartwatches showed complementary products, such as applications, can enhance the device's value and influence consumers' use decisions (Dehghani, 2018). Participants also preferred wireless connectivity between haptic device and other devices such as CI processor and mobile phone though this could be somehow challenging without industry collaboration with others. Another technological concern expressed was related to the batteries. The longer battery life and easy practical charging method were the main recommendations regarding the battery. A waterproof design of the device was also a desirable to appeal users toward using the device. Meeting these technical properties would improve the adoption of the device.

The electro-haptic device's cost was another factor that may influence device adoption. Participants in the study had varying opinions about the cost of the electro-haptic device, but they agreed that a low-cost option would improve the uptake the device. This highlights the importance of considering affordability in the device's design and marketing. However, it is crucial that any cost reductions do not compromise the device's quality and functionality of the device. This is in line with other wearable technology studies that showed cost as a significant adoption influencers (Kim and Shin, 2015). Additionally, many participants suggested that the device be made available as part of the bundle of equipment provided by NHS.

6.6.3 Phase 3

This phase was intended to gather feedback from CI professionals and users regarding a prototype haptic device.

The majority of respondents had positive comments about the prototype's design and aesthetics. Furthermore, the overall feedback regarding the prototype's comfort was favourable, due to the placement, size, weight, and adjustability. However, there was some criticism focused on the buckle's comfort. It is important to note that it can be challenging to accurately predict comfort based on a photograph of a prototype and the device developers should be aware of these concerns and take into consideration.

Respondents noted some aspects that need to be considered in further development and factors that are likely to influence the use of haptic devices in the future. Many of these aspects were discussed in more details during focus groups. The fact that these aspects were mentioned again in the questionnaire would indicate their importance to the end-users. Indeed, this phase has highlighted some feedback, and future requirements of the prototype have been identified that need to be addressed to optimise the full potential of the device.

6.6.4 Limitations and strengths

It is important to point out that this study has some limitations. One limitation is that the sample of participants was primarily composed of CI professionals and users in Southern England, which may limit the generalisability of the findings to the wider United Kingdom (UK) and the rest of the world. This may have been due, in part, to the timing of the study during the peak of the first COVID-19 lockdown, when many people were not working and were experiencing distractions and stress related to the pandemic that made it difficult for them to focus on research participation. It is important to note that the university where the research was conducted has one of the biggest implant service in the south of England, which may have had a role in recruiting participants who

were more motivated to support the research. Additionally, the participants' feedback about the prototype was based on a photograph of the device which may not provide an accurate representation of the user experience since it is a static image.

However, this study has several strengths. One of the strengths is that it included CI users and a range of different CI professionals, not just audiologists, but also other rehabilitationists, which provides a more comprehensive view of the perspectives and experiences of those involved in the CI fields. Moreover, the CI professionals, who work in the same centre, may have also created a comfortable environment for participation in focus groups. Furthermore, the study's inclusive approach to accommodating the needs, preferences, and hearing abilities of CI users is worth noting. By offering both synchronous and asynchronous focus groups, the study ensured that all participants, regardless of their communication needs, were able to provide their valuable insights.

6.7 Conclusion

This qualitative study, the first on this topic, explored the perspectives of CI users and professionals about haptic listening devices for CI users. Several potential advantages of using haptic devices were identified, including maximising speech perception, pre-CI tool, enhancing sound localisation, greater music enjoyment, and alertness and safety. Both groups of participants agreed that perceived benefit, ease of use, design aesthetics, wearing comfort, clear instructions and early introduction were the most important attributes for the device's adoption. Incorporating and delivering haptic stimulation through existing wearable devices was an aesthetic and functional priority. Participants also identified several potential user groups who could benefit most from the technology.

The study highlights the importance of engaging stakeholders in the development process of medical device development, as it can help in identifying potential users' preferences which is important to the success of a new haptic device. Based on these findings, haptic device developers are encouraged to take the identified comments and suggestions onboard to produce a successful product.

Chapter 7 General discussion, conclusion and future work

The aim of this thesis was to enhance our understanding of EHS and optimise its ability to improve speech perception in noisy environments, as well as to gather the perspectives and recommendations of CI users and professionals regarding the technology. In order to achieve this general aim, three secondary aims were pursued through three experiments:

1. Compare the effectiveness of different vibrotactile cues for improving speech-in-noise performance of simulated CI users (Chapter 4);
2. Investigate whether speech-in-noise performance can be improved by administering vibrotactile cues at various body locations (Chapter 5). In addition, this study also assesses the subjective experience of simulated CI users when vibrotactile cues are administered at these body locations.
3. Explore the views and recommendations of CI professionals and CI users to inform the design and development of wearable haptic devices (Chapter 6).

This chapter provides an overview of the findings of this thesis, a general discussion and to suggest future direction of research. Lastly, this chapter will conclude this thesis.

7.1 Overview of the main findings

The first experiment (Chapter 4) aimed to determine the effectiveness of three vibrotactile cues (F0, amplitude envelope, and speech presence) in improving the speech-in-noise performance of NHCIS participants. While significant evidence supports the benefits of vibrotactile cues (F0 or ENV) on the speech-in-noise performance of CI users and NHCIS participants, the aim of this experiment was to distinguish which specific vibrotactile cue is most effective, rather than simply establishing whether any cue works at all. However, the comparison of the benefit in SRT between different vibrotactile cues post-training did not reveal any statistically significant differences. Furthermore, in contrast to other studies that have shown statistically significant benefits from adding F0 and Env vibrotactile cues for CI users and simulated users (Ciesla et al., 2022, Fletcher et al., 2018, Fletcher et al., 2020a, Fletcher et al., 2019, Huang et al., 2017) , the SRT of the NoVib condition post-training was not statistically different from the SRTs obtained with any vibrotactile cues (F0, Env, and SP) in the first experiment. The reasons for the lack of statistical significance could include a type-I error resulting from an inadequate sample size or insufficient/inappropriate training, the presence of outliers, and high variability in the results that

is greater than in the previous studies. Despite the absence of statistical significance, there was a trend toward benefit from some of the cues (F0 and Env) used in the study. The results of this study may make one question whether the non-significant difference between cue findings was correct. Thus, to better understand which of these vibrotactile cues are better for improving speech-in-noise performance, future research should employ a larger sample size and optimise the training regime to reduce cognitive factors and procedural variables, such as the time required to learn and adapt to the use of vibrotactile cues. This would help determine whether the non-significant findings in this experiment were due to methodological limitations or whether they reflect the true nature of the relationship between vibrotactile cues and speech-in-noise performance for NHCIS participants.

The second experiment (Chapter 5) involved two distinctive research questions: (1) to compare the effects of amplitude envelope vibrotactile cues applied to three different locations on the upper limbs (fingertips, wrists, and forearms) on speech-in-noise performance measures, and (2) to compare subjective experiences of the different vibrotactile cue locations. The results of the experiment indicated that vibrotactile cues at different body locations on the arm did not result in any statistically significant differences in SRT between locations. Similarly, the subjective questionnaire did not reveal any significant differences between the three body locations in terms of comfort and perceived benefit. Consistent with the previous EHS research on CI users (Fletcher et al., 2020a, Fletcher et al., 2019, Huang et al., 2017), this study found that vibrotactile cues significantly enhanced the speech-in-noise performance of NHCIS participants compared to the no-vibration condition after training. Therefore, all the evaluated body locations could, in principle, be fitted with effective electro-haptic devices. However, designers may decide to place a wearable electro-haptic device at one body location over another for various reasons, including functionality, practicality, body site capabilities, and appropriate technological components. For example, applying vibrotactile stimulation to certain body locations, such as the arms, may require more powerful shakers due to their higher detection threshold compared to other locations. However, this could result in increased power consumption which may not be practical as it could require more frequent charging or battery changes, ultimately increasing the device's running cost. Also, some body locations, like the fingertips, may have limited design space, which may require smaller technical components that are more complex and expensive. In addition, certain body locations may be more practical to be used on, such as the wrists, because they are easily accessible, do not interfere with the use of the hands for other tasks and are relatively sensitive.

The third study (Chapter 6) was a qualitative study that aimed to explore the ideas and recommendations of CI professionals and users regarding CI listening limitations and the use of

electro-haptic devices as a potential solution. Feedback from CI professionals and users regarding an early theoretical electro-haptic device prototype revealed valuable information for developers of electro-haptic devices. Many challenges associated with CI listening were illustrated by participants, including hearing in a noisy environment, difficulty understanding speech at a distance, sound localisation, and enjoyment of music, and they also described how they overcome some of these difficulties. They also believed that using a haptic device may assist them in overcoming some of these difficulties, as well as other benefits, such as awareness of sound and safety. Furthermore, both groups of participants viewed perceived benefit, ease of use, design aesthetics, wearing comfort, and early introduction as important attributes for adopting the device. Integrating and delivering haptic stimulation via existing wearable devices was suggested as another aesthetic and functional priority. Potential candidates for this technology were suggested including hearing aid users, individuals with limited benefit from CI, those who do not meet the CI criteria, pre-lingual deaf individuals, deaf people with significant additional disabilities, individuals with sudden hearing loss waiting for CI, and unilaterally implanted subjects. Stakeholder engagement in the development of medical devices is an important stage as it integrates potential users' preferences into the process, which is critical to the success and adoption of a new EHS device.

7.2 Discussion

This section will provide an overview of three main areas of discussion regarding EHS: ecological validity, training regime, and cost-effectiveness.

7.2.1 Ecological validity

The ecological validity of a study is the degree to which its results correspond to real-life situations. Many of the previous EHS experiments attempted to improve ecological validity by using naturalistic noises that mimic real-world situations, as well as free-field stimuli while using their CIs and real-time processing haptic cues (Fletcher et al., 2020a, Fletcher et al., 2019). In fact, all of the EHS experimental studies in this thesis (Chapter 4 and 5), and the previous literature provided in 2.3.3, were conducted in controlled environments that removed natural visual cues, such as lipreading that might make the task easier, in order to isolate the EHS-related benefit. These environments are often optimal for listening, with minimal distractions so the subject can concentrate on the task. Even though these laboratory-based paradigms may lack of face validity, meaning they may not accurately simulate real-world situations, researchers are interested to examine haptic cues' effects on a targeted dependent variable in more carefully controlled settings to eliminate confounding variables in the first instance. Thus, future studies could

examine the benefits of EHS using methods with better ecological validity that reflect daily life, such as incorporating self-reported measures and qualitative studies, as well as conducting studies in the field that more accurately reflect daily life experiences. Study 2 of this thesis serves as an example of how incorporating subjective questionnaires in addition to quantitative laboratory-based measures of EHS benefit can provide valuable insights.

7.2.2 Training regime

Training is a crucial aspect of using vibrotactile stimulation to improve speech performance, as discussed in Section 2.3.2 for the old tactile aids and in Section 2.3.3 for EHS. Manufacturers recognised the significance of training and thus recommend customised programs for old tactile aids, taking into consideration the type of aid, user's age, and communication abilities and needs (Galvin et al., 1993, Plant, 1995b, Vergara et al., 1995). For instance, the training program for adults with acquired deafness differs from that of children, as well as the training for deaf-blind children differing from that of sighted children. For effective training of adults, it is essential to follow specific guidelines that involve a combination of analytic and synthetic exercises. Analytic exercises focus on improving the ability to distinguish simple tasks such as phonemes or syllables, while synthetic exercises aim to enhance more challenging tasks using more meaningful materials. Additionally, it is crucial to provide training in both vibrotactile-only tasks and those that require integrating both tactile and visual cues.

One of the concerns with using EHS devices is the level of training required to achieve effective results. Some previous studies on EHS to improve speech-in-noise performance of CI users or NHCIS participants have shown that few sessions of short basic sentences training with vibrotactile cues is crucial to observe benefits with Env vibrotactile cues (Fletcher et al., 2018, Fletcher et al., 2019). However, other studies have observed significant speech-in-noise improvement in applying F0 vibrotactile cues even without any form of training(Ciesla et al., 2019). The authors of one of these studies repeated a similar study to assess the effect of training and found that although there was a significant improvement prior to training with vibrotactile cues, the training significantly enhanced the benefits of F0 vibrotactile cues (Ciesla et al., 2022, Huang et al., 2017). In this thesis, two experimental studies were conducted to improve the speech-in-noise performance of NHCIS participants using similar vibrotactile cues (Env). Although the same setting, equipment, and training paradigm were used for both studies, one study showed significant improvement with vibrotactile cues, while the other did not. The difference between these studies may be attributed to the type of materials used for training. Study 2, which used more challenging IEEE sentences for training and testing, showed benefits, while study 1, which used Matrix sentences for training and IEEE for testing, did not. This could highlight that not

only the time of training is important for observing the vibrotactile benefits but also the type of training and materials could. However, there is a lack of investigation in training area, and there is a need to evaluate different training durations, approaches, and materials to determine the most effective training methods.

Additionally, it was noted in study 2 and several other studies (Fletcher et al., 2018, Fletcher et al., 2019) have reported a high variability in the benefits of EHS between participants after training. For instance, in study 2 the highest improvement in study 2 with vibrotactile was 6.4 dB SNR and the minimum improvement was 0.4 dB SNR. It is unclear which factors caused this variability between participants. However, it is possible that the same training regime may not be suitable for all users. This highlight the possible need for individualised EHS training at clinics, although may be challenging due to factors such as time constraints, and scheduling difficulties. Fortunately, advancements in software applications, artificial intelligence, and machine learning could made it possible to conduct remote training that can analyse the performance of each subject and provide personalised tailored EHS training plans based on that performance in order to maximise the effectiveness of the training. Thus, developing effective artificial intelligence-based training software could be another research area that is needed after understanding the optimal training regime and identifying the factors that may affect the learning process of utilising vibrotactile cues.

7.2.3 Cost effectiveness

In study 3, participants provided feedback on the electro-haptic device, highlighting importance of providing meaningful benefits and commented about the cost aspect of device, as important aspects to encourage the adoption of the device. They also expressed a preference for the EHS device to be funded by NHS to improve affordability and accessibility. This feedback ties into the concept of cost-effectiveness, which refers to the degree to which an intervention (in this case, EHS) provides benefits that outweigh its costs. To determine the cost-effectiveness of EHS devices, policymakers need evidence that the benefits of the device outweigh its extra costs compared to other alternatives. A health intervention's effectiveness is usually measured by standard measures such as health utility-gain, sometimes referred to as incremental gain in quality-of-life (NICE, 2013). These data are then combined with estimations of the additional cost of providing and maintaining the device to determine its incremental cost-effectiveness.

Recently, several studies, including the second study in this thesis, have demonstrated that supplementing CI electric stimulation with haptic stimulation can enhance speech perception in noise (Ciesla et al., 2022, Fletcher et al., 2018, Fletcher et al., 2019, Fletcher et al., 2020a, Huang

et al., 2017), and in other studies, it can enhance pitch perception (Fletcher et al., 2020c), and sound localisation (Fletcher et al., 2020b, Fletcher et al., 2021a). In spite of this evidence supporting the potential effectiveness of EHS, it was observed that the benefit was highly variable between subjects and that not all subjects received this advantage from the additional haptic cues. Moreover, while it was observed in this thesis' experiments and reported in other studies that vibrotactile cues degraded speech-in-noise perception for a few participants, further research is needed to determine the reliability of this observation and to rule out the possibility of chance results due to test-retest error or other factors (Fletcher et al., 2018, Fletcher et al., 2019). Since all experiments were conducted in laboratory environments, it is also unknown what users' perspectives would be and how often they would use EHS devices after trying them for extended durations in real-life situations. However, EHS devices, which are typically planned to be used to supplement electrical stimulation from cochlear implants to improve hearing in challenging tasks such as speech-in-noise, can also serve as an alternative to vibrotactile awareness and safety devices. Therefore, adding such features can increase the benefits and use of the EHS device.

While the cost of EHS devices is still unknown, since they are not yet widely commercially available, experts indicate that the core components like motors, batteries, and signal processing chips are fairly inexpensive (Fletcher and Verschuur, 2021). However, it is expected that the cost of these devices might be similar to available ALDs used by individuals with hearing impairment. Currently, there is only one known commercially available haptic device used as a standalone device: the Neosensory Clarify wristband, designed to improve speech perception through tactile sensation on the wrist (Neosensory, 2022). This device costs around one thousand US dollars. The high price of existing products like the Clarify wristband could be resulted from small-scale production and distribution. If EHS devices were mass-produced, the cost could become comparable hearing aids or other ALDs based on the affordability of the underlying technology. Another potential cost saving aspect of this technology is that EHS devices may not require the intensive clinical fitting and adjustments. However, it is possible that other factors, aside from the cost of the haptic device itself, could impact the price, such as distribution, development, and marketing expenses. These additional costs need consideration when evaluating the overall cost-efficiency of haptic devices.

Although haptic stimulation devices have the potential to be a useful tool for assisting CI users' hearing, a thorough cost-effectiveness analysis is still required. This should be done after overcoming the following issues: (a) assessing the benefits of the device on a representative sample of CI users, including bimodal, unilaterally and bilaterally implanted adults and children; (b) understanding the quality-of-life data associated with the use of EHS devices; (c) collecting

these data from a larger population than previously studied; and (d) knowing the exact cost of the EHS devices and other expenses.

7.3 Recommendation for future research

Despite the fact that a considerable amount of scientific lab-based studies exists regarding the benefits of vibrotactile stimulation for CI users, there are still many gaps in our understanding that could be illuminated by further research.

7.3.1 Effect of different EHS cues on speech-in-noise

Based on the results of the first experiment in this thesis, it is still unclear which vibrotactile cue (F0, amplitude envelope, and speech presence) is most effective in improving speech-in-noise performance for NHCIS, as no statistically significant benefit was observed with any of these cues. This is in contrast to Study 2 in this thesis and previous EHS research. Therefore, further research is needed to investigate the efficacy of different EHS cues, after addressing the limitations identified in the first experiment. Future studies should address the limitations by increasing the sample size, optimising the training regime using speech materials for training that are compatible with those used for testing, and avoiding some design pitfalls, such as testing the different cues on different days. Additionally, it would be beneficial to evaluate the potential benefits of combining multiple cues to enhance speech-in-noise perception.

7.3.2 Effect of adding visual cues on EHS speech-in-noise benefits

In daily life, visual cues can be important for cochlear implant users. For example, lip-reading and facial expression can provide valuable information about what someone is saying especially in noisy environments where it could be difficult to rely only on acoustic information. In studies of users of the obsolete tactile aids, discussed earlier, lipreading skills were significantly improved by integrating tactile stimulation (Geers, 1986, Goldstein and Proctor, 1985, Plant, 1988, Proctor and Goldstein, 1983). Furthermore, multisensory studies have indicated a set of brain regions in humans that integrate visual and tactile information (Gentile et al., 2011). Recent research investigated speech-in-noise perception when multimodal amplitude envelope cues (audio-haptic, audio-visual, and audio-visual-haptic) were associated with auditory signals, and the results showed that adding multimodal cues improved speech perception significantly (Oh et al., 2022). Moreover, integrating all sensory models led to the greatest improvements. However, all the previous EHS research and experiments in this thesis, tested the effect of EHS without including visual cues to the stimuli. Therefore, a future direction for research would be to explore

the potential of incorporating multimodal (audio-haptic-visual) stimuli in experiments to better understand the effects of EHS on speech perception.

7.3.3 Effect of different training regimes on EHS performance for different tasks

Training is a crucial aspect of enhancing EHS performance. However, research shows that there is considerable inter-subject variability in EHS performance within studies, which may be due to the different training approaches used. This one-size-fits-all approach might not work effectively because users may learn the integration of the new multisensory task at different levels. Therefore, the effectiveness of the training program used for EHS depends on various factors such as the type of training provided, and the personal characteristics of the user. However, a comprehensive evaluation of the process of training EHS users for different listening tasks is required to determine the best approach.

In addition, another area of research that can be explored is the use of machine learning and artificial intelligence to develop customized training plans. This approach involves analysing vast amounts of data to identify patterns that can inform the design of personalised training programs for individuals. The algorithms can analyse data on factors such as an individual's age, vibrotactile sensation, or multisensory tasks experience to create a tailored training plan that is more effective for users.

7.3.4 Determine candidacy of EHS devices

While EHS improved the performance of many participants, there was considerable variability in the degree of improvement observed. Some individuals experienced significant gains in speech performance, while others showed little improvement or even a decline in performance for unknown reasons. The factors that may influence EHS users' performance should be examined in greater detail in order to maximise EHS benefits.

Based on the qualitative study in Chapter 6, CI users and professionals suggested a number of candidates who may benefit from EHS devices such as individuals with visual impairments or specific CI users (unilaterally implanted, limited CI benefit, prelingually deafened). It is therefore possible to compare the EHS performance of these individuals to determine the potential benefits of each group of candidates in future studies.

While some research has demonstrated that EHS can benefit individuals of all age groups, including older adults, it is important to investigate and compare EHS performance across different age groups due to the potential impact of age-related changes on vibration sensitivity,

multisensory integration, and learning abilities (Mozolic et al., 2012). Therefore, investigating the differences in EHS effectiveness between various age groups is an important area for further research.

Additionally, the past experiences of individuals may have an impact on their performance in EHS. An example of the potential impact of haptic perception experience can be seen in the study by Fletcher et al. (2019), where one participant showed enhanced speech-in-noise performance without any training, possibly due to their musical experience reliance on touch to play the flute when they were without a CI. Therefore, it is beneficial to investigate these subjects with some haptic perception experience in greater detail.

7.3.5 Utilise ecologically relevant auditory assessments to evaluate the effects of EHS

The majority of the methods previously used, including those in this thesis to evaluate the benefits of EHS, lack ecological validity. These methods usually evaluate how much a change in a precisely controlled independent variable or variables affects a carefully measured dependent variable or variables. Despite their sensitivity to detect hearing impairments, this approach may not accurately reflect an individual's hearing ability in real-life situations where there may be multiple sources of sounds that are not recorded carefully in an anechoic chamber. They may also not account for visual distractions, and multiple sources of background noise. Together, maximal cognitive demands are required, which could make listening more effortful. Additionally for CI users, lipreading and other cues are crucial to communication and should also be considered. Therefore, additional work is required to test EHS benefits using ecologically relevant measures.

Additionally, lab-based measures only provide an objective assessment of EHS users' hearing ability and do not capture how devices are impacting their daily lives or their satisfaction with devices. Therefore, to gain a more comprehensive understanding of the benefits of EHS devices for CI users, self-reported measures, such as questionnaires and interviews, should complement these lab-based measures whenever portable EHS devices are produced. These self-reported measures can identify areas where the devices may need improvement and address issues that may not have been captured in lab-based studies.

7.3.6 Cost-effectiveness evaluation of EHS devices compared with other existing options

EHS has been shown to enhance CI performance in adverse listening conditions and challenging listening tasks in laboratory studies. Other management approaches such as bimodal CI also improved CI users' performance in similar challenging tasks (Balkenhol et al., 2020). For this reason, whenever developers produce EHS devices, a cost-effectiveness analysis should be

conducted to evaluate both the costs and improvements in quality of life that the available interventions can provide. Based on these findings, the authorities, such as NHS, or developers can decide whether they should fund EHS devices or not.

7.4 General conclusions

This thesis aimed to enhance our understanding of EHS and optimise its ability to improve speech perception in noisy environments, as well as gather the perspectives and recommendations of CI users and professionals regarding EHS technology. Three studies were conducted to address this general aim. The first study aimed to determine the most effective vibrotactile cues (amplitude envelope, F0, and speech presence) for improving the speech-in-noise performance of NHCIS participants. While certain trends appeared to demonstrate a positive effect of certain cues, statistical analysis did not demonstrate a significant advantage of any cue over the others, nor did any vibrotactile cue result in significant improvement of speech-in-noise performance compared to the no vibration condition. As this contradicts previous research and the second study of this thesis where some of the utilised cues failed to provide statistically significant improvement in the speech-in-noise performance of CI users and NHCIS participants, future research with a larger sample size and optimised study design is needed to address the unanswered research question about the most effective cues. The second experiment compared the effects of amplitude envelope vibrotactile cues applied to three different locations on the upper limbs (fingertips, wrists, and arms) on speech-in-noise performance measures and subjective experiences of NHCIS participants. The results showed that vibrotactile cues statistically significantly enhanced the speech-in-noise performance of NHCIS participants compared to the no-vibration condition after training, but there was no statistically significant difference in SRT between locations indicating that all the tested body locations could be fitted with effective electro-haptic devices. The third study explored the views and recommendations of cochlear implant professionals and users on the use of electro-haptic devices as a potential solution to some challenges associated with cochlear implant listening. The study identified challenges associated with listening through CI and demonstrated the potential benefits of using electro-haptic devices. The study also provided insight into the attributes necessary for adoption of the EHS devices and potential candidates for this technology.

Overall, this thesis has contributed to the knowledge of EHS and its potential application in improving speech perception in noisy environments for CI listening. The results of the experiments highlighted the importance of developing and optimising the training regime for the use of vibrotactile cues, as well as the need to consider practical and functional factors when designing and placing wearable electro-haptic devices. The qualitative study provided insights into

the potential users' opinions and preferences, which are important for the successful adoption and implementation of EHS technology.

Appendix A : Study 1 and 2- Participant Screening Questionnaire

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Participant Questionnaire

Study Title: Improving Cochlear Implant Listening Using Vibrotactile Stimulation
Researchers: Dr Mark Fletcher and Ahmed Bin Afif
Participant ID:
Please fill in the following questionnaire to determine your eligibility for this experiment. If yes to any of the questions 4 to 7, please give additional details below. All data will be kept confidential.

1. What is your age in years? _____ Years

2. What is your gender? **Male/ Female/ Other**

3. Are you right or left handed? **Left/ Right**

4. Do you suffer from any conditions that might affect your sense of touch? **Yes/ No**

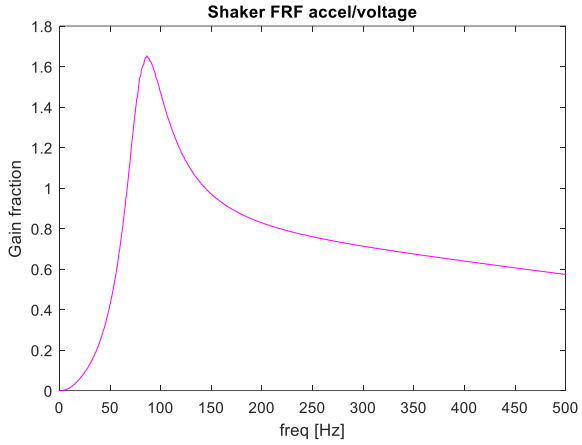
5. Have you had any injury or surgery on your hands? **Yes/ No**

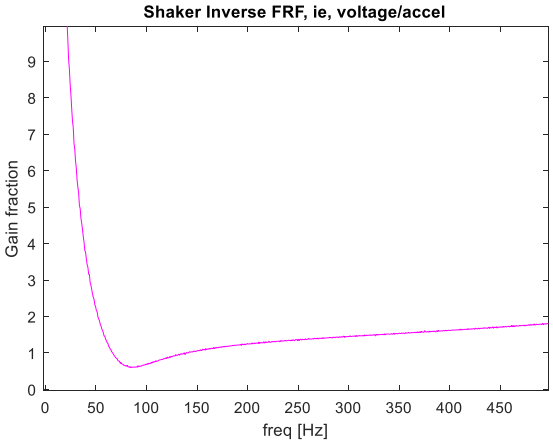
6. Have you been exposed to severe or long periods of hand vibration? **Yes/ No**

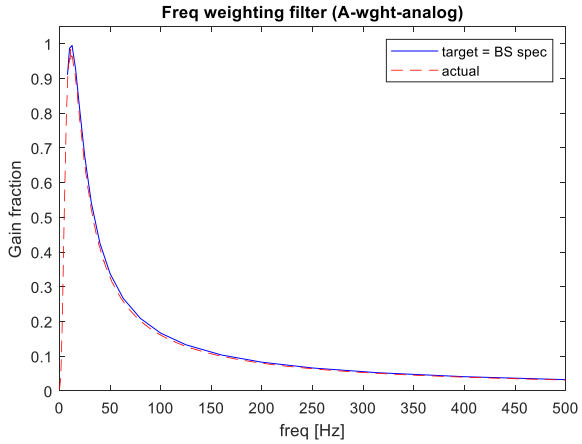
7. Have you had very recent exposure to hand vibration? **Yes/ No**

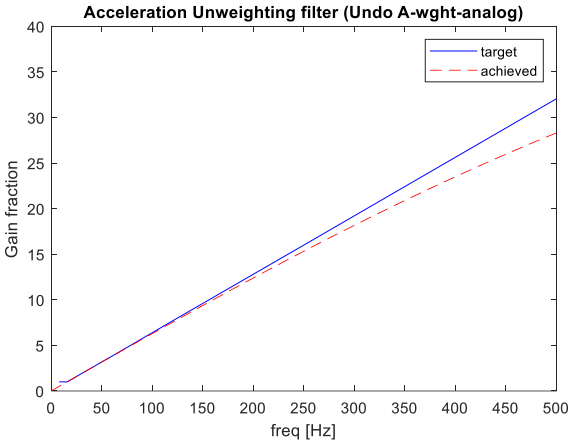
If you have answered "yes" to any of questions 4-7, please give further details below.
Details for Question number (s): _____:

Appendix B Validation of Weighting Filters to Account for the Frequency Response of the Shaker and Vibrotactile Sensitivity









Appendix C: Study 1- Order of Conditions and the Utilised Lists in Each Session.

Participant	Order	Condition	Training 1 (SRT) Matrix	Training 2 (SRT) Matrix	Training 3 IEEE	Testing (SRT) IEEE
P1	1	No Vibration	113	120	D	G
	2	Amp Env	64	118	A	E
	3	F0	68	105	B	F
	4	Speech presence	74	69	C	H
P2	1	Amp Env	59	25	C	H
	2	F0	18	47	B	F
	3	Speech presence	91	81	A	G
	4	No Vibration	17	22	D	E
P3	1	No Vibration	33	83	B	H
	2	Amp Env	66	73	C	F
	3	Speech presence	92	38	D	G
	4	F0	5	76	A	E
P4	1	Amp Env	41	42	A	E
	2	Speech presence	60	49	D	F
	3	F0	48	51	C	H
	4	No Vibration	7	23	B	E
P5	1	No Vibration	67	95	C	H
	2	F0	85	55	D	F
	3	Amp Env	110	12	A	G
	4	Speech presence	82	19	B	E
P6	1	F0	115	57	B	F
	2	Amp Env	56	75	A	H
	3	Speech presence	106	1	D	G
	4	No Vibration	97	10	C	E
P7	1	No Vibration	78	119	A	F
	2	F0	98	79	B	H
	3	Speech presence	31	11	C	E
	4	Amp Env	32	93	D	G
P8	1	F0	77	13	D	G
	2	Speech presence	116	94	C	E
	3	Amp Env	6	36	B	H
	4	No Vibration	86	39	A	F
P9	1	No Vibration	14	87	D	G
	2	Speech presence	100	104	B	H
	3	Amp Env	29	50	C	E
	4	F0	112	108	A	F
P10	1	Speech presence	21	80	A	F
	2	Amp Env	40	24	C	E
	3	F0	53	65	B	H
	4	No Vibration	88	96	D	G
P11	1	No Vibration	112	30	A	E
	2	Speech presence	106	77	C	F
	3	F0	76	47	D	G
	4	Amp Env	103	101	B	H
P12	1	Speech presence	18	66	B	H
	2	F0	93	1	D	G
	3	Amp Env	40	26	C	F
	4	No Vibration	3	104	A	E

Appendix D : Study1- Ethical Approval

UNIVERSITY OF Southampton

ERGO II – Ethics and Research Governance Online https://www.ergo2.soton.ac.uk

Submission ID: 61502
Submission Title: Improving cochlear implant listening by presenting sound information through vibration on the skin
Submitter Name: Ahmed Bin Afif

Your submission has now been approved by the Faculty Ethics Committee. You can begin your research unless you are still awaiting any other reviews or conditions of your approval.

Comments:

- Approved.

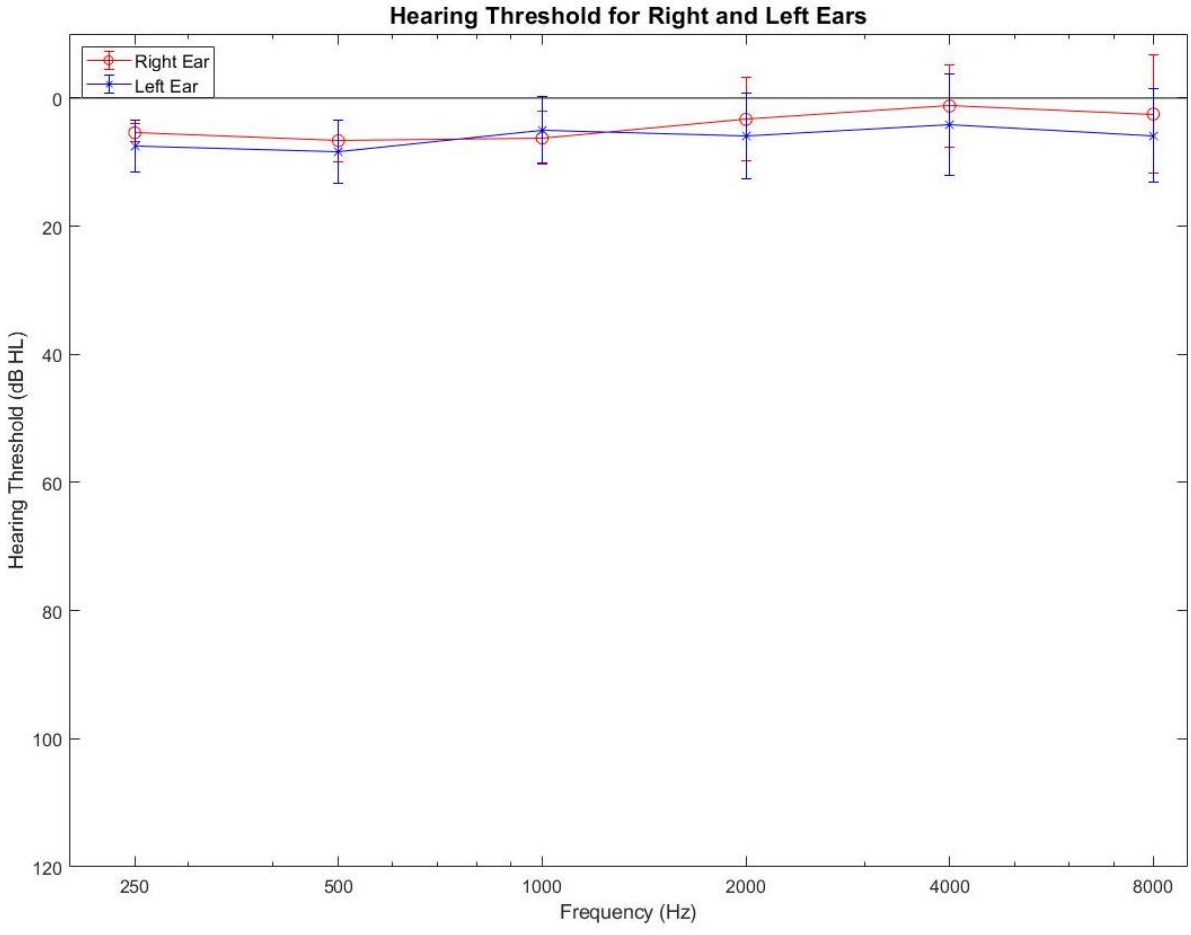
Click here to view the submission

TId: 23011_Email_to_submitter___Approval_from_Faculty_Ethics_committee__cat_B___C_ Id: 326712

aaba1n17@soton.ac.uk coordinator

Appendix E: Study 1- The Demographics and Vibrotactile and Hearing Thresholds of Participants

	Age	Handedness	Gender	Thresholds of the right index (ms^{-2} RMS)		Thresholds of the left index (ms^{-2} RMS)	
				31.5 Hz	125 Hz	31.5 Hz	125 Hz
P01	40	Right	Male	0.162	0.199	0.262	0.269
P02	25	Right	Female	0.1	0.165	0.084	0.366
P03	39	Right	Male	0.137	0.203	0.112	0.236
P04	26	Right	Male	0.16	0.182	0.062	0.114
P05	33	Right	Female	0.16	0.248	0.065	0.062
P06	36	Right	Female	0.245	0.69	0.126	0.32
P07	21	Right	Male	0.106	0.143	0.129	0.177
P08	24	Right	Male	0.176	0.184	0.137	0.174
P09	25	Right	Female	0.089	0.186	0.062	0.117
P10	25	Left	Female	0.038	0.152	0.107	0.177
P11	25	Right	Male	0.196	0.151	0.107	0.149
P12	21	Right	Male	0.095	0.44	0.223	0.628
Mean	28.33			0.14	0.25	0.12	0.23
SD	6.79			0.06	0.16	0.06	0.15



Appendix F : Study 1 and 2- Participant Information Sheet for both studies

Participant Information Sheet

Study title: Improving cochlear implant listening by presenting sound information through vibration on the skin

Researchers: Ahmed Bin Afif, Dr Mark Fletcher, Dr Ben Lineton, Prof. Nicci Campbell

ERGO ID: 61502

Please read this information carefully before deciding to take part in this research. If you are happy to participate you will be asked to sign a consent form.

What is the research about?
This study is part of a PhD project. The aim of this study is to evaluate different speech cues for enhancing the speech-in-noise performance of cochlear implant (CI) listening when they are delivered though vibrotactile stimulation on different body placements (i.e., wrists, fingertips, and forearm).

Why have I been asked to participate?
You have been chosen for this experiment because you are an adult native English speaker who has normal-hearing and report no touch perception issues.

What will happen to me if I take part?
At your first session, you will receive a hearing test, you will also be asked to complete a questionnaire about your touch perception, and a test will be conducted to measure the lowest vibration intensity that you are able to detect. Another hearing test will be conducted to measure the lowest sounds you are able detect. After these screening tests are completed, it is possible that you will not be invited to take part in the study. During the study, you will listen to speech and have small vibrations applied to your body (i.e., wrists, fingertips, and forearms). You will complete no more than 90 minutes of training in each of the experiment condition. Each training session will last no more than an hour. The last training session for each condition will be followed by a testing session.

Are there any benefits in my taking part?
Your participation may lead to the development of new methods to improve cochlear implant listening. You will receive an inconvenience payment of £10 per hour after completing all conditions for your participation.

Are there any risks involved?
There are no anticipated risks to participants. You are free to stop the experiment at any time, without giving a reason, either by removing your hand and arm from the contactor or by informing the experimenter.

The sounds and vibrations you will experience are at levels known to be safe, and fall well below recommended maximum dose values.

What data will be collected?
Measurements of your ability to detect speech-in-noise with or without having vibration cues applied to your skin will be collected. Consent forms will be scanned and the paper copies destroys. All data will be stored anonymously on password- protected university computers.

Will my participation be confidential?
The use of data collected in the study will comply with the Data Protection Act. All data will be stored in an anonymised format. Data will be kept on a password protected computer. Records may be looked at and/or copied for research and regulatory purposes by the University of Southampton. The results of this research may be presented in an anonymous format at meetings or in publications.

What happens if I change my mind?
Your participation in this study is voluntary. You have the right to withdraw from the study at any time without having to give a reason.

What will happen to the results of the research?
Your personal details will remain strictly confidential. Research findings made available in any reports or publications will not include information that can directly identify you without your specific consent.

What happens if something goes wrong?
In the unlikely case of concern or complaint, you should contact the Research Governance Manager at the University of Southampton (02380 595058, rgoinfo@soton.ac.uk).

Where can I get more information?
If you have any questions about the study or your participation in it, you can contact the researchers at aaba1n17@soton.ac.uk (Ahmed Ben Afif) or M.D.Fletcher@soton.ac.uk (Mark Fletcher).

Data Protection Privacy Notice
The University of Southampton conducts research to the highest standards of research integrity. As a publicly-funded organisation, the University has to ensure that it is in the public interest when we use personally-identifiable information about people who have agreed to take part in research. This means that when you agree to take part in a research study, we will use information about you in the ways needed, and for the purposes specified, to conduct and complete the research project. Under data protection law, 'Personal data' means any information that relates to and is capable of identifying a living individual. The University's data protection policy governing the use of personal data by the University can be found on its website (https://www.southampton.ac.uk/legalservices/what-we-do/data-protection-and-foi.page).

This Participant Information Sheet tells you what data will be collected for this project and whether this includes any personal data. Please ask the research team if you have any questions or are unclear what data is being collected about you.

Our privacy notice for research participants provides more information on how the University of Southampton collects and uses your personal data when you take part in one of our research projects and can be found at:
http://www.southampton.ac.uk/assets/sharepoint/intranet/ls/Public/Research%20and%20Integrity%20Privacy%20Notice/Privacy%20Notice%20for%20Research%20Participants.pdf

Any personal data we collect in this study will be used only for the purposes of carrying out our research and will be handled according to the University's policies in line with data protection law. If any personal data is used from which you can be identified directly, it will not be disclosed to anyone else without your consent unless the University of Southampton is required by law to disclose it.

Data protection law requires us to have a valid legal reason ('lawful basis') to process and use your Personal data. The lawful basis for processing personal information in this research study is for the performance of a task carried out in the public interest. Personal data collected for research will not be used for any other purpose.

For the purposes of data protection law, the University of Southampton is the 'Data Controller' for this study, which means that we are responsible for looking after your information and using it properly. The University of Southampton will keep identifiable

information about you for 10 years after the study has finished after which time any link between you and your information will be removed.

To safeguard your rights, we will use the minimum personal data necessary to achieve our research study objectives. Your data protection rights – such as to access, change, or transfer such information - may be limited, however, in order for the research output to be reliable and accurate. The University will not do anything with your personal data that you would not reasonably expect.

If you have any questions about how your personal data is used, or wish to exercise any of your rights, please consult the University's data protection webpage (https://www.southampton.ac.uk/legalservices/what-we-do/data-protection-and-foi.page) where you can make a request using our online form. If you need further assistance, please contact the University's Data Protection Officer (data.protection@soton.ac.uk).

Appendix G : Study 1 and 2- Consent Form for both studies

CONSENT FORM

Study title: Improving cochlear implant listening by presenting sound information through vibration on the skin

Researcher name: Ahmed Bin Afif, Dr Mark Fletcher, Dr Ben Lineton, Prof Nicci Campbell

ERGO ID: 61502

Please initial the box(es) if you agree with the statement(s):

I have read and understood the information sheet and have had the opportunity to ask questions about the study.	
I agree to take part in this research project and agree for my data to be used for the purpose of this study.	
I understand my participation is voluntary and I may withdraw (at any time) for any reason without my participation rights being affected.	
The 'validity' of my consent is conditional upon the University complying with the Data Protection Act and I understand that I can request my details to be removed from this database at any time.	
I agree to allow the researchers to make public the raw data that the researchers collect during this study in a form that is anonymised. I can withdraw this consent at any time in the future by contacting the researchers or the research governance office.	

I understand that should I withdraw from the study then the information collected about me up to this point may still be used for the purposes of achieving the objectives of the study only. I also understand that I will not be directly identified in any reports of the research.

Name of participant (print name)……

Signature of participant……

Date……

Name of researcher (print name)……

Signature of researcher ……

Appendix G

Date……

Appendix H : Study 2- Ethical Approval

From: ERGOII
Sent: 29 October 2021 14:01
To: Ahmed Bin Afif
Subject: Approved by Faculty Ethics Committee - ERGO II 61502.A1

Approved by Faculty Ethics Committee - ERGO II 61502.A1

ERGO II – Ethics and Research Governance Online https://www.ergo2.soton.ac.uk

Submission ID: 61502.A1
Submission Title: Improving cochlear implant listening by presenting sound information through vibration on the skin (Amendment 1)
Submitter Name: Ahmed Bin Afif

Your submission has now been approved by the Faculty Ethics Committee. You can begin your research unless you are still awaiting any other reviews or conditions of your approval.

Comments:

- Approved.

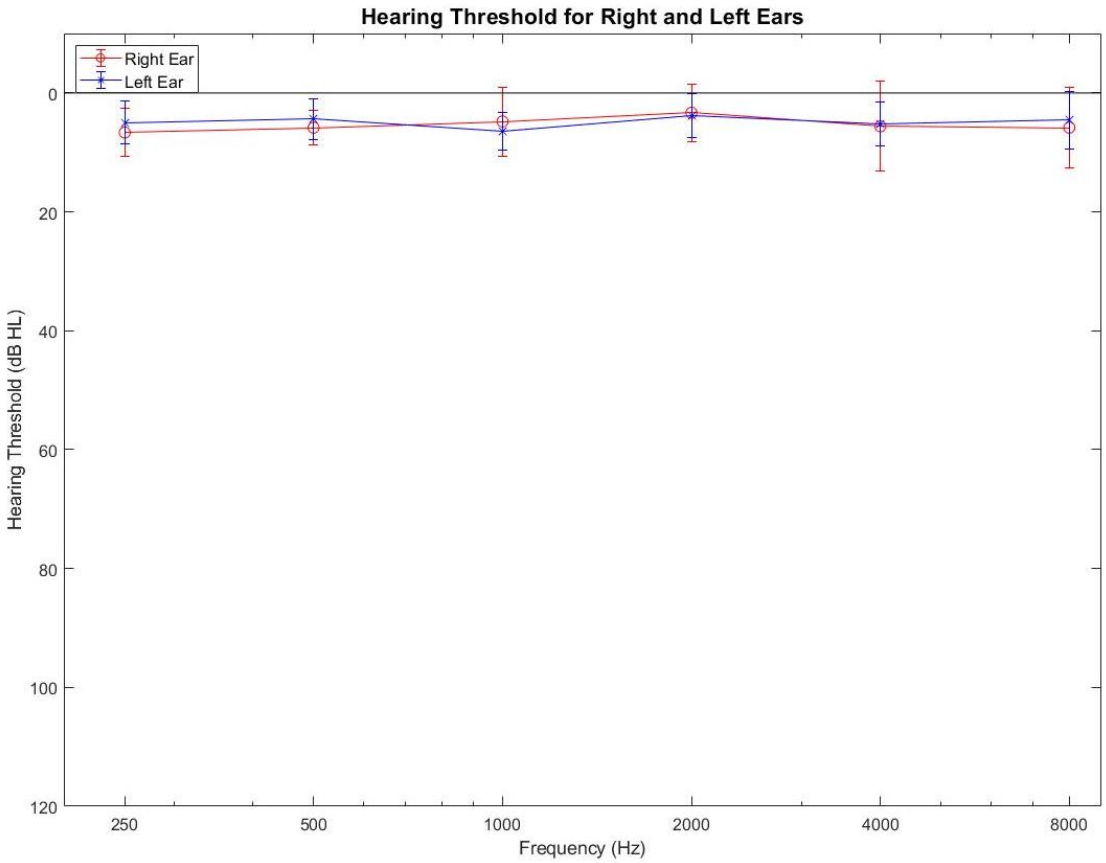
Click here to view the submission

TId: 23011_Email_to_submitter___Approval_from_Faculty_Ethics_committee__cat_B___C_ Id: 422476

aaba1n17@soton.ac.uk coordinator

Appendix I : Study 2- The Demographics and Vibrotactile and Thresholds Participants

	Age	Handedness	Gender	Thresholds of the right index (ms^{-2} RMS)		Thresholds of the left index (ms^{-2} RMS)	
				31.5 Hz	125 Hz	31.5 Hz	125 Hz
P01	22	Right	Male	0.126	0.494	0.126	0.494
P02	19	Right	Male	0.113	0.176	0.113	0.176
P03	24	Right	Male	0.169	0.185	0.169	0.185
P04	20	Left	Female	0.095	0.407	0.095	0.407
P05	29	Right	Male	0.081	0.136	0.081	0.136
P06	20	Left	Male	0.149	0.2	0.149	0.2
P07	24	Right	Female	0.093	0.166	0.093	0.166
P08	34	Right	Male	0.156	0.68	0.156	0.68
P09	20	Left	Male	0.112	0.11	0.112	0.11
P10	21	Right	Male	0.171	0.3	0.171	0.3
P11	19	Right	Female	0.087	0.076	0.087	0.076
P12	33	Right	Female	0.176	0.306	0.176	0.306
P13	20	Left	Male	0.109	0.363	0.109	0.363
P14	19	Right	Female	0.165	0.312	0.165	0.312
P15	25	Right	Female	0.137	0.293	0.137	0.293
P16	35	Right	Male	0.141	0.406	0.141	0.406
P17	21	Right	Male	0.152	0.422	0.152	0.422
P18	18	Right	Female	0.094	0.174	0.094	0.174
P19	18	Right	Female	0.189	0.685	0.189	0.685
P20	18	Right	Male	0.377	0.683	0.377	0.683
P21	18	Right	Male	0.046	0.06	0.046	0.06
P22	19	Right	Female	0.084	0.685	0.084	0.685
P23	19	Left	Male	0.078	0.197	0.078	0.197
P24	18	Right	Female	0.091	0.133	0.091	0.133
Mean	22.21			0.16	0.34	0.13	0.31
SD	5.28			0.11	0.20	0.06	0.20


Hearing Threshold for Right and Left Ears
Right Ear
Left Ear
Hearing Threshold (dB HL)
0
20
40
60
80
100
120
250
500
1000
2000
4000
8000
Frequency (Hz)

Appendix J :Study 2- Post-testing Survey

Vibrotactile Experiment Survey

Please respond to this post-experiment survey about the vibrotactile stimulation of different body placements. The focus of this survey is your opinion on the vibration, not the sitting condition inside the testing room. Your response will provide rich information that will help us to gather variables that need to be considered in the development of the future vibrotactile device

1. Please write your participation number *

Enter your answer

2. How does the vibrotactile stimulation at different placements affect your speech perception performance? *

	makes speech perception much harder	makes speech perception more challenging	makes no difference	makes speech perception a bit easier	makes speech perception much easier
Wrists	○	○	○	○	○
Forearms	○	○	○	○	○
Fingertips	○	○	○	○	○

3. How comfortable is the vibrotactile stimulation at different placements? *

	Uncomfortable	Slightly uncomfortable	Neither comfortable nor uncomfortable	Slightly comfortable	Very comfortable
Wrists	○	○	○	○	○
Forearms	○	○	○	○	○
Fingertips	○	○	○	○	○

4. Are there any other parts of the body that you think it could be considered for the vibrotactile stimulation to potentially aid speech perception? *

- ◯ Yes
- ◯ No

5. If yes, please explain *

Enter your answer

6. Is there any additional comments or information you would like to add?

Enter your answer

Appendix K : Study 3: Ethical Approval

From: ERGOII
Sent: 29 October 2021 14:01
To: Ahmed Bin Afif
Subject: Approved by Faculty Ethics Committee - ERGO II 61502.A1

Approved by Faculty Ethics Committee - ERGO II 61502.A1

ERGO II – Ethics and Research Governance Online https://www.ergo2.soton.ac.uk

Submission ID: 61502.A1
Submission Title: Improving cochlear implant listening by presenting sound information through vibration on the skin (Amendment 1)
Submitter Name: Ahmed Bin Afif

Your submission has now been approved by the Faculty Ethics Committee. You can begin your research unless you are still awaiting any other reviews or conditions of your approval.

Comments:

- Approved.

Click here to view the submission

TId: 23011_Email_to_submitter___Approval_from_Faculty_Ethics_committee__cat_B___C_ Id: 422476

aaba1n17@soton.ac.uk coordinator

Appendix L : Study 3- Participant Information Sheets

L.1 Participant Information Sheets for Cochlear Implant Users

Participant Information Sheet for Cochlear Implant Users

Study Title: The perspectives and recommendations of cochlear implant professionals and users for the development of a wearable haptic device.

Researcher: Ahmed Bin Afif

ERGO number: 61075

Please read the following information carefully before you make your decision. If you are happy to participate, you will be asked to sign a consent form. If anything is unclear or if you need additional information, please do not hesitate to contact Ahmed Bin Afif (aaba1n17@soton.ac.uk).

What is the research about?

This research is part of a PhD project. The aims of this study are to explore the perspectives and experiences of UK cochlear implant (CI) users and professionals concerning:

a) The listening challenges experienced by CI users,
b) The current strategies and assistive technology devices used to minimise listening challenges and
c) The perceived potential value of haptic stimulation (vibration to the skin) and variables that must be considered in the development of a potential haptic device for CI users. Haptic or vibrotactile device is worn on skin, either one or both sides of the body, that picks up speech and sounds in the environment and converts them into gentle vibration that can be felt on the skin.

Why have I been asked to participate?

You have been asked to take part because you are an experienced CI user who is either unilaterally or bilaterally implanted for at least 12 months.

What will happen to me if I take part?

The research comprises three phases:

a) initial questionnaire,
b) focus group discussion and
c) post-focus group questionnaire.

Phase one

Interested participants who sign the consent form electronically will be sent the initial questionnaire via email. The initial questionnaire comprises two sections that might take approximately 10-15 minutes to complete. In the first section, you will be asked to identify your demographics to ensure you meet the eligibility criteria of the research. Eligible participants will be asked to complete section two, which consists of four open-ended questions about hearing challenges, strategies and assistive technologies used to minimise challenges and any experience with haptic devices.

Phase two

When the initial questionnaire is received, the researcher will arrange with you via email the date, time and type of focus group. The invitation email will include some instructions and ground rules that you must read. The discussions will cover recommendations concerning the development of a haptic device for CI users. You will have the choice of taking part in either a live online meeting or a 'bulletin board' discussion. For the live meeting, a British Sign Language interpreter can be offered if required.

The online live meeting will be an approximately one-hour discussion with a small group (3–4) of CI users. With your consent, the discussion will be recorded and anonymously transcribed. After the transcription, the recorded videos will be deleted.

Alternatively, the bulletin board is a discussion forum that enables about ten participants to sign in and post written comments, answer questions and read other posts. This discussion thread will last for one week, and it can be accessed at a time/s convenient to you.

Phase three

In this phase, you will receive a survey that will allow you to add any further comments or thoughts you have on the phase two discussion. You will also be asked to provide your feedback on the design of a haptic device prototype. This survey will take approximately 10-15 minutes to complete.

Are there any benefits in my taking part?

There will be no direct benefit to you as an individual; however, providing your insights in this study will contribute towards the improvement of the potential haptic device and may be of benefit to you and other cochlear implant users in the future.

Are there any risks involved?

There are no anticipated risks to participants who take part in this study. Contact details for the researcher and project supervisors have been included below in the event that you may require any support after taking part in the study.

Ahmed Bin Afif: aaba1n17@soton.ac.uk

Dr.Ben Lineton: Bl@isvr.soton.ac.uk

Prof.Nicci Campbell: N.G.Campbell@soton.ac.uk

Dr.Mark Fletcher: M.D.Fletcher@soton.ac.uk

What data will be collected?

The following is a list of all data obtained by researcher Ahmed Bin Afif:

- Your email address to contact you
- Your demographics (i.e. age, gender, geographic location, hearing loss history, CI device information etc.)
- Your answers to the four open-ended questions about listening challenges among CI users, strategies and assistive technologies used to minimise challenges and any experience with haptic devices among CI users.
- The online focus groups will be video-recorded for subsequent anonymous transcription. Following transcription, the recording will be deleted.
- The contextual data of the bulletin board discussion will be anonymously coded.
- Your answers to the post-focus group survey.

All electronic data will be stored on a password-protected computer in the University of Southampton secure servers. The data will be held in accordance with the University of Southampton policy on data retention.

Will my participation be confidential?

Your participation and the information we gather about you during the study will be kept strictly confidential.

Only research team members and responsible University of Southampton members can access data about you for monitoring purposes and/or perform a study audit to ensure that the work complies with relevant regulations. Individuals from regulatory authorities (people who check we are doing the study properly) who may require access to your data. They all have a responsibility to keep your details strictly confidential as a research participant, strictly confidential.

The research team will not disclose whether you or anyone else have participated in this study. All discussions contextual data will be anonymised. Furthermore, any names of individuals mentioned in during discussions will be replaced with a pseudonym. All electronic data will be stored on a password-protected computer. The data will be held in accordance with University of Southampton policy on data retention. Only the researcher and supervisors will have access to it.

With your consent, the researcher will retain your contact information so that you can be contacted once again in relation with future work on this project. The University's data protection policy governing the use of personal data by the University will apply which can be found on its website (https://www.southampton.ac.uk/legalservices/what-we-do/data-protection-and-foi.page). If at any time you wish to remove your contact details from future-research contact list, you can contact the researcher or the research team at any time.

Do I have to take part?

No, it is entirely up to you to decide whether or not to take part. If you decide you want to take part, you will need to sign a consent form to show you have agreed to take part.

Please contact the researcher (aaba1n17@soton.ac.uk) if you wish to participate. You have to sign a consent form, and all other phases will be arranged.

What happens if I change my mind?

You have the right to change your mind and withdraw at any time without giving a reason and without your participant rights being affected.

If you withdraw from the study, we will keep the information that we have already obtained for the purposes of achieving the objectives of the study only

What will happen to the results of the research?

The results of the study will be written up and form the basis of my doctoral thesis. Some of the findings may be submitted for publication. All personal details will remain strictly confidential. Research findings made available in any reports or publications will not include information that can directly identify you without your specific consent.

Where can I get more information?

Please contact Ahmed Bin Afif on aaba1n17@soton.ac.uk if you have any queries.

What happens if there is a problem?

If you are concerned with any aspect of this study, you should contact to the researchers who are going to make every effort to address your questions.

If you remain unhappy or have a complaint about any aspect of this study, please contact the University of Southampton Research Integrity and Governance Manager (023 8059 5058, rgoinfo@soton.ac.uk).

The researcher: Ahmed Bin Afif (aaba1n17@soton.ac.uk)

Supervisor: Dr. Ben Lineton(Bl@isvr.soton.ac.uk)

Supervisor: Prof. Nicci Campbell (N.G.Campbell@soton.ac.uk)

Supervisor: Dr. Mark Fletcher: (M.D.Fletcher@soton.ac.uk)

Data Protection Privacy Notice

The University of Southampton conducts research to the highest standards of research integrity. As a publicly-funded organisation, the University has to ensure that it is in the public interest when we use personally-identifiable information about people who have agreed to take part in research. This means that when you agree to take part in a research study, we will use information about you in the ways needed, and for the purposes specified, to conduct and complete the research project. Under data protection law, 'Personal data' means any information that relates to and is capable of identifying a living individual. The University's data protection policy governing the use of personal data by the University can be found on its website (https://www.southampton.ac.uk/legalservices/what-we-do/data-protection-and-foi.page).

This Participant Information Sheet tells you what data will be collected for this project and whether this includes any personal data. Please ask the research team if you have any questions or are unclear what data is being collected about you.

Our privacy notice for research participants provides more information on how the University of Southampton collects and uses your personal data when you take part in one of our research projects and can be found at http://www.southampton.ac.uk/assets/sharepoint/intranet/ls/Public/Research%20and%20Integrity%20Privacy%20Notice/Privacy%20Notice%20for%20Research%20Participants.pdf

Any personal data we collect in this study will be used only for the purposes of carrying out our research and will be handled according to the University's policies in line with data protection law. If any personal data is used from which you can be identified directly, it will not be disclosed to anyone else without your consent unless the University of Southampton is required by law to disclose it.

Data protection law requires us to have a valid legal reason ('lawful basis') to process and use your Personal data. The lawful basis for processing personal information in this research study is for the performance of a task carried out in the public interest. Personal data collected for research will not be used for any other purpose.

For the purposes of data protection law, the University of Southampton is the 'Data Controller' for this study, which means that we are responsible for looking after your information and using it properly. The University of Southampton will keep identifiable information about you for ten years after the study has finished after which time any link between you and your information will be removed.

To safeguard your rights, we will use the minimum personal data necessary to achieve our research study objectives. Your data protection rights – such as to access, change, or transfer such information - may be limited, however, in order for the research output to be reliable and accurate. The University will not do anything with your personal data that you would not reasonably expect.

If you have any questions about how your personal data is used, or wish to exercise any of your rights, please consult the University's data protection webpage (https://www.southampton.ac.uk/legalservices/what-we-do/data-protection-and-foi.page) where you can make a request using our online form. If you need further assistance, please contact the University's Data Protection Officer (data.protection@soton.ac.uk).

Thank you for taking the time to read the information sheet and considering taking part in the research.

L.2 Participant Information Sheet for Professionals

Participant Information Sheet for Professionals

Study Title: The perspectives and recommendations of cochlear implant professionals and users for the development of a wearble haptic device.

Researcher: Ahmed Bin Afif
ERGO number: 61075

Please read the following information carefully before you make your decision. If you are happy to participate, you will be asked to sign a consent form. If anything is unclear or if you need additional information, please do not hesitate to contact Ahmed Bin Afif (aaba1n17@soton.ac.uk).

What is the research about?

This research is part of a PhD project. The aims of this study are to explore the perspectives and experiences of UK cochlear implant (CI) users and professionals concerning:

d) The listening challenges experienced by CI users,
e) The current strategies and assistive technology devices used to minimise listening challenges and
f) The perceived potential value of haptic stimulation (vibration to the skin) and variables that must be considered in the development of a potential assistive haptic device for CI users. Haptic or vibrotactile device is worn on skin, either one or both sides of the body, that picks up speech and sounds in the environment and converts them into gentle vibration that can be felt on the skin

Why have I been asked to participate?

You have been asked to take part because you are a professional working in the field of CIs with at least one year of clinical experience.

What will happen to me if I take part?

The research comprises three qualitative phases:

a) initial questionnaire,
b) focus group discussion and
c) post-focus group survey.

Phase one

Interested participants who sign the consent form electronically will be sent the initial questionnaire via email. The initial questionnaire comprises two sections that might take approximately 10-15 minutes to complete. In the first section, you will be asked to identify your demographics to ensure you meet the eligibility criteria of the research. Eligible participants will be asked to complete section two, which consists of four open-ended questions about hearing challenges among CI users, strategies and assistive technologies used to minimise challenges and any experience with haptic devices among CI users.

Phase two

Then, the researcher (the PhD student) will arrange with you via email the date and time of the focus group, which will be an approximately one hour online video meeting with four to six other CI professionals across the UK, guided and moderated by the study researcher(s). The invitation email will include some instructions and a reminder of the ground rules that you must read. The online video conference discussion will cover recommendations concerning the development of a haptic device for CI users. With your consent, the discussion will be recorded and anonymously transcribed. After the transcription, the recorded videos will be deleted.

Phase three

In this phase, you will receive a survey that will allow you to comment on the previous focus group discussion. You will also be asked to provide your feedback on the design of the haptic device prototype. The survey will take approximately 10-15 minutes to complete.

Are there any benefits in my taking part?

There will be no direct benefit to you as an individual. However, you will contribute towards the improvement of a potential haptic device for cochlear implant users.

Are there any risks involved?

There are no anticipated risks to participants who take part in this study. Contact details for the researcher and project supervisors have been included below in the event that you may require any support after taking part in the study.

Ahmed Bin Afif: aaba1n17@soton.ac.uk

Dr.Ben Lineton: Bl@isvr.soton.ac.uk

Prof.Nicci Campbell: N.G.Campbell@soton.ac.uk

Dr.Mark Fletcher: M.D.Fletcher@soton.ac.uk

What data will be collected?

The following is a list of all data obtained by the researcher (the PhD student):

- Your email address to contact you
- Your demographics (i.e. occupation, working location, years of experience, etc.)
- Your answers to the four open-ended questions about listening challenges among CI users, strategies and assistive technologies used to minimise challenges and any experience with haptic devices among CI users.
- The focus groups will be video-recorded for subsequent anonymous transcription. Following transcription, the recording will be deleted.
- Your answers to the post-focus group survey

All electronic data will be stored on a password-protected computer on the University of Southampton's secure servers. The data will be held in accordance with the University of Southampton's policy on data retention.

Will my participation be confidential?

Your participation and the information we collect about you during the course of the research will be kept strictly confidential.

Only members of the research team and responsible members of the University of Southampton may be given access to data about you for monitoring purposes and/or to carry out an audit of the study to ensure that the research is complying with applicable regulations. Individuals from regulatory authorities (people who check that we are carrying out the study correctly) may

require access to your data. All of these people have a duty to keep your information, as a research participant, strictly confidential..

The research team will not disclose whether you or anyone else have participated in this study. Furthermore, any names of individuals mentioned in the focus group will be replaced with a pseudonym. All electronic data will be stored on a password-protected computer. The data will be held in accordance with the University of Southampton policy on data retention. Only researchers and supervisors will have access to it.

With your consent, the researcher will retain your contact information so that you can be contacted once again in relation with future work on this project. The University's data protection policy governing the use of personal data by the University will apply which can be found on its website (https://www.southampton.ac.uk/legalservices/what-we-do/data-protection-and-foi.page). If at any time, you wish to remove your contact details from the future-research contact list, you can contact the researcher or the research team at any time.

Do I have to take part?

No, it is entirely up to you to decide whether or not to take part. If you decide you want to take part, you will need to sign a consent form to show you have agreed to take part.

Please contact the researcher (aaba1n17@soton.ac.uk) if you wish to participate. You have to sign a consent form, and all other phases will be arranged.

What happens if I change my mind?

You have the right to change your mind and withdraw at any time without giving a reason and without your participant rights being affected.

What will happen to the results of the research?

The results of the study will be written up and form the basis of my doctoral thesis. Some of the findings may be submitted for publication. All personal details will remain strictly confidential. Research findings made available in any reports or publications will not include information that can directly identify you without your specific consent.

Where can I get more information?

Please contact Ahmed Bin Afif on aaba1n17@soton.ac.uk if you have any queries.

What happens if there is a problem?

If you have a concern about any aspect of this study, you should speak to the researchers who will do their best to answer your questions.

If you remain unhappy or have a complaint about any aspect of this study, please contact the University of Southampton Research Integrity and Governance Manager (023 8059 5058, rgoinfo@soton.ac.uk).

The researcher: Ahmed Bin Afif (aaba1n17@soton.ac.uk)

Supervisor: Dr.Ben Lineton(Bl@isvr.soton.ac.uk)

Supervisor: Prof. Nicci Campbell (N.G.Campbell@soton.ac.uk)

Supervisor: Dr.Mark Fletcher: (M.D.Fletcher@soton.ac.uk)

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when we use personally-identifiable information about people who have agreed to take part in research. This means that when you agree to take part in a research study, we will use information about you in the ways needed, and for the purposes specified, to conduct and complete the research project. Under data protection law, 'Personal data' means any information that relates to and is capable of identifying a living individual. The University's data protection policy governing the use of personal data by the University can be found on its website (https://www.southampton.ac.uk/legalservices/what-we-do/data-protection-and-foi.page).

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Any personal data we collect in this study will be used only for the purposes of carrying out our research and will be handled according to the University's policies in line with data protection law. If any personal data is used from which you can be identified directly, it will not be disclosed to anyone else without your consent unless the University of Southampton is required by law to disclose it.

Data protection law requires us to have a valid legal reason ('lawful basis') to process and use your Personal data. The lawful basis for processing personal information in this research study is for the performance of a task carried out in the public interest. Personal data collected for research will not be used for any other purpose.

For the purposes of data protection law, the University of Southampton is the 'Data Controller' for this study, which means that we are responsible for looking after your information and using it properly. The University of Southampton will keep identifiable information about you for 10 years after the study has finished after which time any link between you and your information will be removed.

To safeguard your rights, we will use the minimum personal data necessary to achieve our research study objectives. Your data protection rights – such as to access, change, or transfer such information - may be limited, however, in order for the research output to be reliable and accurate. The University will not do anything with your personal data that you would not reasonably expect.

If you have any questions about how your personal data is used, or wish to exercise any of your rights, please consult the University's data protection webpage (https://www.southampton.ac.uk/legalservices/what-we-do/data-protection-and-foi.page) where you can make a request using our online form. If you need further assistance, please contact the University's Data Protection Officer (data.protection@soton.ac.uk).

Thank you for taking the time to read the information sheet and considering taking part in the research.

Appendix M : Study 3- Consent Form

Consent form

Study title: The perspectives and recommendations of cochlear implant professionals and users for the development of a wearable haptic device.

Researcher name: Ahmed Bin Afif

ERGO number: 61075

Please initial the box(es) if you agree with the statement(s)

I have read and understood the information sheet (dated 09/11/2020, version 2) and have had the opportunity to ask questions about the study, and understand I can contact the researcher if I have further questions.	
I agree to take part in this research project and agree for my data to be used for the purpose of this study.	
I understand my participation is voluntary and I may withdraw (at any time) for any reason without my rights being affected.	
I confirm that have read, understand and agree to the study's focus group ground rules	
I understand that the focus groups will be video recorded.	
I understand that my responses and all files containing any personal data will be anonymised in the reports of the research.	
I understand that I may be quoted directly in reports of the research but that my name will not be used.	
I am happy to be contacted again in relation to future research related to this project.	

Data Protection

I understand that information collected about me during my participation in this study will be stored on a password-protected computer and that this information will only be used for the purpose of ethically approved research studies.

Name of participant (print name)……

Signature of participant……

Date……

Name of researcher (print name)……

Signature of researcher……

Date……

Appendix N : Study 3- Initial Questionnaires

N.1 Initial Questionnaire for CI Users

Initial Questionnaire (cochlear implant users)

Dear Participant
Please complete this questionnaire which consists of two sections. In the first section, you will be asked about your demographics. In the second section, you will be asked to answer four open-ended questions about cochlear implant users' listening challenges after cochlear implantation, strategies & technology to overcome listening challenges and experience with haptic devices (devices that apply vibration to the skin).

Section 1

Section1:

Demographic information

1. Please write your participation number *

Enter your answer

2. Are you: *

- [ ] Male
- [ ] Female
- [ ] Prefer not to answer

3. Which age group applies to you? *

- ( ) 18-34
- ( ) 35-44
- ( ) 45-54
- ( ) 55-64
- ( ) 65-74
- ( ) 75 or older
- ( ) prefer not to answer

4. In which region of the UK are you located? (please specify city and county) *

Enter your answer

5. What is your primary language (i.e., the one you speak most of the time)? *

- English
- Other

6. At what age did your hearing loss start? *

Enter your answer

7. The onset of your hearing loss was: *

- sudden
- progressive (become worse over time)

8. At what age did your hearing loss become severe enough for a cochlear implant to be considered *

The value must be a number

9. What is the cause of your hearing loss? *

Enter your answer

10. How long have you had your cochlear implant? *

Enter your answer

11. Are you fitted with: *

- Single CI
- Bilateral CIs
- Cochlear implant + Hearing aid (in the other ear)
- Cochlear implant+ Hearing aid (in the same ear), e.g. electro-acoustic fitting
- Other

12. From the list below, please choose the manufacturer(s) of your CI(s): *

- [ ] Advanced Bionics
- [ ] Cochlear
- [ ] Med-El
- [ ] Nurotorn
- [ ] Oticon Medical
- [ ] Other

Section 2 ...

Section 2: Cochlear implants, technology/strategies and haptic devices

please respond to questions as much detail as you feel appropriate.

13. Do CI users in general and you, in particular, continue to experience any listening difficulties following implantation? *

- ( ) Yes
- ( ) No

14. Please outline what situations and tasks are more challenging *

Enter your answer

15. In your opinion, what strategies and technology can be used to help CI users overcome listening difficulties? *

Enter your answer

16. Hearing and vision are the primary senses used for communication by most people. Individuals with hearing loss rely more heavily on visual cues and lipreading. Vibrotactile stimulation of the skin through haptic devices could be another hearing assistive option for CI users.

In your opinion, could a haptic assistive device provide an additional benefit to CI users? *

- ( ) Yes
- ( ) No

17. In what ways do you anticipate a haptic assistive device could offer benefits to CI users? *

Enter your answer

18. Vibrotactile stimulation has been incorporated in some technologies, e.g. to alert/warn, for music appreciation, etc. Have you ever used such devices? *

- yes
- No

19. Could you please explain what vibrotactile stimulation devices are you using and how? *

Enter your answer

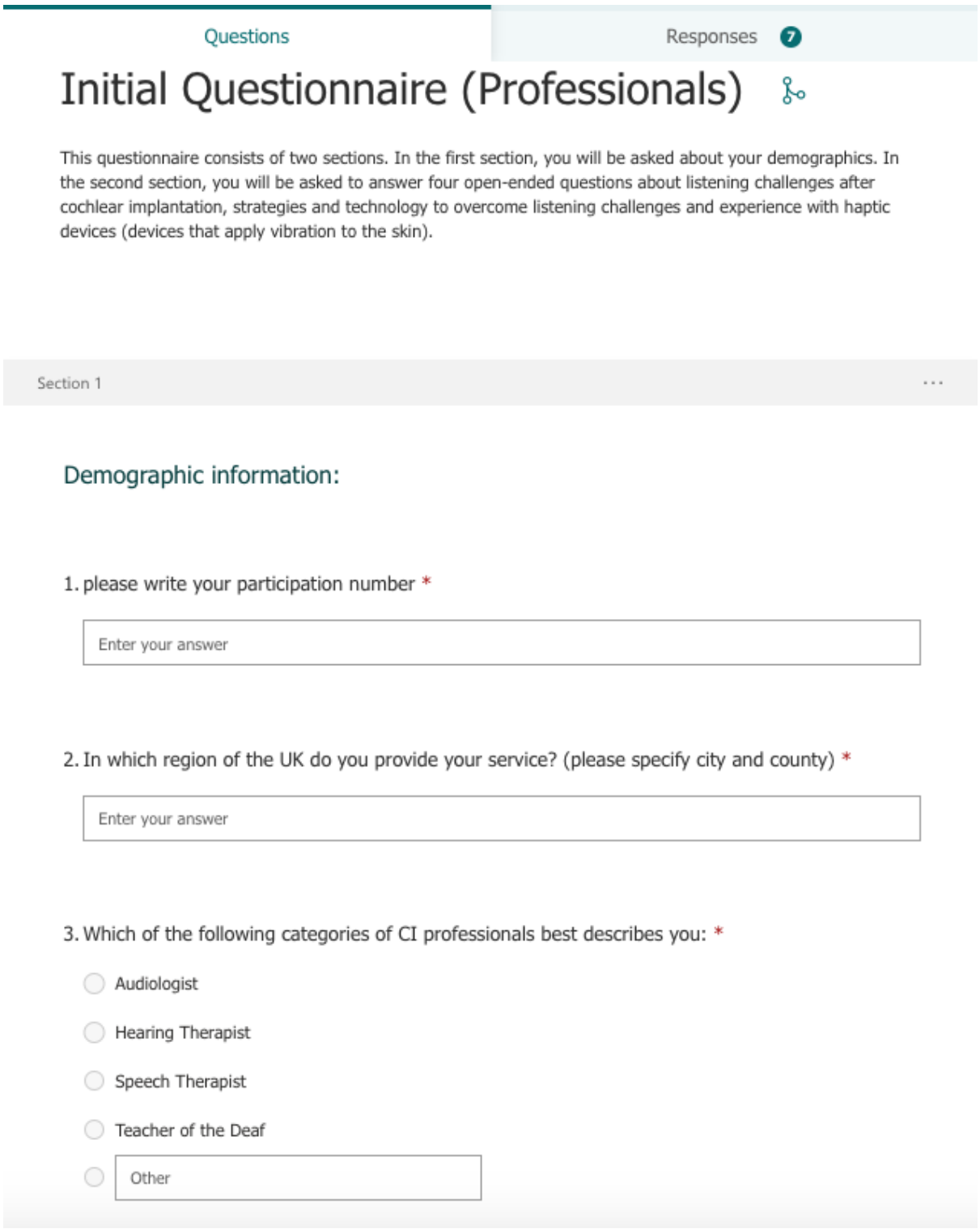
20. Feel free to add any additional comments in the space below: (optional)

Enter your answer

21. The next phase of the study will be an online focus group exploring the aspects that need to be considered when developing a haptic device. Would you prefer to participate in? *

- An online live meeting with captions (with 4-5 other participants) (1 hour)
- An online live meeting with captions and a British Sign Language interpreter present (with 4-5 other participants) (1 hour)
- A "bulletin board" focus group where written contributions can be made (discussion will be open for one week)

N.2 Initial Questionnaire Professionals



Questions Responses 7

Initial Questionnaire (Professionals)

This questionnaire consists of two sections. In the first section, you will be asked about your demographics. In the second section, you will be asked to answer four open-ended questions about listening challenges after cochlear implantation, strategies and technology to overcome listening challenges and experience with haptic devices (devices that apply vibration to the skin).

Section 1

Demographic information:

1. please write your participation number *

Enter your answer

2. In which region of the UK do you provide your service? (please specify city and county) *

Enter your answer

3. Which of the following categories of CI professionals best describes you: *

- Audiologist
- Hearing Therapist
- Speech Therapist
- Teacher of the Deaf
- Other

4. What is your highest education level? *

- [ ] Bachelor's degree
- [ ] Master's degree
- [ ] PhD degree
- [ ] Other

5. How many years of experience do you have with cochlear implant users? *

The value must be a number

Section 2 ...

Section 2: Cochlear implants, technology/strategies and haptic devices

please respond to this section as much detail as you feel appropriate.

6. Do CI users continue to experience any listening difficulties following implantation? *

- ( ) yes
- ( ) No

7. Please outline what situations and tasks are more challenging *

Enter your answer

8. In your opinion, what strategies and technology can be used to help CI users overcome listening difficulties? *

Enter your answer

9. Hearing and vision are the primary senses for communication among most people. Individuals with hearing loss rely more heavily on visual cues and lipreading. Vibrotactile stimulation of the skin through haptic devices could be another hearing-assistive option for CI users.

   In your opinion, could a haptic assistive device provide additional benefit to CI users? *

   - Yes
   - No

10. In what ways do you anticipate a haptic assistive device could offer benefits to CI users? *

Enter your answer

11. Vibrotactile stimulation (alert vibration) has been incorporated in some technologies, e.g. to alert/warn, for music appreciation, etc.. Have your CI patients ever used such devices? *

- ○ Yes
- ○ No

12. Could you please explain what vibrotactile stimulation devices they are using and how? *

Enter your answer

13. Feel free to add any additional comments in the space below: (optional)

Enter your answer

Appendix O Study 3: Focus Group's Ground Rules

Focus Groups' Ground Rules

Study title: The perspectives and recommendations of cochlear implant professionals and users for the development of a wearable haptic device.

Researcher name: Ahmed Bin Afif

ERGO number: 61075

To participate in the focus group, you must consent to comply with the following ground rules:

- Treat all participants with respect, even though their views may differ from yours.
- We would like to hear everyone's perspectives, and everyone's ideas and experiences are valuable. Therefore, allow others the opportunity and time to give their view.
- We welcome and encourage comment and discussion between members of the group, i.e. the discussion is not focussed on simply addressing the researcher's question but is rather an opportunity to share ideas and 'bounce' ideas around and off one another for a richer discussion. Something one person says may make another think of adding to that of another related point. Please do allow others the opportunity and time to give their view and make their points.
- Resect and uphold the confidentiality of everything that is shared in this discussion

If a participant were to breach these ground rules or add any inappropriate material, they will be excluded from the group

Name of participant ……

Signature of participant……

Date……

Appendix PStudy 3: Post-focus Group Questionnaire

Post-focus Group Questionnaire

please respond to this final survey as much detail as you feel appropriate. Your response will provide rich information that will help us to gather variables that need to be considered in the development of the future haptic device

Section 1 ...

Further thoughts and previous knowledge about haptic devices

1

Please write your participation number *

Enter your answer

2

Is there anything else you would like to add to the focus group discussion topic?

Enter your answer

3

Have you attended a presentation or read an article about haptic devices in the past two years? *

- Yes
- No

Section 2

Haptic Prototype Device

We have a haptic prototype device that we are developing. It consists of a band worn on each wrist to allow for localisation and directionality of sound. It converts sounds into vibrotactile (haptic) stimulation.

4

What do you think about this haptic device? *

Enter your answer

5

What would you change to improve this device? *

Enter your answer

6

How likely would CI users be to use this device once it is finished and why? *

Enter your answer

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