Exploring the use of speech in audiology: A mixed methods study

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Declaration

I, Bhavisha J Parmar, confirm that the work presented in this thesis is my own. Where information has been derived from other sources, I confirm that this has been indicated in the thesis. It has not been previously submitted, in part or whole, to any university or institution for any degree, diploma, or other qualification.

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Abstract

This thesis aims to advance the understanding of how speech testing is, and can be, used for hearing device users within the audiological test battery. To address this, I engaged with clinicians and patients to understand the current role that speech testing plays in audiological testing in the UK, and developed a new listening test, which combined speech testing with localisation judgments in a dual task design. Normal hearing listeners and hearing aid users were tested, and a series of technical measurements were made to understand how advanced hearing aid settings might determine task performance.

A questionnaire was completed by public and private sector hearing healthcare professionals in the UK to explore the use of speech testing. Overall, results revealed this assessment tool was underutilised by UK clinicians, but there was a significantly greater use in the private sector. Through a focus group and semi structured interviews with hearing aid users I identified a mismatch between their common listening difficulties and the assessment tools used in audiology and highlighted a lack of deaf awareness in UK adult audiology.

The Spatial Speech in Noise Test (SSiN) is a dual task paradigm to simultaneously assess relative localisation and word identification performance. Testing on normal hearing listeners to investigate the impact of the dual task design found the SSiN to increase cognitive load and therefore better reflect challenging listening situations. A comparison of relative localisation and word identification performance showed that hearing aid users benefitted less from spatially separating speech and noise in the SSiN than normal hearing listeners. To investigate how the SSiN could be used to assess advanced hearing aid features, a subset of hearing aid users were fitted with the same hearing aid type and completed the SSiN once with adaptive directionality and once with omnidirectionality. The SSiN results differed between conditions but a larger sample size is needed to confirm these effects. Hearing aid technical measurements were used to quantify how hearing aid output changed in response to the SSiN paradigm.

Impact Statement

The cornerstone of audiological assessment involves the detection of pure tones; however, the main complaint of people with hearing aids is the difficulty they have hearing speech in noise. Current speech perception tests evaluate how a listener perceives and discriminates speech, although the prevalence and use of such tests in UK clinical practice remains uncertain. Furthermore, common speech test techniques often do not reflect complex listening scenarios. During everyday communication, listeners are required to locate target speech in complex environments and discriminate between target words and competing noise. This is particularly challenging for hearing device users as amplification strategies often hinder localisation cues and exacerbate background noise. To address these clinically relevant issues, the work presented in this thesis explored the perspectives of audiology clinicians and patients, and further developed a spatial speech in noise test to assess the spatial hearing abilities of hearing device users.

A questionnaire was developed to evaluate the use of speech testing in UK audiology, unveiling an underutilisation of speech testing tools, relative to many other countries. Regular speech testing practice was almost exclusively reported in the private sector, rather than in government-funded facilities. Furthermore, organisational and regulative factors were identified as common barriers to speech testing uptake. Although hearing healthcare professionals found value in speech testing, it is not currently mentioned in current UK National Institute of Health and Care Excellence (NICE) guidance on adult hearing assessment (NICE, 2018). Findings from this study could help shape future clinical guidance and improve consistency of care.

An ecologically relevant spatial speech in noise (SSiN) task that simultaneously measures relative localisation and word discrimination was refined and evaluated with normal hearing listeners and hearing aid users. The SSiN increased cognitive load to better reflect complex listening scenarios. Hearing aid users had significantly reduced spatial release from masking abilities, compared to normal hearing listeners. Findings also suggested that the SSiN may have the potential to assess the benefits of advanced hearing aid features.

Experienced hearing aid users' perspectives of assessment and communication within audiology practice were also explored within this work, to compliment the quantitative findings with lived experiences. In this case, hearing aid users valued audiological assessment methods that represented the specific listening challenges they commonly experienced. A lack of deaf awareness within UK audiology services and the need for enhanced patient-centred care was also emphasised.

Collectively, the outcomes of this research provide some of the first insights into speech testing practices and communication strategies in the private and public sector audiology services in the UK and have the potential to shape and inform future clinical guidance. The inclusion of spatial hearing assessments, like the SSiN, and improvement of communication and deaf awareness has the capacity to: i) improve customisation and monitoring of hearing device intervention options, ii) strengthen patients' understanding of device benefits and limitations, and iii) lead to enhanced patient-centred care. Although hearing healthcare professionals find value in speech testing, it is important to highlight that standardised speech testing is not currently part of relevant UK clinical guidelines. This research is an important first step to help inform audiology training curricula and service provision to enhance accessibility for hearing aid users.

Contents

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List of Abbreviations and Acronyms

4FHA	4 frequency hearing average
4AFC	4- alternative forced choice
AIHHP	Association of Independent Hearing Healthcare Professionals
AUC	Area under the curve
BAA	British Academy of Audiology
BKB SIN	Bamford-Kowal-Bench Speech in Noise
BSA	British Society of Audiology
BSHAA	British Society of Hearing Aid Audiologists
BTE	Behind-the-ear
CAPT	Chear auditory perception task
CI	Cochlear Implant
CoS	Crescent of sound
dB	Decibel
dB HL	Decibel hearing level
dB SPL	Decibel sound pressure level
EMA	Ecological momentary assessment
FD	Full directional microphone
HA	Hearing aid
HHP	Hearing healthcare professional
HI	Hearing impaired
HINT	Hearing in Noise Test
Hz	Hertz
HCPC	Health and Care Professions Council
ICF	International Classification of Functioning, Disability and Health
ILD	Interaural level difference
ITD	Interaural time difference
KEMAR	Knowles Electronics Manikin for Acoustic Research
kHz	kilohertz
LiSN	Listening in Spatialised Noise
MAA	Minimum audible angle

MHAS	Modernising Hearing Aid Services
NAL-NL2	National Acoustic Laboratories' prescription for non-linear hearing aids
NH	Normal hearing
NHS	National Health Service
NICE	National Institute for Health and Care Excellence
OMNI	Omni directional microphone
OR	Odds ratio
OSM	Open Sound Navigator
PTA	Pure tone audiometry
REMs	Real ear measurements
RCCP	Registration Council for Clinical Physiologists
RMSE	Root-mean-square error
RNID	Royal National Institute for Deaf People
ROC	Receiver Operating Characteristic
RT	Reaction time
SII	Speech Intelligibility Index
SIN	Speech in noise
SNR	Signal-to-noise ratio
SRM	Spatial release from masking
SRT	Speech reception threshold
SSiN	Spatial Speech in Noise Test
SSiN-HA	Spatial Speech in Noise Test- Hearing aid
SSiN-VA	Spatial Speech in Noise Test- Virtual Acoustics
UA	Unaided
UCL	University College London
UK	United Kingdom
US	United States of America
WHO	World Health Organisation

Chapter 1: Introduction

The overall goal of this thesis is to further develop and trial a spatial speech in noise test to assess the word identification and relative localisation performance of hearing aid users. To understand the clinical applicability of this assessment tool, and factors that would influence its uptake and use, this thesis also aims to explore the current audiological speech testing landscape from hearing aid user and clinicians' perspectives.

1.1 Background

Globally, the World Health Organisation (WHO, 2021) estimates that by 2050 over 700 million people will have disabling hearing loss (i.e., greater than 35 dBHL in the better ear). Currently, around one in five adults in the United Kingdom (UK) have a hearing loss (Royal National Institute for Deaf People, 2018a). Hearing loss can hinder physical, emotional, social, cognitive, employment and educational well-being (Chia et al., 2007; Ciorba et al., 2012; Genther et al., 2013; Helvik et al., 2013; Helvik et al., 2006). In 2017, the World Health Assembly adopted a new resolution on the prevention of deafness and hearing loss. The document outlined important actions that should be initiated worldwide to reduce the burden of hearing loss and included the implementation of effective audiological rehabilitation programmes for hearing device users (WHO,2017).

Audiology-related healthcare, including training, financing, and delivery, varies across the world. While many patients worldwide rely on private insurance or self-funded care, many countries (e.g., the United Kingdom (UK), Australia, Norway, Sweden, Belgium, France) provide public insurance for audiology services (Moller, 2016; Yong et al., 2019). Audiology education also differs globally (Goulios & Patuzzi, 2008), and between health sectors. For instance, an audiologist (private or publics sector) in the United States of America (US) qualifies with a Doctorate in Audiology (AuD) whereas a hearing aid dispenser private sector clinician in the UK can register with the Health and Care Professions Council (HCPC) with a foundation degree (FdSc) and internship (or an equivalent qualification). Currently, a public sector audiologist, working in the National Health Service (NHS) in the UK, will require an undergraduate degree in audiology, or its equivalent. Due to this disparity in audiology provision, regular evaluation of practices, globally, could help monitor whether hearing healthcare services adhere to evidence-based guidance, identify changes needed to improve quality of care (e.g., policy or financing), and track practice trends over time.

Collecting patient feedback is an important service evaluation process and efforts have been made for healthcare services to partner with consumers to incorporate their feedback into service development mechanisms (Conklin et al., 2015; Farmer et al., 2018). In fact, the UK government has encouraged patients to be involved in the planning and delivery of health services for over two decades (Barker et al., 2014; Barker et al., 2016; Department of Health, 2001; NHS England Executive, 1996; NHS England Public Participation Team, 2017). Public involvement can help identify what patients want and need from their clinical services, e.g., accessible healthcare structures (Panagiotopoulou & Tsirintani, 2020) and healthcare researchers have recommended that audiology service users should “be involved in the shaping of such services” (Kelly et al., 2013, p. 300). However, there can be organisational barriers to using the feedback to improve patient care (Sheard et al., 2019). An audiology patient involvement study in the UK found that the significant lack of accessible information can result in patients feeling like they are unable to make informed decisions about their care.

Within healthcare, patient-centred care is advocated for in the rehabilitation of patients with chronic health conditions (Eaton, 2016), involves including the patient in decision making processes and customises the care to the patients’ specific needs. Key features of patient-centred care include the patient–clinician relationship (including communication and information sharing), qualities of the clinician (e.g., interpersonal skills and technical knowledge) and the influence of organisational structure (e.g., care transition, coordination of care between services and accessibility) (Cooper et al., 2008; Cott, 2004; Kidd et al., 2011). Patient-centred care is an integral component of best practice in aural rehabilitation. However, there is no ‘gold standard’ patient-centred care approach in this area, and there is need for additional research focussing on the patient experience in audiology (Bennett et al., 2021; Grenness et al., 2014b). Further work in this area is necessary to help inform patient-centred clinical practice and training opportunities for audiologists’ on-going professional development.

A number of clinical practice guidelines are available to inform UK practice and enhance consistency of care. The audiological assessment of adults with hearing difficulties involves: i) taking a clinical history, ii) otoscopic examination, iii) pure tone audiometry to record hearing thresholds, iv) tympanometry to assess middle ear function and v) questionnaires to assess any restrictions to activities (NICE, 2018). Based on these assessments, well established classifications exist to diagnose the degree of hearing loss (Olusanya et al., 2019) and serve as the basis for clinical decisions. It is important to recognise, however, that people often face more disabling hearing difficulties in everyday situations due to the increased complexity of social environments and background noise (e.g., workplace, restaurants, family gatherings), an effect that is present for those with normal hearing as well as those with hearing loss (Monzani et al., 2008; Scherer & Frisina, 1998). Difficulties understanding speech in the presence of noise is one of the most common complaints among people with hearing loss (Takahashi et al., 2007). Therefore, reliance on audiometric findings alone is not recommended (Hallberg et al., 2008), as existing research demonstrates a poor relationship between speech in noise perception and audiometric findings (Vermiglio et al., 2012). Assessments involving speech recognition in the presence of speech related maskers is more predictive of real-world listening abilities (Hillock-Dunn et al., 2015). This indicates the need for additional research and additional assessment tools in this field, to better align with the key difficulties people with hearing loss report.

Unlike the clinical audiology assessment setting (which relies solely on detecting sounds in silent environments), real-world listening requires listeners to segregate the target speech or sound from many competing noises, thereby relying on the ability to exploit multiple cues (which may be disrupted in cases of hearing loss). Spatial cues may also be used to isolate speech from competing sounds, and selective attention mechanisms can help listeners successfully track the sound of interest.

Collectively, the ability to locate target sounds and ‘unmask’ them from noise is referred to as *spatial hearing* (Culling & Akeroyd, 2010). When a listener attempts to discriminate speech in the presence of noise, spatial cues play a critical role in improving speech understanding. For example, speech and noise presented spatially separated (i.e., 90 agrees apart) will lead to an enhancement of speech intelligibility compared to when they are presented from the same location (Arbogast et al., 2005; Hawley et al., 2004; Litovsky, 2005; Plomp & Mimpen, 1981). This phenomenon is referred to as the *spatial release from masking* (SRM). Hearing loss significantly impacts SRM, such that listeners with hearing loss have distinct reductions in SRM compared to listeners with normal hearing (Glyde et al., 2013). Therefore, patient groups will show varying degrees of benefit from a given speech-noise spatial separation, with some not achieving any SRM even with the largest separations. (Srinivasan et al., 2016).

Based on current audiological practice guidance, bilateral hearing aids (HAs) are recommended for people with hearing loss in both ears. However, there is no standard clinical assessment of binaural hearing involving complex listening environments. When fitting HAs, the technology is adapted to compress sounds into the patient's available dynamic range, with speech frequencies prioritised in an effort to reduce noise interference and maximise speech perception. However, other critical functions of the auditory system can help listeners in complex, dynamic environments, including localisation and SRM. Hearing aid users tend to have poorer frequency resolution, leading to distorted signals (Moore, 2007), and difficulty focussing on a target sound whilst filtering out the wanted sounds around them (Gatehouse & Akeroyd, 2006). Clinical hearing assessments generally do not account for these complex systems (Gatehouse & Noble, 2004). However, a growing body of research has highlighted the impact of poor sound localisation and spatial hearing, particularly for those with hearing loss or hearing aids (Akeroyd & Whitmer, 2016; Dai et al., 2018; Dorman et al., 2016; Van den Bogaert et al., 2006). From a patient's perspective, difficulties localising and perceiving speech in noise could contribute to HA dissatisfaction, with the potential for poor HA uptake and compliance, if these areas remain unaddressed. Some clinical assessment techniques are available to assess spatial release from masking over headphones (Cameron & Dillon, 2007; Jakien et al., 2017), but these are often not suitable for free field testing of aided listeners, e.g., hearing aid users and cochlear implant users. Thus, the inclusion of ecologically relevant spatial hearing assessments has the potential to improve HA intervention customisation and patients' understanding of HA device benefits and limitations, as well as acting as an outcome measure of intervention benefits, leading to enhanced patient-centred audiology care.

This thesis presents five experimental chapters including the refinement and use of a Spatial Speech in Noise test (SSiN: Bizley et al 2015) to assess bilateral HA users. Qualitative methods were used alongside the quantitative data collection to yield rich data on stakeholder perspectives (patients and clinicians) and understand the context in which the SSiN may be delivered. An outline of each chapter of this thesis is presented in the next section.

1.2 Thesis Outline

1.2.1 Chapter 2: Literature review

Introducing the concept of sound localisation as it relates to listeners with normal hearing and HA users, Chapter 2 overviews the benefits and limitations of HA noise reduction and directionality systems on speech intelligibility, localisation, and listening effort. Concluding with background information about audiology service provision in the UK, this chapter sets the stage for the following experimental chapters and provides a solid framework for the aims and objectives of this thesis. **Figure 1.1** presents a visual representation of the experimental chapters from this thesis.

1.2.2 Chapter 3: Patterns of speech perception testing in adult audiology

This first study explores the use of speech perception testing in the public and private UK adult audiology service sectors through the implementation of an online questionnaire with hearing healthcare professionals (*N* = 295). These results indicate speech and localisation testing tends to be used infrequently in UK audiology practice, although hearing healthcare professionals feel speech testing is beneficial for counselling patients and adjusting HA settings, and for use within the diagnostic test battery. Notable differences were observed between private and public sector service provision. This study supports the importance of speech testing, from the clinicians' perspective. Further work is needed to investigate whether more complex speech test designs that can be incorporated into adult audiology assessments. In response, Chapters 4, 5, and 6 outline the developmental stages of a Spatial Speech in Noise

(SSiN) test and its efficacy (including participant feedback) in assessing hearing abilities in patients with normal hearing and HA users.

1.2.3 Chapter 4: Development of a Spatial Speech in Noise Test (SSiN)

The Spatial Speech in Noise Test (SSiN) was created by Bizley et al (2015) to provide a reliable, sensitive assessment of relative localisation and word identification performance. Here, Chapter 4 outlines the modifications made to the SSiN methodology to improve clinical applicability, including adjusting the initial threshold seeking task to avoid floor effects in performance. The adapted SSiN is then evaluated in a group of adults with normal hearing (*n* = 28) and explored whether the dual task paradigm increases cognitive demands, to better reflect challenges faced by listeners in realistic acoustic scenes. All listeners performed the SSiN dual task, and the single tasks of relative localisation and word identification found within the dual SSiN. Findings support the use of the dual task SSiN for increasing listening effort of listeners with normal hearing, although more work is needed to understand the potential clinical applications of the SSiN, particularly for HA users.

1.2.4 Chapter 5: Using the SSiN to assess normal hearing listeners and hearing aid users

Chapter 5 uses the SSiN to compare relative localisation and word identification performance between normal hearing listeners (*n* = 38) and bilateral hearing aid users (*n* = 22). This study demonstrates reduced spatial release from masking in the hearing aid users compared to normal hearing listeners. HA users' relative localisation performance followed a similar pattern of performance across azimuthal location to that of the NH listeners, but they performed significantly poorer. Finally, HA users' reaction times to identify the location shift in the SSiN task was significantly slower than NH listeners, and this was modulated by azimuthal space with faster reaction times at the midline. Collectively, Chapter 5 highlights important differences in spatial hearing abilities for adults with and without hearing loss and serves as a base from which to make further refinements to enhance the task's ecological validity (e.g., increasing the level and duration of background babble). To further investigate the use of the SSiN for assessing HA users, specifically advanced HA features, it is important to control for HA type. Chapter 6 presents a subset of refinements made to the SSiN (SSiN-HA) and explores how the test paradigm can be used to assess the impact of a specific type of adaptive directionality and noise reduction feature.

1.2.5 Chapter 6: Use of the SSiN-HA in assessing advanced hearing aid features

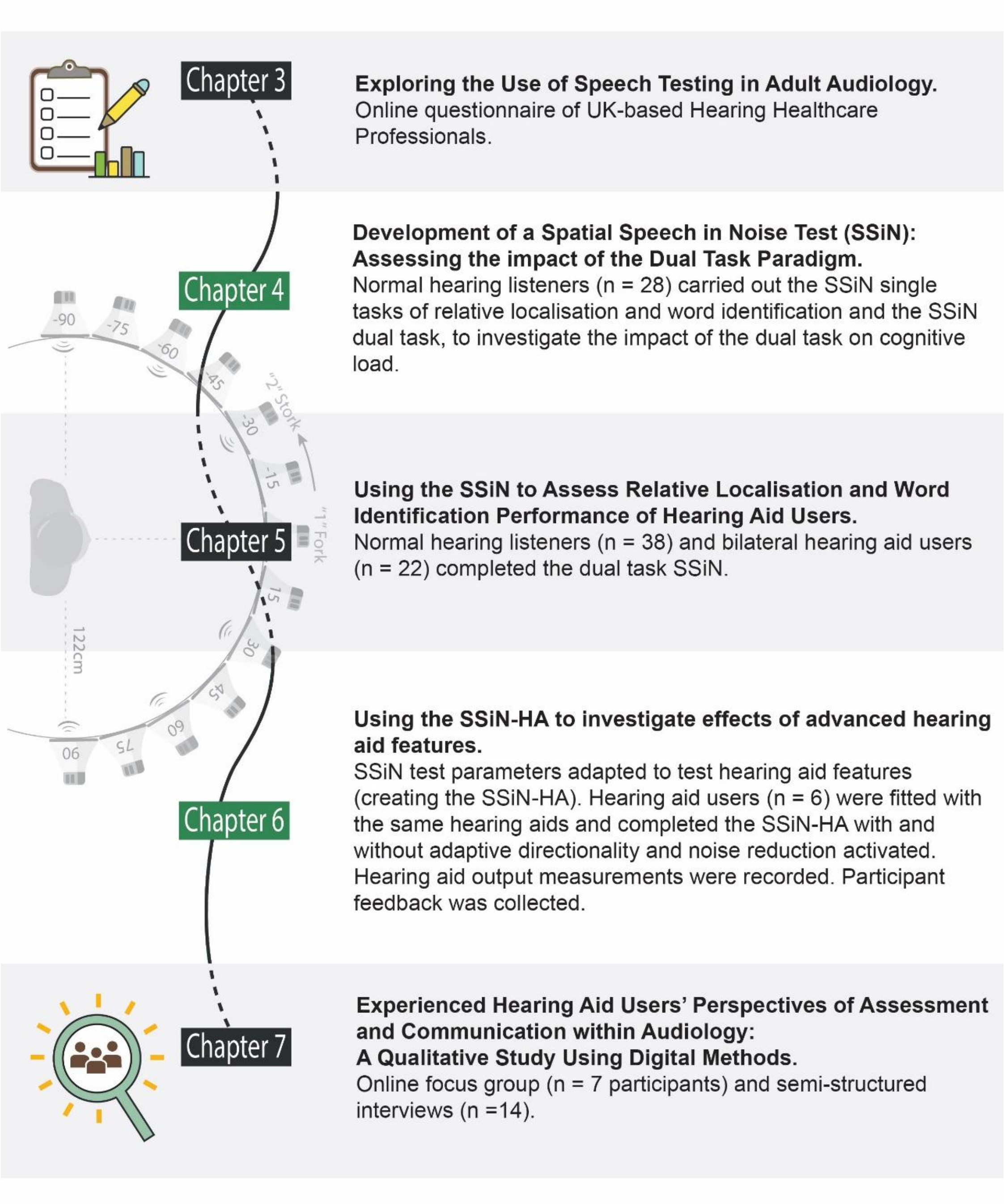
This chapter outlines the final set of amendments made to the SSiN methodology and how it was used to assess advanced HA features (SSiN-HA). Presented in three parts, this chapter follows an action research approach to actively involve key stakeholders in the development of the SSiN-HA. Phase 1 uses of the SSiN-HA to assess six hearing aid users, all fitted with the same hearing aids. Hearing aid users performed the SSiN-HA with and without adaptive directionality activated. Results found no significant performance enhancement with adaptive directionality activated, but listeners performed with faster reaction times. Phase 2 explores the usability of the SSiN-HA from the participants' perspective, using qualitative techniques (i.e., self-report questionnaire and focus group). Here, participants reported that the current audiology assessment process does not relate to everyday listening difficulties. Participants also identified some potential improvement indicators for the SSiN-HA. Phase 3 presents hearing aid technical measurements from the SSiN paradigm, using the same hearing aids, stimuli and speaker locations as in Phase 1. Taken together, findings from Chapter 6 highlight the need for hearing healthcare professionals to identify HA users' key priorities and individual/device needs, ad presents the SSiN-HA as a possible tool to achieve this.

1.2.6 Chapter 7: Experienced hearing aid users' perspectives of assessment and communication within audiology: A qualitative review using digital methods

To further explore HA users' perspectives and individual experiences with assessment and communication within audiology, Chapter 7 presents a qualitative study carried out with experienced HA users in an online focus group (*n* = 7 participants) and 1:1 semi-structured online interviews (*n* = 14) to investigate the use of speech (as a testing technique, in relation to everyday listening difficulties, and during audiologist–patient communication) in the audiology assessment. In this context, adult HA users report the importance of relative tests to real-world listening scenarios and of thoroughly explaining test results in plain (non-technical) language. Examples of accommodations made within the testing procedure that improved or impeded ecological validity are also discussed (e.g., speech perception of the audiologist's voice, explanation of the relevance of pure tone audiometry to real-world listening). Regarding audiologist-patient communication and rapport, HA users indicate a distinct lack of Deaf awareness within audiology service provision, as well as a need for enhanced patient-centred care. Through the implementation of digital qualitative data collection methods with specific accessibility accommodations for HA users, this research demonstrates the feasibility of online methods for HA users and provides some of the first insights into a diverse range of HA users' experiences of audiology assessment across the private and public UK sectors.

1.2.7 Chapter 8: General discussion

This chapter concludes the thesis by describing how each chapter contributes to understanding and potentially improving the clinical assessment of hearing impairment, further adding to the existing knowledge in the field. The core contributions are the highlighted inconsistencies of speech testing practice in the UK, the introduction of a new relative localisation and word identification task that can be adapted for audiological clinical practice and the exploration of HA users' experience of the use of speech within assessment. A proposed logic model is presented to integrate the findings of this thesis and explore possible outputs and impact.



Chapter 3

Exploring the Use of Speech Testing in Adult Audiology.
Online questionnaire of UK-based Hearing Healthcare Professionals.

Chapter 4

Development of a Spatial Speech in Noise Test (SSiN): Assessing the impact of the Dual Task Paradigm.
Normal hearing listeners (n = 28) carried out the SSiN single tasks of relative localisation and word identification and the SSiN dual task, to investigate the impact of the dual task on cognitive load.

Chapter 5

Using the SSiN to Assess Relative Localisation and Word Identification Performance of Hearing Aid Users.
Normal hearing listeners (n = 38) and bilateral hearing aid users (n = 22) completed the dual task SSiN.

Chapter 6

Using the SSiN-HA to investigate effects of advanced hearing aid features.
SSiN test parameters adapted to test hearing aid features (creating the SSiN-HA). Hearing aid users (n = 6) were fitted with the same hearing aids and completed the SSiN-HA with and without adaptive directionality and noise reduction activated. Hearing aid output measurements were recorded. Participant feedback was collected.

Chapter 7

Experienced Hearing Aid Users' Perspectives of Assessment and Communication within Audiology:
A Qualitative Study Using Digital Methods.
Online focus group (n = 7 participants) and semi-structured interviews (n =14).

Figure 1.1: Summary of the experimental chapters (Chapter 3 – Chapter 7) presented within this thesis

Chapter 2: Literature Review

The following chapter critically evaluates the literature on sound localisation and spatial release from masking in both normal hearing listeners and hearing aid users. Background information about audiology service provision is also presented. The literature in this chapter focusses on the adult patient population, with and without hearing aids, but does not include detail concerning other hearing devices or cochlear implant technology. This chapter concludes with the key research questions addressed within this thesis.

2.1 Sound Localisation

The ability to localise sound sources is critical for safety and communication. In contrast to the visual system, where the stimulus location is directly mapped onto the receptors surface in the retina, sound localisation judgements are based on the central processing of a number of acoustical cues (King, 2009). Comparing a sound's level and arrival time at each ear are the most critical cues for localising sounds. An interaural level difference (ILD) is the intensity difference of a sound arriving at each ear, as the head acts as an acoustic obstacle (ILD; Blauert, 1997). ILDs vary with wavelength and high frequencies are reflected rather than diffracted around the head like low frequencies (Feddersen et al., 1957). The interaural time difference (ITD) is the difference in the arrival time of a sound at the two ears.

Lord Rayleigh introduced the duplex theory, which describes the use of ITD and ILD cues for sound localisation in the horizontal plane. The duplex theory details how localisation of low-frequency sounds depends on ITD cues, whilst localisation of high-frequency sounds relies on ILD cues (Rayleigh, 1907). The human auditory system combines these cues—as well as monaural or spectral cues originating from direction dependent filtering of sounds performed by the torso, head and the intricate folds of the external ear—to give the listener a sense of sound localisation in horizontal and vertical planes respectively (Middlebrooks & Green, 1991). Given that individuals have differently sized heads, torsos and ears, both monaural and binaural cues will be specific to each listener. Furthermore, these differences can vary significantly between listeners (Middlebrooks & Green, 1990) and will change as the listener develops from childhood (King et al., 2001). Although sound localisation ability is present at birth

(Clifton, 1992), there is considerable development in the ability to lateralise (i.e., discriminate left from right), localise sounds in quiet and in noise (Lovett et al., 2012) and track moving objects as a child ages (Litovsky, 1997). In particular, children reach adult-like sound localisation performance at 5 years of age (Van Deun et al., 2009).

Localisation accuracy varies with the azimuthal position of the target sound source with the highest level of uncertainty found at lateral locations compared with frontal and rear sound sources. Bizley et al. (2015) found listeners had limited ability to detect changes in location based on ILDs in the periphery, correlating with the observation that sounds at positions beyond +/-60 degrees elicit near-identical performance. Since the availability of localisation cues is frequency dependent, sound source frequency significantly affects sound localisation. Performance is best at low frequencies (< 1 kHz) and worse at frequencies between 1 kHz and 3 kHz due to insufficient binaural cues (Yost & Zhong, 2014). In addition, room acoustics can affect localisation accuracy (Giguere & Abel, 1993). This includes the presence of noise and reverberation in the room. Reverberation is the cumulative effect of sound reflections in a sound environment and depends on the size of the room, items within the room, and how the room was constructed. For normal hearing listeners, localisation performance is reduced in reverberant rooms, compared to those that are acoustically treated, and localisation accuracy decreases when reverberation time (the amount of time for a sound to be attenuated by 60 dB from its original value) was increased (Giguere & Abel, 1993).

2.1.1 Sound localisation assessments

Multiple factors are involved in testing spatial hearing abilities, including the type, level and position of all sound sources involved. Factors including age, cognition and hearing ability also affect how a listener hears and interprets sound across space. Poor sound localisation can cause communication difficulties, potentially putting a listener in danger if they cannot locate incoming signals (e.g., position of vehicles in a busy street; Dobreva et al., 2011). Early descriptions of sound localisation assessments and associated theories began with Italian researcher Giovanni Battista Venturi in 1800. Although best known for works in fluid mechanics, he also wrote about colour and sound localisation. Wade and Deutsch (2008) translated and quoted Venturi’s findings from his experiments which include comparing sound localisation with and without one ear blocked with a finger: “Therefore the inequality of the two impressions, which are perceived at the same time by both ears, determines the correct direction of the sound” (Wade and Deutsch, 2008, p. 18). Following Venturi’s seminal work, localisation assessments included the movement of sound source speakers around the listener (Duyff et al., 1950).

Psychophysical assessments of localisation may include measuring absolute localisation and relative localisation. The assessment of absolute localisation involves listeners identifying the origin of a perceived sound (Makous & Middlebrooks, 1990). On the other hand, relative measures like assessing the minimum discriminable difference between sound locations can result in the measurement of the minimum audible angle (MAA) (Mills, 1958). Many testing techniques are available to assess sound localisation and spatial hearing abilities. The assessment of absolute sound localisation has been carried out through methods including head tracking (Best et al., 2011), head tracking with magnetic search coil induction techniques (Van Wanrooij & Van Opstal, 2007), eye tracking (Asp & Reinfeldt, 2018; Volck et al., 2015), laser pointing (Ludwig et al., 2019) and verbal identification of sound sources (Noble et al., 1994). Volck et al. (2015) reported there is no gold standard test of localisation. Measures of absolute localisation suffer a number of disadvantages including the time and additional equipment needed to complete the assessment and the higher cognitive demands of the listener.

The MAA is the smallest detectable change in direction and involves the presentation of two successive sounds. Listeners hear two tones, the first being from a standard location, and are asked whether the second came from the left or the right of the first. Therefore, this can be assessed by using a two-alternative forced-choice paradigm. The MAA for an individual with NH abilities in both ears can be 1° (Akeroyd & Whitmer, 2016), but depends on frequency and base azimuth (Yost, 2017). For NH individuals, the MAA is smaller when the sound is located at the front compared to more lateral presentations (Senn et al., 2005). MAA measures can often be time consuming compared to measures of absolute localisation measures if the aim is to understand performance throughout space. However, absolute localisation tasks will require an increased number of response options, to match the number of sound locations, which can add to the listener’s cognitive load.

Methods of testing relative localisation have been designed to also reflect everyday listening challenges. In a task modified from the MAA task, proposed by Wood and Bizley (2015), listeners identified whether the target sound had moved to the left or right of the reference sound. Results found relative localisation ability declined with less favourable signal to noise ratios (SNR) and at peripheral locations. The two-alternative forced-choice task measures relative localisation acuity at a fixed separation to give percentage correct performance scores across space, rather than a threshold value like MAA. Therefore, the task paradigm could be used in a variety of settings and could be adapted for use clinically as it could provide a quick, ecologically relevant relative localisation task for human listeners.

2.1.2 Effect of hearing loss on localisation

Numerous studies have detailed the sound localisation abilities of NH listeners (Blauert, 1997; Middlebrooks & Green, 1990), amplification device users such as HAs and cochlear implants (Godar & Litovsky, 2010; Grieco-Calub & Litovsky, 2012; Senn et al., 2005) and the unaided hearing impaired (HI) population (Häusler et al., 1983; Lorenzi et al., 1999; Noble et al., 1994). Generally, HI listeners have a lower ability to localise sounds than NH individuals (Angell, 1901; Lorenzi et al., 1999).

Despite the frequency-specific nature of horizontal localisation cues, Durlach et al. (1981) reported that the audiogram was a poor predictor of localisation ability, and localisation ability can be more significantly affected by conductive hearing losses than by sensorineural hearing losses. Furthermore, Noble et al. (1994) tested localisation in the horizontal and vertical planes for NH listeners (*n* = 6) and HI listeners without their HAs. HI listeners consisted of 66 with sensorineural hearing loss and 21 with conductive/mixed hearing loss. The author reported that localisation ability was negatively affected by the degree of hearing loss and that conductive hearing loss causes further difficulties in localisation in the horizontal plane due to increased low-frequency loss and associated issues related to the ITD (Noble et al., 1994).

In addition, Lorenzi et al. (1999) assessed localisation performance in the presence of noise of four unaided adults with bilateral symmetrical high-frequency hearing impairment. The authors reported that localisation accuracy and consistency of localisation judgements were poorer for HI listeners compared to the performance of the NH control group.

Otte et al (2013) tested listeners from three age groups (7-11 years, 20-34 years and 63-80 years) to investigate effects of ageing and high frequency hearing loss on localisation performance. Results found that older adults with high frequency hearing loss had significantly worse localisation performance in the vertical plane, compared to normal hearing peers, but horizontal localisation was unaffected (Otte et al., 2013; Zheng et al., 2022). Furthermore, van Esch et al (2013) assessed thirty normal hearing listeners (19-39 years) and 72 hearing impaired listeners (22-91 years) to investigate the clinical applicability of an audiological test battery. One of the tests included in the test battery was the minimum audible angle. All tests were completed under headphones and auditory tests were completed to find auditory levels to equalize audibility across participants. Stimuli (low pass noise, high pass noise and broadband white noise) were filtered with generic head related transfer functions to achieve the perception of spatial location. The test started with a 32° virtual separation and the angle was reduced adaptively following a 2-down-1-up procedure with a 4° initial step size which was eventually reduced to 1°. Results found normal hearing listeners to have smaller minimum audible angles compared to hearing impaired listeners (mean difference approximately 5° in all conditions), but there was considerable overlap between groups (van Esch et al., 2013). Akeroyd and Whitmer (2016) reviewed studies from 1983 to 2016 (29 studies) that measured horizontal localisation abilities in listeners with hearing loss. The authors reported large variations in individual performance, and test methods as well as a lack of age matched control participants in some studies. The overall horizontal localisation performance deficit of hearing impaired listeners compared to normal hearing listeners, from twelve studies that reported this comparison, was 5° (Akeroyd & Whitmer, 2016).

2.1.3 Spatial release from masking

Cherry (1953) introduced the “cocktail party effect”, which described a situation where listeners in noisy, dynamic situations attempt to detect and understand a target speaker in the presence of interfering background sounds. Spatially separating the target sound and interfering sounds improves understanding of target speech and this effect is known as the spatial release from masking (SRM) (Bronkhorst & Plomp, 1992; Plomp & Mimpen, 1981).

Hearing with two ears improves an individual's speech perception ability in the presence of noise (Marrone et al., 2008b; Martin et al., 2012). One way to measure this benefit is to assess the SRM. For NH listeners, spatially separating speech from interfering noise results in significant SRM, thus improving speech intelligibility in noise. SRM assessment involves comparing speech perception performance where speech and noise come from the same location (commonly the frontal location) and two different locations (commonly speech at the front and noise at 90° to one side). When speech and noise are spatially separated, NH listeners may have better speech detection due to the head providing acoustic protection and associated better-ear listening (Cubick et al., 2018). In addition, the ILD and ITD will vary, which can be computed by the auditory system to alleviate some effects of the noise (Culling & Summerfield, 1995).

Compared to NH listeners, HI listeners have inferior SRM. This disadvantage hearing impaired listeners face when performing multitalker segregation tasks has been fairly well documented (Arbogast et al., 2005; Best et al., 2010a; Hopkins & Moore, 2010). In the study by Glyde et al. (2013), the Listening in Spatialized Noise-Sentences test (LiSN-S) was used (Cameron & Dillon, 2007). The task involves the presentation of sentences to establish a speech reception threshold in different spatial configurations of target speech and distractor speech. Target sentences are perceived to come from 0-degrees azimuth (in front of the listener), while distractor stimuli was presented from 0-degrees azimuth or +/-90 degrees azimuth. The task is clinically appropriate as it can be completed under headphones by using head related transfer functions, however this limits its use in the free-field for aided assessment. Participants were aged 7–89 years of age and hearing thresholds ranged from normal hearing to moderately severe. Results found a significant relationship between spatial advantage and hearing loss, and poorer hearing was associated with poorer spatial processing ability. Normal hearing listeners achieved 13.5 dB benefit from accessing spatial cues and this reduced to a 2 dB benefit for listeners with moderately severe hearing loss. Finally, some test conditions did not involve a change in spatial cues, e.g., speech and distractor collocated. In this condition, each 10 dB increase in hearing loss resulted in the need for a 0.7 dB increase in SNR. However, in the condition with spatial cues, each 10 dB of hearing loss required a 2.8–3.4 dB increase in SNR. Therefore, the authors recommended that clinical speech in noise tests should include spatial separations of speech and distractor stimuli to avoid underestimation of speech in noise difficulties.

Other studies have also examined SRM in listeners with hearing loss and normal hearing. Dubno et al (2002) used the Hearing in Noise Test (Nilsson et al., 1994) with speech and speech-shaped noise, either both co-located at the midline or with speech presented from the midline and speech-shaped noise present at 90 degrees azimuth (at the side of the listener). They reported a 6.1dB benefit of spatial separation for younger listeners with normal hearing, 4.9dB benefit for older listeners with normal hearing and a 2.7dB benefit for older listeners with hearing loss (Dubno et al., 2002). Older NH listeners often require greater speech-noise separations to discriminate speech, and older HI listeners do not gain significant benefit from separating speech and noise, even in the presence of large spatial separations of speech and noise (Srinivasan et al., 2016).

van Esch (2013) also investigated spatial release from masking in a range of hearing-impaired listeners and compared performance to normal hearing listeners. Sentences were presented either co-located to the speech shaped or spatially separated from it (by +/-90°). Results found that hearing impaired listeners benefitted less from spatially separating speech and noise, compared to normal hearing listeners (van Esch et al., 2013). For older listeners, reductions in SRM could be due to age related changes in cognition (Fullgrabe et al., 2014) and high frequency hearing loss (Whitmer et al., 2014).

Traditional SRM listening experiments summarised above have presented speech and noise co-located from the front of the listener and spatially separated so that the noise stimulus is presented at +/-90° (on the left or the right of the listener). However, Srinivasan et al (2016) compared speech perception with speech and noise co-located at 0° to conditions where noise was at 2°, 4°, 6°, 8°, 10°, 15° or 30° from the speech stimuli. Overall, findings suggest that participants needed different amounts of spatial separation to achieve spatial release from masking, depending on their age category. Also, results indicate that hearing loss was a contributing factor to predicting SRM at larger speaker separations whereas ageing was a predictive factor at smaller separations (Srinivasan et al., 2016). Similarly, Gallun et al (2013) reported ageing to significantly reduce SRM, when hearing loss is controlled for.

2.2 Hearing Aid Development and Use

HAs are designed to amplify sound to overcome difficulties associated with hearing loss. HA technology has significantly advanced over time. In its earliest form, a simple acoustic horn designed to collect sound energy when held close to the ear was illustrated between 1650–1673 (Berger, 1984; Hvidt, 1972). The use of a wearable device containing a carbon microphone, battery, amplifier and receiver followed in 1902, and the next 60–70 years saw the use of electronic amplifiers, transistors and integrated circuitry to improve sound quality and reductions in size (Dillon, 2012). With further developments in microphone technology and receiver volume, most HA components could fit into the ear by the 1980s (Griffing & Heide, 1983). The advent of digital technology in the 1990s represented a significant milestone for HA technology due to enhanced frequency response shaping and compression capabilities, feedback management, frequency lowering and automatic gain control according to user preference (Levitt, 1997).

Modern-day HAs can be custom fitted to each individual, accounting for factors including hearing thresholds, ear canal size, ear mould type, gender, native language and HA experience. In addition, wireless technology enables connectivity between HAs and many devices are now rechargeable. Digital HAs were introduced into the NHS in 2000, initiated by the Modernising Hearing Aid Services (MHAS) programme funded by the Department of Health (NHS England Department of Health, 2004), with analog HAs phased out of audiology services soon after. In their simplest form, digital HAs pick up sound signals with a microphone, which are converted into electrical waveforms that pass through an analog-to-digital converter. This conversion allows for the signal to be represented in binary format. Once digitised, the signal can be processed and amplified as needed and converted back to analog so that the acoustic signal can be transmitted to the listener’s ear through a receiver (Levitt, 1997). Until the 1980s, clinicians had allowed patients to try several analog HAs and compare their performance (Palmer & Lindley, 2002). When fitting a digital HA, clinicians use a strategy or prescription formula to assess the patient’s specific audiometric thresholds to create a frequency-specific fitting gain target. Once the target is established, hearing output can be verified in the listener’s ear or an ear simulation coupler. This strategy is multifactorial, and clinicians can choose which signal processing techniques and fitting rationales are used to determine the final fit.

The sustained benefits of HA usage for individuals with hearing loss are well established (Cox & Alexander, 1991; Johnson et al., 2018b; Mulrow et al., 1992). However, a large proportion of those with HAs do not use these devices regularly (Davis, 2007). In 2018, the European Hearing Instrument Manufacturers Association (EHIMA) conducted a survey based on a sample of 14,855 people in the UK, finding that 1,300 had some form of hearing loss and 698 wore HAs (75% were issued by the NHS; EHIMA 2018). Generally, conclusions from this survey were favourable; 94% reported HAs improved their quality of life to some extent and 74% were satisfied with their HAs. However, 55% of nonusers did not wear HAs because they felt that these devices do not work well in noisy situations (EHIMA, 2018).

2.2.1 Hearing aid compression

Signal processing techniques include linear amplification, wide dynamic range compression (WDRC) and many others. Linear processing applies amplification in a sound level independent manner (Lunner et al., 1998). However, sensorineural hearing losses are nonlinear in that sensitivity to quieter levels becomes more impaired, whilst sensitivity to louder sounds remains unchanged. Therefore, the auditory dynamic range (i.e., the area between hearing sensitivity and uncomfortable loudness levels) is reduced, particularly in high-frequency areas where hearing loss is more common (Dillon, 1996). To alleviate some effects of reduced dynamic range and better mimic how the healthy ear processes sound, Steinberg and Gardner (1937) introduced automatic gain control (AGC), enabling HAs to react more strongly to weaker sound input levels compared to the response to louder sound input levels. In general, this meant input sounds with wide dynamic range parameters could be compressed into narrow dynamic ranges at the output. Modern HAs feature compression strategies (Souza, 2002).

HA compression can vary in timing in which nonlinear functionality starts and stops (i.e., attack and release time). Most commonly, attack times of less than 10 ms ensure a fast reduction of gain to loud input signals (Jenstad & Souza, 2005). However, release times vary considerably between commercial devices despite evidence showing that the choice of release time affects perceptual HA outcome (Rallapalli & Alexander, 2019). Recently, Kowalewski et al. (2018) assessed the impact of slow and fast acting compression consonant-vowel identification in noise whilst using an attack time of 5 ms. The researchers found a nominal benefit of fast (10 ms) compared to slow (500 ms) release times on consonant identification at lower speech levels (45 dBSPL) in quiet and noisy conditions (Kowalewski et al., 2018).

Typically, HAs therefore have a range in which amplification is linear before compression is activated. The compression ratio reflects the amount of compression applied once compression starts (commonly referred to as the “knee point”). For example, a compression ratio of 5:1 indicates that for every 5 dB increase of input sound pressure level (SPL), there is only a 1 dB increase of output SPL. Therefore, more compression is indicated by higher compression ratios. WDRC is commonly associated with knee points below 60 dBSPL and low compression ratios (Dillon, 1996). These factors help a WDRC HA apply compression across a wide range of inputs and remain close to linear for very soft input signals in order to provide maximal gain in those areas. This process aims to restore normal loudness growth and compensate for the effects of sensorineural hearing loss and loudness recruitment.

The introduction of digital HAs meant clinicians could programme these devices based on patient requirements and specifically adjust gain parameter frequency. Digital HAs can assess listening environments and adjust advanced noise reduction and directionality parameters. Furthermore, different programmes can be stored within digital Has, Each with their own frequency response, noise reduction, compression and directionality settings so that the patient can switch between programmes if required.

Studies exploring the benefits of WDRC, and linear signal processing tend to differ in methodology, making conclusions across studies challenging. First, WDRC parameters can vary between systems depending on the processing strategy goal (e.g., loudness normalisation or loudness equalisation across frequency; Dillon, 1996).

Second, since compression helps to individualise the listening experience depending on the input signal, performance outcomes between strategies may vary significantly based on the input signal type and testing environment used (Gatehouse et al., 2006). Overall, there is a lack of randomised control trial data comparing effects of many advanced HA processing schemes with sufficient sample sizes to make robust conclusions. Therefore, a relatively weak research base has led to conflicting evidence regarding the optimal compression parameters used in HA technology (see Gatehouse et al., 2006 for a full review). A hearing aid user's individual aided speech intelligibility in dynamic situations can be impacted by a multitude of factors including both device factors (noise reduction, directional microphones, remote microphones) and patient factors (age, attention, tiredness, cognition). Traditionally, hearing aid processing algorithms were designed to improve speech intelligibility in a variety of ways including enhancing the Spectro temporal contrast in order to help the listener gain more from the spectro temporal structure of the sound source (Baer et al., 1993). However, the most common ways to enhance the target speech source and suppress the competing noise are to use noise reduction/noise suppression algorithms and directional microphones to enhance the target sound in front of a listener (Ricketts & Dittberner, 2002).

2.2.2 Hearing aid noise reduction systems

Social noise exposure has increased dramatically in the UK since the 1980s (Smith et al., 2000). General conversational levels are estimated to be 60 dBSPL, and prolonged exposure to sounds above 85 dBSPL are known to be harmful to the human auditory system (Royal National Institute for Deaf People, 2018b). Rusnock and Bush (2012) conducted a study to measure the sound levels in 30 restaurants and found only seven restaurants had noise levels low enough for a person to communicate at normal conversational levels, whilst eight had peak sound level recordings of above 85 dBA.

Despite HAs successfully amplifying sounds, poor speech discrimination in the presence of noise is still a significant concern. Noise reduction strategies aim to enhance overall SNR by estimating within frequency bands and reducing areas dominated by noise, leading to improved listening comfort (Brons et al., 2013). Furthermore, noise reduction approaches have traditionally not been designed to allow the listener to listen to multiple target sources, across different directions, simultaneously. In static situations, e.g., if a listener has a long conversation with one person sat directly in front, noise reduction algorithms will suppress the “noise” content that has less fluctuating spectral content and this will result in the target speech being more audible. However, noise reduction features will not generally perform as effectively when the “noise” is unpredictable, in content and location. There is limited evidence suggesting noise reduction systems successfully improve speech intelligibility (Lakshmi et al., 2021). Despite this, research suggests that hearing impaired listeners prefer noise reduction in hearing aids even if it’s use leads to worse speech intelligibility (Brons et al., 2014). Alcantara et al. (2003) fitted eight experienced HA users (all participants had bilateral moderate sensorineural hearing loss) with digital HAs to assess the device’s specific noise reduction system. The authors found no significant difference between speech recognition in noise scores between conditions with and without noise reduction (Alcántara et al., 2003).

Kim et al. (2020) tested 16 adult hearing aid users to examine the effect of digital noise reduction on speech recognition and music perception. Words in noise and sentences in noise tests were used at 6 dB SNR in the unaided condition as well as with noise reduction on and noise reduction off. At the group level, results found no significant difference between noise reduction–on and noise reduction–off conditions for either speech perception measure. However, when looking at word identification scores at the individual level, twelve out of sixteen listeners achieved improvement in the noise reduction–on compared to noise reduction–off. This type of improvement was only observed in five listeners during the sentence in noise test (Kim et al., 2020). However, as three different types of hearing aids were used in the study, direct comparison of the noise reduction algorithm is not possible. Variability in participant characteristics would also impact results, e.g., some participants had unilateral hearing loss and others had bilateral hearing loss.

Since studies have found listeners prefer noise reduction features even if they are detrimental to speech intelligibility, further research has been carried out to better understand reasons for this. One potential reason was that the use of noise reduction systems reduces listening effort. Research has shown noise reduction can lead to less effortful cognitive processing, even if a behavioural performance advantage is not present (Kim et al., 2021). This also has been evaluated within dual task paradigms and by analysing reaction time (Reinten et al., 2021; van den Tillaart-Haverkate et al., 2017). Studies have also suggested that the influence of the noise reduction system depends on the difficulty of the listening environment. Specifically, the noise reduction system improved performance in the secondary task of the dual task but only when the hearing impaired listener was in a more difficult listening situation and not when speech was already fully intelligible (Desjardins & Doherty, 2014). Micula et al. (2021) used pupillometry and a sentence recall test to explore the effects of noise reduction hearing aid systems on working memory resource allocation to processing and storing speech in noise. They found better recall performance and higher sentence baseline dilation when noise reduction was activated and proposed that noise reduction frees up cognitive resources so they can be used for the storage of speech (Micula et al., 2021).

There is no specific audiological clinical guidance document that outlines the use of noise reduction systems in HAs in the UK. The British Society of Audiology (BSA, 2018) "*Practice Guidance: Guidance on the Verification of Hearing Devices Using Probe Microphone Measurements*" suggests real ear probe measurements can be used in the verification of noise reduction systems but does not detail the process.

2.2.3 Hearing aid directionality

Unaided HI listeners require about a 5–15 dB greater SNR than their NH peers to achieve similar speech intelligibility, due to reduced frequency selectivity, loss of peripheral compression and overall reduced audibility (Peters et al., 1998). Directional microphones attempt to increase the SNR by focussing on sounds in front of the listener and attenuating those coming from other locations around the listener (Park et al., 2015). Currently, there is no clinical criterion to specifically identify HA users who would benefit from directional microphone features. With the advent of wireless bilateral hearing devices, information between an individual's HAs can be shared and combined. Furthermore, this feature resulted in binaural beamforming capabilities (Picou et al., 2014). However, combining signals between HAs can lead to further disruptions to natural binaural cues, hindering localisation and spatial hearing abilities (Picou et al., 2014).

Fixed directional microphones have been used so that the listener can focus on conversation directly in front of them, and if conversation strays away from the front, the listener will have to move their head accordingly for the hearing aid to keep target facing. Additionally, a listener’s ability to hear speech from the side locations or the rear will be compromised. The impact of the directional microphone technology relies on the listener being able to move their head towards the appropriate target sound location. If the hearing aids, with directional microphones, are already focussing in a forward-facing way, the listener will miss out on cues coming from other locations and may not know which way the conversation has moved. Overall, research has found directional microphones to offer listeners an advantage when compared to omnidirectional amplification alone (Boymans & Dreschler, 2000; Cord et al., 2002; Yueh et al., 2001).

There are mixed reviews regarding listener preference for directionality. Some studies have found listeners often do not report any self-rated preference of directional microphones compared to omnidirectional microphones (Cord et al., 2002; Palmer et al., 2006). However, others have found hearing impaired listeners to prefer the maximum directional setting (Recker et al., 2020). Walden et al. (2005) found that hearing aid users tended to prefer directional microphones when they improved speech intelligibility (*n* = 31), but that the relationship was not highly predictive of individual preference (Walden et al., 2005). If the auditory scene is complex, and target sounds are presented from the most off-axis target angles (+/-90° – +/-150°), a listener using directional microphones may miss the initial target speech while searching for and turning towards the new signal or be unaware that the sound source is present (Archer-Boyd et al., 2018; Brimijoin et al., 2014). Therefore, an automatic adaptive approach may help listeners follow conversation in dynamic auditory scenes.

Adaptive directional microphones use algorithms which adopt different polar plots (frequency specific plots displaying the sensitivity of the microphone to sounds from different directions), in different environments. The ideal adaptive directional microphone would involve the system automatically changing polar pattern (with minimal noise output) and preserving maximum sensitivity to the front of the listener. In studies where the noise sources are positioned to the side of a listener (70° and 110°), adaptive directional microphones have provided a 2.5 dB improvement in speech recognition compared to the full directional setting (Ricketts & Henry, 2002). This benefit disappeared when the noise was located to the rear of the listener. Another study tested speech perception in the presence of noise presented from 5 locations behind the listeners (110°–250°) (Bentler et al., 2004), The authors reported no additional effectiveness of the adaptive directional microphone over the fixed polar pattern and self-report measures found participants did not perceive any difference between these systems.

As observed in the literature, many factors influence the measured performance of directional microphones including location and number of competing noise sources, reverberation, head orientation, microphone port orientation, ear mould vent size and access to visual cues (Bentler et al., 2004; Brimijoin et al., 2014; Picou et al., 2014; Pumford et al., 2000; Ricketts, 2000a, 2000b; Ricketts & Dhar, 1999).

Studies have also investigated the impact of directional microphones and listening effort. Desjardins (2016) used a dual task paradigm to test fifteen older adults with hearing loss. The study found that listening effort was significantly reduced when directional microphones were activated (Desjardins, 2016). A study by Winneke et al. (2020) compared two different hearing aid microphone set ups: one wide directional microphone and one narrow directional microphone. They found subjective listening effort (using a rating scale) to be reduced with the narrow directional microphone and this setting also resulted in better memory performance in a sentence recall task (Winneke et al., 2020).

2.2.4 Effect of hearing aids on sound localisation and spatial release from masking

As hearing aids aim to restore audibility, commonly of higher frequencies, it could be predicted that their use would result in improved SRM as they restore high frequency dependant ILD cues. However, given the intricate comparisons of level and timing differences between the two ears, the introduction of two independently functioning HAs with distinct noise reduction, directionality and compression strategies could create signal timing delays that destroy binaural cues (Dawes et al., 2013). Research studies have found hearing aid users' SRM to be poorer than that of normally hearing listeners. However, there are mixed findings when comparing results of aided vs. unaided conditions. Some studies report greater spatial advantage in the bilaterally aided condition compared to the unaided condition (Ahlstrom et al., 2009). Whereas, others have found there to be similar SRM when listening unaided and aided (Marrone et al., 2008a).

Best et al. (2010b) compared the localisation abilities of bilateral HA users with NH listeners. Despite good residual high-frequency hearing and access to binaural cues, the HA users did not perform better than in the unaided condition. The authors concluded that three factors affect poor performance: (a) the use of speech stimuli and its low spectral density; (b) the restricted bandwidth of HAs; and (c) the prescribed gain formula used possibly not giving enough high-frequency gain (Best et al., 2010b).

Van den Bogaert et al. (2006) tested 10 experienced HA users (aged 44–79 years) in both the unaided and aided conditions and compared results against a NH control group (aged 20–25 years). A 200 ms 1/3 octave high-frequency noise band centred at 3150 Hz and a low-frequency noise band centred around 500 Hz were chosen to obtain both ITD and ILD processing paths as well as a 1-second broadband telephone alerting signal. Stimuli were presented through one of the 13 speakers arranged in the frontal horizontal plane from -90° to +90° with 15° spacing between speakers. Listeners were asked to identify the location of the target signal. Although results revealed significantly better performance among NH listeners, 39% of HA users' performance was within one standard deviation of NH listeners (Van den Bogaert et al., 2006). These results were similar to Lorenzi et al. (1999), who noted that many HA listeners could reach NH performance. In addition, results showed that localisation performance varies based on the azimuthal position of the target signal, with superior performance in frontal positions compared to lateral regions (Van den Bogaert et al., 2006). After accounting for audibility, HA users' localisation performance was better without their HAs compared to the aided condition. The investigators reported that the positioning of the microphones would not explain this effect but that the internal signal processing of the HAs would most likely distort the interaural cues.

Meuret et al. (2017) assessed the localisation and spatial discrimination abilities of children and youth aged 7–17 with moderate congenital bilaterally symmetrical sensorineural hearing loss without their HAs. The frontal azimuthal hemifield was used, absolute localisation was tested using a pointing task and discrimination was assessed by measuring the MAA. Low-frequency (0.3–1.2 kHz) and high-frequency (2–8 kHz) Gaussian noise bursts were presented at a 35 dB sensation level to ensure audibility. Results showed a reduction in hit accuracy during the localisation task for the HI group compared to the NH group (Meuret et al., 2017). HI children also showed more intraindividual variability than children in the NH group. Additionally, MAA was greater for the HI group, with more variability than the NH group. Unfortunately, although all participants were experienced HA users, the aided condition was not assessed, as the authors reported that such testing would have become overly time consuming and that the 14 different HA processing strategies present in their sample would have been a confounding factor. However, the study aimed to investigate the effects of hearing impairment rather than the impact of HA processing. All children tested had been wearing HAs in both ears since infancy. Despite this, and accounting for audibility, their localisation ability was still inferior to age-matched NH control participants. This finding indicates that a listener’s localisation ability is a central auditory feature present in early childhood and therefore does not improve significantly in the presence of auditory stimulation for an individual with hearing loss (Meuret et al., 2017).

Dorman et al. (2016) also investigated the localisation abilities of NH listeners and HA users. Localisation accuracy was in root means square error (RMSE) in degrees. The authors reported HA users had similar localisation ability to that of NH listeners but with significantly larger variability across participants despite comparable audiometric configurations and HA usage (Dorman et al., 2016).

Researchers have also assessed inter-ear coordinated compression between HAs and the impact of HA pinna compensation strategies to alleviate the effects of previous HA compression strategies working independently between a listener’s HAs. Also, behind-the-ear HAs are the most common, but with the microphone positioned behind the ear, spectral cues from the intricate folds of the pinna are not available (Noble & Byrne, 1990). Therefore, pinna compensation strategies have also been introduced in some HA systems to mimic the effects of the external ear on localisation ability (Korhonen et al., 2015). Studies have found inter-ear coordinated compression improves horizontal localisation at peripheral locations. Also, pinna compensation strategies significantly improve localisation accuracy for sounds arriving from behind the listener. Korhonen et al. (2015) tested 10 experienced HA users with bilateral symmetrical hearing loss. Loudspeakers were positioned with 30° separations and aided performance was compared between omnidirectional settings, the unaided condition, omnidirectional with pinna compensation and omnidirectional with inter-ear coordinated compression. A 3-second short sentence was presented at a 30 dB sensation level, and participants were asked to identify their perceived location of the stimulus to test absolute localisation ability.

Johnson et al (2017) assessed horizontal localisation performance in 45 hearing aid users. Participants were adults with hearing loss who had been fitted with basic and premium hearing aids from two hearing aid manufacturers. After a 4- week acclimatisation period, results found no significant difference in sound localisation performance in the aided condition compared to the unaided condition. However, participants made fewer errors when using the premium hearing aids compared to the basic hearing aids, when the stimulus was high frequency and when the environment was quiet. The study also used self-report questionnaire measures of localisation. Participants reported being able to localise better with the premium hearing aids compared to the basic hearing aids. However, this difference in listening experience may be due to overall enhancement in audibility.

As highlighted in the literature, the flexibility needed to follow speech in complex, noisy environments have often been lacking within hearing aid technologies. This, coupled with the physiological effects of hearing loss, contributes to hearing aid users’ reduced abilities to separate, discriminate and follow sounds sources, compared to their normal hearing peers. However, within the research setting, there is a significant variation in the assessment methods used to measure the benefit of hearing aid features. Within the clinical domain, there are no specific guidelines on the use of or validation of noise reduction and directional microphones for patients with hearing aids. Also, traditional speech recognition tasks do not account for the allocation of resources to multiple cognitive processes. For example, during everyday communication resources are allocated for storing speech, preparing responses and therefore communication involves working memory and attention as well as speech recognition abilities (Koelewijn et al., 2012; Ng et al., 2013). Finally, as the dynamic nature of everyday communication requires a listener to locate sounds, listen to speech in the presence of competing sounds and use spatial separations between target and competing sounds to improve intelligibility, it would be advantageous for clinical test designs to also assess spatial hearing abilities and the benefit or hindrance advanced hearing device features may have on these abilities.

2.3 UK Audiology Provision

In the UK, hearing assessment and audiological rehabilitation are carried out in NHS audiology departments as well as through national and independent private providers. Despite significant enhancement to audiology service provision and digital hearing aid technology, many adults with hearing loss in the UK struggle to access and use hearing aids. To improve access, several strategies have been implemented including minimizing the number of appointments for new hearing aid users (Smith et al., 2008), and increasing patients' choice of service provider (NHS England Department of Health, 2012). However, research suggests that some evidence-based hearing loss support mechanisms are not reflected in audiology quality standards, clinical guidance and this may affect uptake within clinical practice (Barker et al., 2014). The Department of Health's Action Plan on Hearing Loss (2015) outlined key service provision areas that audiology patients value (NHS England Department of Health, 2015). For adult patients this included: clarity about diagnosis and realistic information about hearing loss and hearing instruments, more support after being provided with hearing aids, support for communication strategies and accessible information. One of the key objectives from the Action Plan on Hearing Loss was for services to focus on the individual needs of the person with hearing loss, to provide patient-centred management. The Action Plan on Hearing Loss also recommended the production of NICE guidance for adults with hearing loss.

National Institute for Health and Care Excellence (2018) recommendations on the assessment and management of hearing loss in adults specifically mention the prescription of HAs. The guidelines recommend a comprehensive audiological assessment that does not solely rely on pure tone audiometry and the fitting of two HAs for adults with hearing loss in both ears. The use of directional microphones and noise reduction features is also recommended if patients with hearing loss are particularly struggling with speech in noise discrimination. However, much of the guidance is based on low level evidence and many areas are based on opinions derived from the clinical experiences of the guideline committee (Ftouh et al., 2018).

2.4 Types of Audiology Assessment

Pure tone audiometry is a standard assessment tool used to diagnose the degree and nature of hearing loss. Although the results, in the form of an audiogram, are used to provide clinical recommendations for diagnosis, communication strategies and hearing technologies, they can be challenging for non-professionals to interpret and understand. For instance, adults with hearing loss have previously reported that audiologists were not in tune with their communication needs, which results in patients having poor recall and understanding for most of the technical information relating to the nature, degree, and severity of hearing loss (Watermeyer et al., 2015a).

Audiologists are “required to provide patient-centred care in the prevention, identification, diagnosis, and intervention and treatment of hearing, balance, and other related disorders for people of all ages” (American Speech-Language-Hearing Association, 2018). Many tools and recommendations for clinical practice have been developed in to improve and monitor the audiological assessment and rehabilitation process, patient motivation and readiness, hearing aid use and hearing aid satisfaction. These include use of outcome measure questionnaires (Gatehouse, 1999), speech recognition testing (Turton et al., 2020), motivational interviewing and engagement (Aazh, 2016; Ferguson et al., 2016; Solheim et al., 2018), group rehabilitation (Collins et al., 2009), computer based auditory training (Henshaw & Ferguson, 2013), mobile health educational interventions (Maidment et al., 2020), counselling (Johnson et al., 2018a), involving communication partners (Meijerink et al., 2020) and using patient-centred care (Barker et al., 2016; Grenness et al., 2014b). However, it is unclear how many of these tools are used in routine UK clinical practice.

Although pure tone audiometry is a useful measure of hearing sensitivity, the use of speech stimuli is more ecologically valid and can help diagnose specific disorders and difficulties that are not identified through pure tone audiometry alone. A range of speech perception tests, in quiet and in the presence of background noise, have been used since the early 1900s (Campbell, 1910; Fletcher & Steinberg, 1929) to assess functional hearing ability—how a listener detects, recognises and discriminates speech. Patients with central auditory lesions and auditory processing disorders can often present with normal audiograms but significant speech perception difficulties (British Society of Audiology, 2018; Saunders et al., 2015; Shub et al., 2020). A speech audiogram can be plotted by measuring an individual's word recognition performance (American Speech-Language-Hearing Association, 1988). Traditionally, this involves the presentation of monosyllabic words, via ear specific transducers, in a consonant-vowel-consonant formation. It is a graphical representation of performance vs presentation level, and the speech reception threshold is calculated as the level required for 50% correct speech perception. The monosyllabic word stimuli commonly uses Arthur Boothroyd (AB) word lists in the UK, which limits access to contextual linguistic information and focusses on bottom-up access to speech sounds. There are no UK guidelines on this use of speech stimuli, but the American Speech-Language-Hearing Association (1988) guidelines "Determining Threshold Level for Speech" details the testing and interpretation process.

Commercially available sentence-in-noise tests include the Quick Speech-in-Noise Test (QuickSIN) and the Bamford-Kowal-Bench in noise test (BKB-SIN). The BKB sentence test is an open set speech perception test consisting of sixteen short sentences and is scored on the number of words correctly repeated from 50 key words. During the QuickSIN, sentences are spoken in the presence of four talker babble and listeners are instructed to repeat the sentences heard. Each sentence contains five key words and performance is based on the proportion of these words correctly repeated. The signal to noise ratio (SNR) loss is calculated and represents the SNR needed above the SNR of a normal hearing listener to achieve 50% correct word identification (Killion et al., 2004) To reduce the effects of linguistic skills on speech in noise test results, the digits in noise test (DIN) was created (Smits et al., 2013). The task measures the digit triplet SRT by using a 1-up, 1-down adaptive process and takes around two minutes to complete. The authors concluded that the task is suitable for a range of listeners from those with normal hearing listeners to cochlear implant candidates. Recently, studies have been carried out to further improve the DIN's efficiency (Dambha et al., 2022).

Speech perception testing results, in quiet or in noise, can be compared between the unaided condition, during assessment, and aided, during the hearing device fitting or follow up, to provide information of device benefit to speech perception. Aided speech recognition testing is recommended in paediatric audiology (McCreery, 2013) to give a “more realistic estimate of how the hearing aid processes speech and how a child uses that input to support perception” (McCreery, 2013).

The British Society of Audiology published the first practice guidance entitled “Assessment of Speech Understanding in Noise in Adults with Hearing Difficulties” in 2019. The guidance recommends use of sentence stimuli during speech in noise testing and outlines how to use certain speech tests and interpret results. However, it does not provide advice detailing how results could be used to improve patient outcomes. The National Institute for Health and Care Excellence (NICE, 2018) published guidelines on the audiological assessment for adult patients (NG98). These guidelines include clinical history taking, assessment of activity limitation by use of self-report measures, otoscopy, tympanometry, and pure tone audiometry. The guidance also states the need for a thorough discussion with the patient to highlight any “hearing deficits (such as listening in noisy environments) that are not obvious from the audiogram”. However, there is no specific recommendation for using speech perception testing, in quiet or in the presence of background noise, during the assessment or management of patients with hearing difficulties. A recent systematic review highlighted the variety of outcome domains and instruments used within studies that evaluate interventions for single sided deafness in adults (Katiri et al., 2021). Speech and spatial hearing domains were the most commonly reported, however, these were measured using 73 and 43 different instruments, respectively. Speech performance was commonly measured with the Hearing in Noise Test (Nilsson et al., 1994), but there was no clear preferred method of speech in quiet testing. There is also no specific guidance on spatial hearing assessment or how to optimise the bilateral hearing device fitting. Clinically available spatial hearing assessments often lack ecological validity by using non speech stimuli e.g., in the Auditory Speech Sound Evaluation ILD localisation test (A§E®, © P.J. Govaerts, Antwerp, Belgium (Otoconsult, 2021)). Some tasks also use a small number of sound source locations with wide spatial separations and require the use of headphone testing, limiting the application to unaided testing only (Cameron et al., 2011).

Although the presentation of speech stimuli may better reflect real world listening situations compared to pure tone audiometry, the speech perception testing methods described above are carried out in a quiet, clinical environment. Technological innovations, such as ecological momentary assessment (EMA) have enabled the collection of listening data whilst the listener is situated within their own environments, outside of the clinic. During EMA patients report real time, real world listening data during everyday situations including level of hearing difficulty, environmental factors and hearing aid use (Timmer et al., 2018).

Another, increasingly common, method of reporting information about a listener's access to speech is the use of the speech intelligibility index (SII) (American National Standards Institute, 1997). The SII is an objective, acoustic measure to represent the audibility of speech rather than speech recognition performance. It is calculated by weighting different frequency bands depending on their importance for speech recognition and is reported as a proportion 0 (no speech information is available) to 1 (all speech information available) to predict speech intelligibility (Leal et al., 2016; Studebaker & Sherbecoe, 1991). Audiologists have used the SII in clinical practice, particularly in paediatric audiology, to provide a quick, objective estimate of the proportion of speech heard through a patient's hearing devices, but there is limited data regarding its use in routine audiology in the UK (Amlani et al., 2002; Bagatto et al., 2011; Rankovic & Van Tasell, 1988).

The World Health Organisation's International Classification of Functioning, Disability and Health model (ICF) has been applied within the hearing healthcare context to recognise that hearing loss is not defined solely by the status of the objective bodily function, but also influenced by factors involving the individual within specific contexts (Lind et al., 2016). Implementation of self-report questionnaires and hearing aid validation measures can help promote a patient-focussed rehabilitation process (Hickson & Scarinci, 2007); however, a lack of consensus regarding the optimal outcome measures to use in audiology practice has been noted (Granberg et al., 2014). To facilitate the use of the ICF in clinical practice, a "Brief ICF Core Set for Hearing Loss" has been created, comprising areas important for everyday life for people with hearing loss. Recent research has confirmed its validity and found it to be relevant for adults with hearing loss internationally (Karlsson et al., 2021; van Leeuwen et al., 2020).

Although there are a variety of different audiological assessment tools, each with their own clinical purpose, a combination of measures could address the specific needs of audiology patients. This multi-faceted approach could lead to appropriate diagnosis of hearing conditions, identification of suitable intervention options, and personalised assessment that relates to the patient’s concerns and difficulties. Development of core outcome sets, and minimum clinical standards could improve consistency and reduce variation between clinical studies and within clinical practice.

2.5 Conclusion

The literature presented in this chapter demonstrates the impact of poor localisation and word identification on HI listeners and the limitations of HAs in these areas. There is increased awareness of the benefit of ecologically valid assessment within hearing care; however, it is unclear how this has translated to audiological clinical practice in the UK. Given the rapid evolution of new hearing aid technology and assessment tools, it is important to monitor trends in clinical practice provision and identify potential barriers. Also, audiological assessment tools should attempt to assess a variety of different sound perception mechanisms necessary for safety, communication, and education—including sound localisation and speech recognition. Involving audiology service users in service evaluation and development could detect key healthcare improvement indicators and lead to enhanced accessibility.

The remainder of this study is divided into five experimental chapters followed by an overall discussion and conclusion. The first experimental chapter (Chapter 3) evaluates UK audiology practices by exploring clinicians’ perspectives of speech perception testing. Chapter 4 describes the design and implementation of a Spatial Speech in Noise Test (SSiN), a simultaneous test of relative localisation and speech identification, and explores the impact of the dual task paradigm on cognitive load. Chapter 5 and 6 highlight the use of the SSiN during the assessment of hearing aid users. The final experimental chapter investigates audiology service users’ perspectives of assessment and communication within audiology. Research questions and objectives are presented in **Section 2.6**.

2.6 Research Questions and Objectives

The aims of this work are to: 1) explore the current use of speech perception testing in UK adult audiology, 2) refine, develop, and trial a spatial speech test to assess clinical populations, and 3) investigate hearing aid users' experiences and perspective of current audiological assessment and communication.

The research questions and objectives are as follows:

1) *How is speech perception testing currently used in UK adult audiology?*

   Objectives:
   a. Explore the current use of speech perception testing in UK adult audiology service provision.

2) *Can a spatial speech in noise test be used to assess advanced hearing aid features?*

   Objectives:
   a. Refine and test a method of simultaneously assessing relative localisation and word identification (SSiN), which was first introduced by Bizley et al. (2015).
   b. Explore how the SSiN's dual task paradigm impacts cognitive load.
   c. Compare HA users' SSiN performance to that of normal hearing listeners.
   d. Consider how the SSiN can be used to assess HA features.

3) *How do hearing aid users experience audiological assessment?*

   Objectives:
   a. Explore experienced HA users' perspectives of communication and assessment in audiology.

Chapter 3: Exploring the Use of Speech Testing in Adult Audiology

The work presented in this chapter has been published in the American Journal of Audiology.

This chapter investigates the use of speech perception testing in the UK adult audiology service pathway, and across the world, through a scoping review and the distribution of an online questionnaire (*n* = 295 UK hearing healthcare professionals). This word presented in this chapter answers the first research question of this thesis. The findings showed how speech testing and localisation testing was used inconsistently and infrequently in UK adult audiology, with variability between sectors. Respondents also provided opinions of the benefits of speech testing in audiology, leading to three main themes derived through thematic analysis: (a) helpful during counselling patients, (b) useful when adjusting hearing aid (HA) settings and (c) valuable as a diagnostic tool.

Given the complexity of realistic listening scenarios, the importance of localisation cues and speech discrimination and the observed benefits of speech perception testing reported in this chapter, it is beneficial to investigate the use of more complex test designs. Therefore, Chapters 4, 5 and 6 outline the development stages, analysis, and evaluation of a Spatial Speech in Noise Test to assess normal hearing listeners and HA users. To understand how the Spatial Speech in Noise Test would impact a hearing aid users' assessment experience in the audiology clinic, chapter 7 explores HA users' perspectives of current hearing assessment techniques and presents feedback from a subset of HA users regarding the spatial speech in noise (SSiN) methodology and usability.

3.1 Abstract

Objective: To evaluate speech testing practices in routine adult audiology services within the UK and across the world, and better understand the facilitators and barriers to speech testing provision

Design: A scoping review and cross-sectional questionnaire study

Sample: A UK sample (*n* = 295) of hearing healthcare professionals (HHPs) from the public sector (64%) and private sector (36%) completed the survey

Results: In the UK, speech testing practice varied significantly between health sectors. Speech testing was carried out during the audiology assessment by 73.4% of private sector HHPs and 20.4% of those from the public sector. During the hearing aid intervention stage speech testing was carried out by 56.5% and 26.5% of HHPs from the private and public sector, respectively. Recognised benefits of speech testing included: 1) providing patients with relatable assessment information, 2) guiding hearing aid fitting, 3) supporting a diagnostic test battery. A lack of clinical time was a key barrier to uptake.

Conclusion: The use of speech testing varies in adult audiology. Study results found a low percentage of UK HHPs utilising speech tests compared to other countries. HHPs recognised different benefits of speech testing in audiology practice, but barriers limiting uptake were often driven by factors derived from decision-makers rather than clinical rationale. Privately funded HHPs used speech tests more frequently than those working in the public sector, where time and resources are under pressure and governed by guidance that does not include a recommendation for speech testing. Therefore, including speech testing in national clinical guidelines could increase the consistency of use.

3.2 Introduction

Health policies for England and Wales are based upon guidance produced by the National Institute for Health and Care Excellence (NICE) and such guidance may also have a wide influence on the development and implementation of global clinical practices (Chandra et al., 2015; van der Straaten et al., 2021; Vasse et al., 2012; Yue et al., 2014). NICE, a public body of the UK government's Department of Health and Social Care, produces evidence based clinical guidance, quality standards and outcome metrics. The latest NICE guidance for the assessment of adults with hearing difficulties does not include recommendations for presenting speech stimuli (e.g., speech perception tests in quiet or in noise) within audiological assessment for this population (NICE, 2018). Such guidance results in relevant resource allocation being cut leading to individual services deciding on whether they can accommodate speech testing in their audiology provision. This can cause further discrepancies across service delivery in audiology practice.

The main audiological assessment of hearing sensitivity is pure tone audiometry. However, the most common complaint of people with hearing loss and hearing aids is the difficulty understanding speech, often in noisy environments (Abrahms, 2015). Research suggests pure tone audiometry does not effectively predict speech perception, because it indicates a listener's access to sound rather than their functional hearing ability (De Sousa et al., 2020; Liberman, 2017; Vinay & Moore, 2007). The discrepancy between clinical practice and patient-reported priorities can result in lower patient satisfaction or poor hearing aid usage. Speech tests include the measurement of an individual's speech recognition thresholds and responses to supra-threshold speech in aided and/or unaided testing conditions, in quiet or in noise. They are commonly used as an outcome measure in auditory research studies, e.g., investigating benefits of hearing devices (Bosen et al., 2021; Ricketts & Picou, 2021) or effects of auditory training (Burk et al., 2006; Zhang et al., 2021) and prior to hearing aid fitting to capture a listener's functional ability and identify appropriate intervention strategies (Ricketts et al., 2018). Assessing speech perception abilities in the presence of noise may better reflect the listening conditions that patients report as more challenging (Carhart & Tillman, 1970; Smits & Houtgast, 2005). A range of commercially available speech in noise (SIN) tests are available to help to quantify abilities (e.g., QuickSIN (Killion et al., 2004), Bamford-Kowal-Bench (BKB) SIN (Bench et al., 1979; Niquette et al., 2003), HINT (Hearing in Noise Test) (Nilsson et al., 1994). A recent systematic review, evaluating behavioural assessment methods used before hearing device fitting, reported that patients who underwent SIN testing were more likely to have higher measures of hearing aid satisfaction (Davidson et al., 2021).

Globally, hearing healthcare professionals (HHPs), clinicians that assess hearing in a variety of settings including audiologists, hearing aid dispensers, audiometrists and audio technicians, may choose to perform audiological assessment methods that involve the presentation of speech stimuli for a variety of reasons depending on patient needs, clinical protocols, and candidacy assessment for further interventions, e.g., cochlear implant candidacy assessment. However, while some countries include speech testing within recommended audiology practice guidance (College of Audiologists and Speech-Pathologists of Ontario, 2018; Rehabilitation Council of India, 2015), others do not (British Academy of Audiology, 2014). According to a global survey of audiology practice, audiologists in 46% of countries (*n* = 62 countries, representing 78% of the world’s population) carried out speech tests (respondents were not asked to report the types of speech tests used) (Goulios & Patuzzi, 2008). Speech testing is also used within cochlear implant (CI) candidacy assessment in the UK, but such practice in other countries varies. This may be driven by the differing service delivery models and funding sources for CI assessment and rehabilitation as well as a lack of clear clinical guidance in many countries (British Cochlear Implant Group, 2017; Vickers et al., 2016a). The inconsistency of practice is particularly concerning as preoperative level of speech understanding is one of the most valuable measures within the CI referral and candidacy assessment (Vickers et al., 2016b; Zwolan et al., 2020). Inconsistency of speech testing practices between HHPs, audiology centres and countries will impact the interpretability of test results, how trends in patient populations are monitored, and how outcomes are compared between sites, depending on the level of disparity.

In general, the private healthcare sector is consumer-oriented and quality services are underpinned with the understanding that the consumer can withhold resources at their discretion, which can have significant implications to the future development and functioning of the organisation (Herrera et al., 2014). The public health sector in the UK (National Health Service: NHS), however, is clinician/systems-centred and services are driven by professional protocol and national clinical guidance rather than end-user review (Bradshaw & Bradshaw, 2004; Shen et al., 2007). In recent years, however, European public healthcare systems have adapted to increase the choice of healthcare provider available to the patient, with the assumption that a competitive market would improve the overall quality of services (Walumbe et al., 2016).

In England, the “Any Qualified Provider” policy was established to allow a specific subset of patients to choose any audiology provider (NHS services, private sector or voluntary sector), as long as they met an agreed quality standard and price (Health, 2011). Given the continuously adapting nature of healthcare service delivery models and national clinical guidance, it is important to explore factors that influence audiological clinical practice across sector, including the use of speech testing. This is particularly important as private hearing aid services for adult patients in the UK, are steadily growing (The British Irish Hearing Instrument Manufacturers Association, 2021).

The aims of this chapter were to evaluate HHPs’ speech testing practices in routine adult audiology services within the UK and across the world, and better understand the facilitators and barriers to speech testing provision. This work is presented within the framework of UK audiology healthcare delivery for both public and private practice. This approach enables comparison with other countries based on a public or private funding infrastructure. The scoping review presented enables comparison with other countries.

3.3 Method

3.3.1 Speech testing around the world: A scoping review

A scoping review was conducted in April 2021 in accordance with the steps outlined in Arksey and O’Malley (2005): (a) identifying potentially relevant records, (b) selecting relevant records, (c) extracting data items and (d) collating, summarizing and reporting results. Studies were included if they utilised questionnaires to report audiologists’ speech testing practices in routine adult audiology. The publication year was limited to studies published after 1995 to reflect more recent practice patterns and highlight practice changes over time. The following keywords were used in the search: “audiolo* practice” AND “speech” AND “survey” OR “questionnaire”. Furthermore, research articles were included if they referred to routine adult audiology practice and were excluded if they referred to specialised services, including CI programmes. The purpose of the scoping review was to answer the following question: What speech testing practices are used within routine adult audiology?

3.3.2 Information sources

Studies were identified by searching the following databases: PubMed, Web of Science, PsycINFO, CINAHL and Google Scholar. The reference lists of the included publications were manually scanned to identify further studies. Google Scholar was used to identify grey literature in addition to peer-reviewed articles. However, due to the large number of search records identified through Google Scholar, only the first 50 records were included (search ordered by relevance). **Figure 3.1** shows the article inclusion flowchart for the present study.

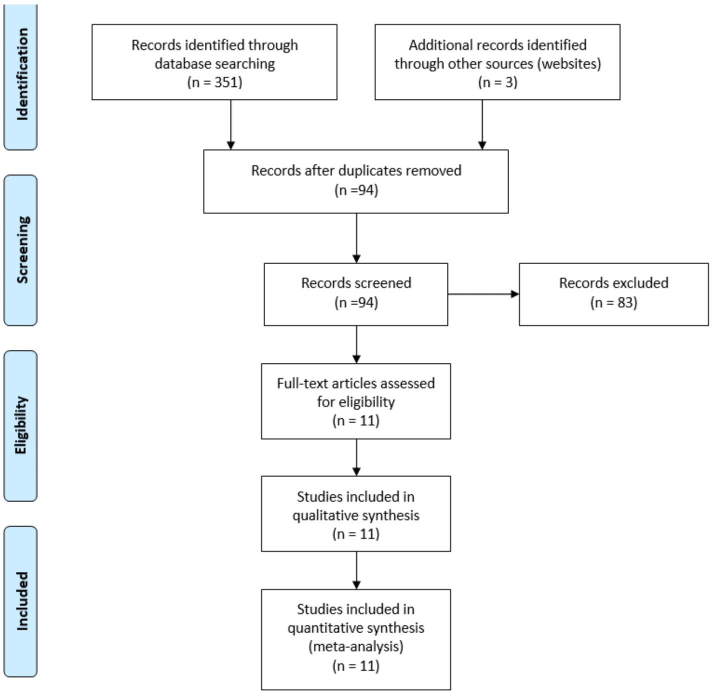


Figure 3.1 Article inclusion flowchart.

3.3.3 Speech testing within routine adult audiology (UK): Questionnaire study

3.3.3.1 Ethical approval

This study was approved by the University College London Ethics Committee (Project no. 3866/001). This research also received internal ethical approval from all professional organisations that assisted in questionnaire distribution. All questionnaires were completed anonymously, and respondents were not asked to provide any personally identifiable details or health information. Data was stored in compliance with the European Union’s General Data Protection Regulation (2016/679), and participant consent was implied based on completion of the questionnaire.

3.3.3.2 Questionnaire development

A questionnaire was developed collaboratively with private sector and public sector UK practicing audiologists. The main aim of the questionnaire was to explore speech testing practices in UK adult audiology. Therefore, the questions were initially drafted by the lead researcher to cover the following areas: respondent demographics, speech testing practice, benefits, and barriers to completing speech testing. A review panel consisting of researchers, private sector hearing aid dispensers and public sector audiologists trialled the questionnaire and were asked to give feedback on questionnaire usability, design, and content. The feedback was used to improve the questionnaire. Some of these amendments included modifying the list of tests listed for the question ‘What type of speech tests do you perform?’ to ensure they reflected common UK practice, the addition of comment boxes so clinicians could add answers that did not feature in multiple choice menus and asking respondents for their regional location to compare provision across the UK.

The questionnaire was created to address three main areas of interest (the full questionnaire is available in Appendices 9.3:

a) *Demographics* (employment sector, main patient population, and geographical location)

b) *Speech testing practice questions:*

  - When seeing an adult patient in audiology for the first time do you perform any kind of speech perception testing as part of the assessment process? (Scale: *Never-Rarely-Sometimes-Often-Always*)
  - What type of speech tests do you perform at the first (assessment) appointment? (If applicable)
  - When fitting an adult patient with hearing aids do you perform any kind of speech testing on the day of the fitting? (Scale: *Never-Rarely-Sometimes-Often-Always*)
  - What type of speech testing do you carry out at the time of hearing aid fitting or follow up? (If applicable)
  - If you perform speech testing, what do you use to present the speech tokens and noise?
  - What are your main barriers/challenges to performing speech testing regularly?

c) What are the benefits of speech testing? (free text answer)

d) Do you perform sound localisation assessments? (Yes/No)

Questions that did not use a response scale or require free text answers presented the respondent with a multiple-choice list of potential answers as well as a comment box. Respondents could select multiple answers for all multiple-choice questions. Given that longer surveys are less likely to be completed (Sahlqvist et al., 2011), the present questionnaire was designed to ensure that it could be completed within five minutes. During questionnaire development, four expert HHPs reviewed the clarity and content of the questionnaire and modifications were made based on these comments. The selection of options for the multiple-choice questions were selected and revised, after discussions with the reviewing clinicians to reflect common UK practice patterns. For example, when respondents were asked to select the type of speech test conducted at the assessment or hearing aid fitting they were presented with options including the Arthur Boothroyd word lists (Boothroyd, 1968) (“AB words”), speech recognition threshold measures, QuickSIN, BKB sentences and the LISN-S. The AB words were developed in the UK and comprise of 15 lists of 10 monosyllabic consonant-vowel consonant words. AB words are used around the world (Myles, 2017), with a variety of clinical applications (Boothroyd, 2006). Also, normative data is available from the UK population (Vickers et al., 2009), and the lists are used within the adult cochlear implant candidacy assessment (National Institute for Health Care Excellence, 2019). QuickSIN (Killion et al., 2004) is a sentence in noise test and can be used for unaided and aided assessment to give an estimate of signal to noise ratio loss within a short duration (Walden & Walden, 2004).

The BKB sentence test is also widely used in the UK for both adult and paediatric populations (Graham et al., 2009). It consists of 21 lists of 16 sentences and each list contains 50 key words for scoring. The Listen in Spatialized Noise sentence test (LISN) determines speech reception thresholds for sentences at 0° with competing speech collocated or spatially separated from the target speech, simulated under headphones. It has been used to assess auditory processing skills in a range of patients (Cameron et al., 2006; Cameron et al., 2011). In the UK, the QuickSIN, AB words and BKB sentences are available within common PC-operated audiometry equipment.

The survey was developed, distributed, and completed via the SurveyMonkey web-based tool and all anonymized data were securely stored. A small number of respondents chose to skip questions about the type of speech tests and equipment used, therefore the results to these multiple-choice questions are presented alongside the total number of respondents for each question.

3.3.3.3 Recruitment

HHPs providing audiological care to adult patients in the UK were invited to take part in an online survey, which was available for 12 weeks between April and June 2019. The hyperlink and information sheet were circulated via email to audiology departments in each of the 124 NHS trusts in England with complete patient pathways for Direct Access Audiology as of March 2019 (NHS England, 2019). To ensure any regional diversity was captured, the same information was sent to the audiology services in each of the five health boards of Wales, the five Health and Social Care Trusts in Northern Ireland and the 14 regional health boards of Scotland. Following a snowball sampling approach, HHPs were also asked to forward the survey to colleagues or others they knew who were working in the audiology field. Additionally, the organisations sent the survey link and information sheet to all members. Each professional body listed below was contacted to provide the number of current full members at the time of writing.

- British Society of Audiology (BSA): 1,048 members
- British Academy of Audiology (BAA): 1,800 members
- British Society of Hearing Aid Audiologists (BSHAA): 1,500 members
- Association of Independent Hearing Healthcare Professionals (AIHHP): 79 members

At the time of writing, 2,312 audiologists were registered to the Registration Council for Clinical Physiologists (RCCP) and 3,063 HA dispensers were registered to the HCPC. However, it is not known how many audiologists specifically work in adult audiology and HHPs may register with multiple organisations.

3.3.3.4 Response rate

Overall, 306 HHP respondents completed the online questionnaire, whilst 11 respondents reported only working in paediatric audiology and were therefore removed from the analyses. This resulted in a total of 295 HHPs providing valid questionnaire data for the study (96% retention). Overall, the response rate in this study (*n* = 295) was approximately 8% to 10% of UK registered HHPs. This sample size reflects approximately 8–10% of UK registered HHPs and is similar to the number of respondents obtained by other UK-based surveys of audiologists (Parmar et al., 2021; Wright et al., 2014).

3.3.3.5 Data analysis

Given that HHPs may have received multiple invitations to participate in this study, IP addresses were checked to ensure respondents only completed the questionnaire once. Descriptive statistics were used to summarize the multiple-choice questionnaire items: the relative frequency (RF) is reported as a percentage of the total number of responses for questions in which multiple answers could be selected. For statistical analysis, the scaled responses “Sometimes”, “Often” and “Always” were combined to present the proportion of HHPs conducting the activity and responses “Never” and “Rarely” were combined to present those that tended not to conduct the activity (Jeong & Lee, 2016).

Two binomial logistic regressions were conducted to determine whether the use of speech testing, at the audiological assessment or the hearing aid fitting, were influenced by sector (public vs. private) or patient population (adults vs. both adults and children). Performance of model fit was evaluated by calculating the area under the curve (AUC) of ROC curves for each model, and sensitivity and specificity were calculated using optimal cut points (Youden, 1950). This analysis method was used due to the presence of binary outcomes and multiple categorical variables, therefore making it more appropriate than the repeated measures analysis of variance originally piloted. Additionally, Chi-squared test of independence was conducted to determine whether the likelihood of speech testing being conducted in the first appointment was associated with the likelihood of speech testing being conducted at fitting.

Inductive thematic analysis was used to analyse free text responses (to the open-ended question “What are the benefits of speech testing?”). The first and second authors double coded all the free text answers, using line-by-line coding, and grouped coded data into themes. Any discrepancies were resolved at two separate timepoints within the study.

3.4 Results

3.4.1 Speech testing around the world: A scoping review

Collectively, 11 studies were identified across seven countries (US, India, Canada, Saudi Arabia, Australia, South Africa and Malaysia) to evaluate the use of speech tests in audiology based on survey methods (**Table 3.1**). Each study used different questionnaires and rating scales to explore speech testing in audiology. Respondents were typically asked about their use of speech testing in two ways: a closed yes/no question of speech testing practice or a Likert scale highlighting practice at specific time points. Overall, the use of speech recognition threshold measurements ranged from 24% to 99% of respondents, and the use of speech in noise testing ranged from 2% to 66% of respondents. Only five studies reported the type of transducer typically used for speech testing (see **Table 3.1**).

Canadian and American audiologists have reported that monitored live voice techniques were implemented in 89% to 94% of audiology practices (DeBow & Green, 2000; Martin et al., 1998), whilst this technique was only reported to occur for 2% of Australian audiologists (Myles, 2017). HHPs also indicated that ear-specific transducers (i.e., supra-aural headphones or inserts) were used commonly in Canada (90%) and Australia (66%; DeBow & Green, 2000; Myles, 2017), although India only reported the use of sound field speech presentation or supra-aural headphones in 15% to 20% of adult audiology practices (Nandurkar et al., 2015). Of note, only two studies evaluated barriers to speech testing in adult audiology (Nandurkar et al., 2015; Thakor, 2020). Barriers were consistent across both studies and included time constraints, lack of equipment and language differences. Three studies asked respondents about the reasons for implementing speech testing in audiology practice (Myles, 2017; Nandurkar et al., 2015; Thakor, 2020; see Table 2.1 for a full list).

Study	Country	HHPs	Use of Speech Tests	Transducer	Use/Barriers
(Martin et al., 1998)	US	218	*SDT: 69%, SRT: 99.5%*	*Monitored live voice*: 94%	N/A
(DeBow & Green, 2000)	Canada	115	*Word recognition threshold measures: 85%*	*Monitored live voice:* 89% *Supra-aural headphones:* 90%	N/A
(Kirkwood, 2005)	US	674	Speech audiometry: *Never: 1.2%, half the time: 1.2%, always: 90.8%*	N/A	N/A
(Easwar et al., 2013)	India	199	*SRT only: 24%, SRT & speech identification: 38.7%,* *SRT & SIN: 2.5%, SIN only: 2%.* *No routine speech tests: 19%*	N/A	N/A
(Nandurkar et al., 2015)	India	59	Speech perception tests: *Always: 22%, often: 34%, sometimes: 36%, rarely/never: 8%.* SIN: *Always: 5%, often: 29%, sometimes: 34%, rarely: 17%*	*Headphones:* 21% *Sound-field:* 15%	Reasons for using speech tests: *assess HA efficacy: 76%, HA candidacy assessment: 63%, assess patient difficulties: 52%, diagnostics: 39%.* Barriers: *Time, lack of adequate material/setting, language*
(Alanazi, 2017)	Saudi Arabia	23	SRT: *65%*, SDT: *48%*, SIN*: 0%*	N/A	N/A
(Ali et al., 2017)	Malaysia	111	Speech audiometry: *Never: 62.24%, half the time: 26.53%, usually/always: 11.22%*	N/A	N/A
(Myles, 2017)	Australia	312	AB word lists: *Routine use: 95%; in quiet: 99.6%, in noise: 5%*	Live voice: 2%, ear specific transducer: 66%	Reasons for use: *cross-check pure tone audiogram: 96%, diagnostic: 83%, counselling: 87%, protocol requirement: 63%, rehabilitative: 79%*
(American Speech-Language-Hearing Association, 2019)	US	751	Implementation of SIN testing to validate treatment outcomes: *Daily/weekly: 35%, monthly: 26%, never: 39%*	N/A	N/A
(Anderson et al., 2018)	US	251	Initial HA fitting: *SRT & word recognition: 98%, unaided SIN: 80%,* *aided SIN: 66% (often or sometimes).* Fine tuning of HAs: SIN*: 67%,* Speech-in-quiet*: 66% (often or sometimes)*	N/A	N/A
(Thakor, 2020)	South Africa	107	SRT: *Never: 13%, rarely: 7%, occasionally: 5%, sometimes: 7%, frequently: 9%, usually: 12%, always: 47%,* SIN: 36%	Live voice: 82% Pre-recorded: 8%	Use of SRT: *calculating correlation with PTA, part of departmental/practice protocol, to obtain a to calculate presentation level for other speech tests, counselling tool.* Use of SIN: *patient counselling, managing patient expectations.* Barriers: *language, lack of equipment, time*

Table 3.1 Scoping review results. Summary of survey study results provided by HHPs related to adult audiology speech testing practices. SRT: Speech recognition threshold, SDT: Speech detection threshold, SIN: Speech in noise tests, AB: Arthur Boothroyd.

3.4.2 Speech testing within routine adult audiology practice (UK): Questionnaire analysis

3.4.2.1 Demographics

Responses from 295 HHPs actively practicing within adult audiology services across the UK were included in the present study. There were 64% of respondents working in the public sector (NHS) and 36% working in the private sector. The regional composition of HHPs is detailed in Figure 3.2.

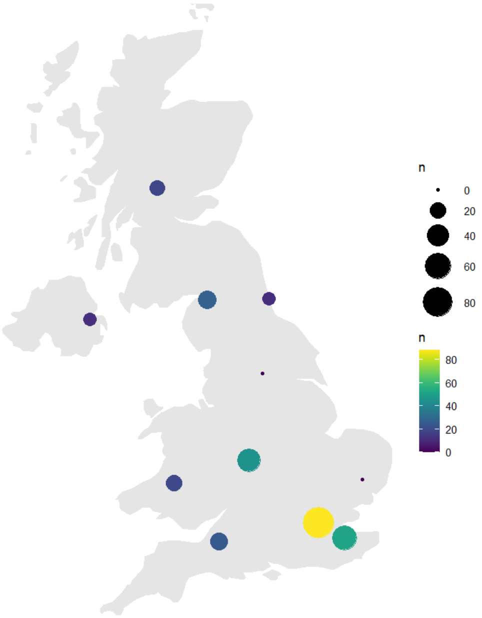


Figure 3.2 Respondents' regional location.

3.4.2.2 Speech tests in routine adult audiology

Overall, 38.2% of HHPs reported carrying out speech testing at the first audiological assessment appointment either “Sometimes”, “Often” or “Always” and 36.5% respondents indicated that they carry out speech testing during the hearing aid fitting stage (see **Figure 3.3**). Furthermore, only 13% reported performing clinical localisation tests within adult audiology.

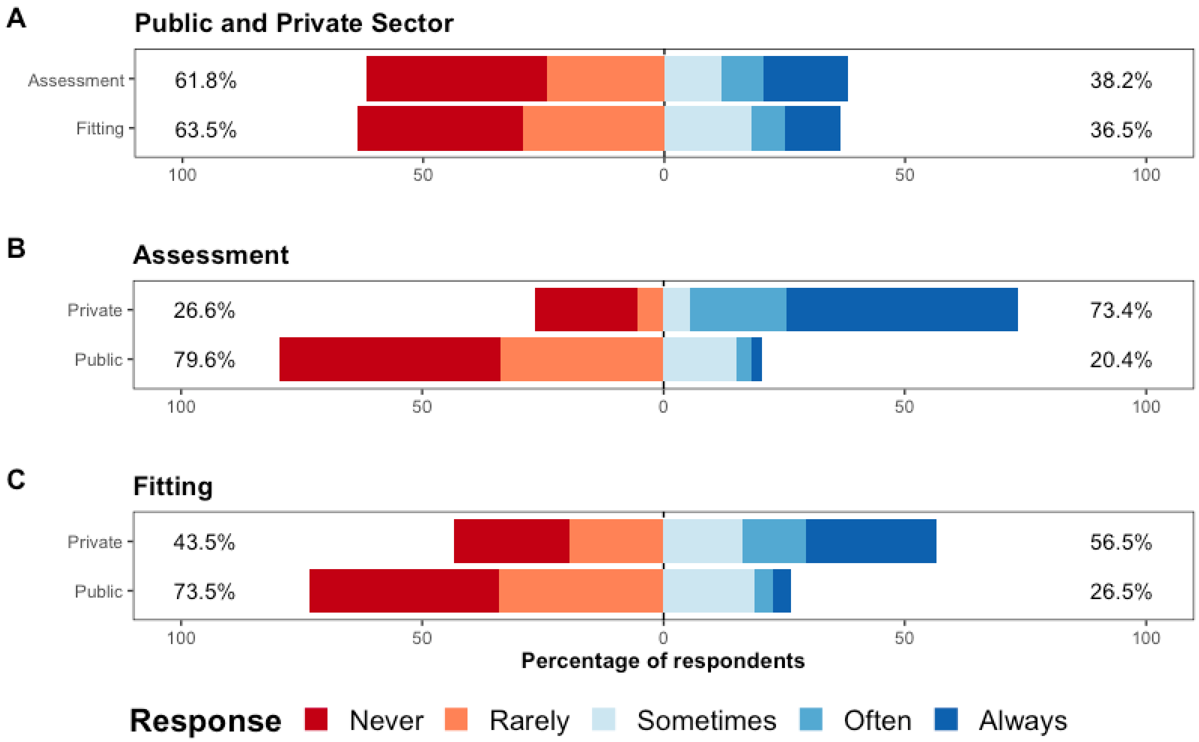


Figure 3.3 Use of speech testing in routine adult audiology. This figure refers to Questions 3 and 5 of the survey. (A) The distribution of HHP respondents’ use of speech testing during adult audiology assessments and fittings, (B) Private and public sector HHPs’ use of speech testing during the hearing assessment and (C) The use of speech testing during hearing aid fittings by private and public sector HHPs. Response categories were grouped to present the percentage of HHPs who responded positively to conducting speech testing, reporting either “Sometimes”, “Often” or “Always”, and those who did not use speech testing by reporting either “Rarely” or “Never”.

3.4.2.3 Predictors of speech testing practice

To investigate whether there is a difference in the use of speech testing between sectors, two binomial logistic regressions were conducted. In the first model (AUC = 0.815, sensitivity = 0.778, specificity = 0.750) speech testing during the audiological assessment was the dependent variable, and predictor variables of sector (public or private) and patient population (adults vs. both adults and children) were included. It was found that speech testing is more likely to be conducted in private than in the public sector (F(1,172) = 32.16.10, $p < 0.001$). The second model (AUC = 0.737, sensitivity = 0.678, specificity = 0.685) also found private sector HHPs more likely to carry out speech testing at the hearing aid fitting compared to those in the public sector (F(1,172) = 8.31, $p = 0.004$) (**Figure 3.3**). There was no significant effect of patient population in either model.

Lastly, a chi-squared test of independence was conducted to determine whether the likelihood of speech testing being conducted in the first appointment was associated with the likelihood of speech testing being conducted at fitting. The test was statistically significant ($\chi^2(1) = 81.51$, $p < 0.001$), implying that there is an association between these two variables.

3.4.2.4 Types of speech tests used in adult audiology practice

The QuickSIN and Arthur Boothroyd (AB) word lists were the most commonly used speech test materials for the initial assessment appointment and the HA intervention (see **Table 3.2**). Four alternative speech measures were identified by respondents as “Other”, including the City University of New York Sentence Test (Boothroyd et al., 1985), the Acceptable Noise Level Test (Nabelek et al., 1991), the Ling Sounds Test (Ling, 1976) and informal conversational speech with and without lip reading cues.

Speech Test	**Private Sector**		**Public Sector**	
	Assessment (%) *n* = 90	Fitting (%) *n* = 88	Assessment (%) *n* = 181	Fitting (%) *n* = 181
QuickSIN	66.7	44.3	29.8	21.6
AB words	38.9	30.7	38.1	34.8
BKB	8.9	10.2	14.4	18.8
LISN-S	10.0	3.4	1.1	2.2
SRT	20.0	9.1	14.4	8.8
Other	10.0	5.7	7.7	14.4

Note. AB: Arthur Boothroyd, SRT: Speech recognition threshold, BKB: Bamford-Kowal-Bench, LISN-S: Listening in Spatialized Noise Test.

Table 3.2 Speech test materials used at the first audiological assessment appointment or follow-up appointment (% of responses).

Ear-specific transducers (either insert or supra-aural headphones) were the most commonly used equipment for speech testing (see **Table 3.3**). The use of one individual loudspeaker (39.7%) or a live voice in a face-to-face context (24.4%) were also common. Three alternative methods (live voice of the patient's family member, live voice with a sound level measurement and bone conduction) were identified as "Other".

Equipment Type	**Public Sector (%) (*n* =188)**	**Private Sector (%) (*n* = 94)**	**Total (%) (*n* = 282)**
Ear specific transducers (Headphones/inserts)	55.3	44.7	51.7
Live voice (face-to-face)	25.0	23.4	24.4
1 loudspeaker	39.8	42.2	39.7
2 loudspeakers	10.2	7.8	9.2
Multi-speaker array	2.2	6.7	3.5
Other	7.1	8.7	4.3

Table 3.3 Equipment used during speech testing in adult audiology (% of responses).

3.4.2.5 Barriers to using speech testing in routine adult audiology

The most commonly reported barrier to performing speech testing was the lack of clinical time (59.8% of respondents). This was followed by the lack of appropriate equipment and a lack of training (see **Table 3.4)**. In addition to the five forced-choice barrier options offered in the questionnaire (lack of clinical time, lack of equipment, lack of training, lack of test sensitivity and lack of benefit), HHPs identified several other factors that they felt posed significant barriers to speech test use. These included the lack of speech test material in non-English language, unfamiliar accents, departmental protocol restrictions, a lack of normative data, a limited availability of tests suitable for adults with additional needs and no clear evidence for patient benefit.

Barriers	**Public Sector (%)** ***n*** **= 188**	**Private Sector (%)** ***n*** **= 90**	**Total (%)** ***n*** **= 291**
Lack of clinical time	78.1	24.4	59.8
Lack of appropriate equipment	34.6	16.7	28.1
Lack of training	21.3	8.9	16.5
Lack of test sensitivity	6.4	10	7.6
Lack of benefit	5.3	1.1	3.8
Other	12.8	16.7	13.8

Table 3.4 Barriers to completing speech testing in adult audiology.

3.4.2.6 Benefits of speech testing

Responses to the open question “What do you think the benefits of using speech testing in routine adult audiology are?” were analysed thematically. Although this question asks for benefits of speech testing and therefore indicates the need for positive responses, respondents were asked to specify “N/A” in the response area if they could not name any benefits. Three main themes were identified: (a) *providing patients with relatable assessment information*; (b) *guiding HA fitting* and (c) *supporting a diagnostic test battery.* All themes were present in responses by HHPs from both the public and private sectors. A high number of respondents in both the public- and private-sector HHP groups indicated that speech tests provided a valuable tool for demonstrating and explaining audiometric data and speech perception in everyday listening difficulties (52% of public sector HHPs and 53% of private-sector HHPs) and also for guiding HA fitting (41.4% of public-sector HHPs and 40% of private-sector HHPs). Private-sector practitioners less commonly suggested that speech testing was helpful in diagnostic test batteries (16.7%) compared to public-sector respondents (27.3%).

1) Providing patients with relatable assessment information

Speech testing provides patients and their families with information about the personal impact of hearing loss on speech understanding. The respondents thought that speech testing was particularly helpful for demonstrating functional hearing difficulties to patients (and their families) and provides the HHP with another tool to identify patients' communication barriers.

> Convinces more than any other test that the patient's problem is: a) real; b) serious. Denial is the biggest barrier to acceptance—speech testing breaks the barrier down better than everything else combined! (Private sector)
>
> For patients, it highlights need and reaffirms their awareness of hearing loss. For clinicians, it helps us understand their communication issues in a way a pure tone audiogram cannot. (Private sector)

HHPs reported that presenting speech to patients with hearing loss was more effective than pure tone audiometry alone for helping patients relate testing results to real world listening scenarios.

> Real life stimulus is often easier for the patient to relate to, and it also gives a better idea of the actual benefit to the patient. Also gives some idea of processing as opposed to just detection of sound. (Public sector)
>
> People will often associate the test with their primary issues with background noise and will often feel listened to when the speech test is complete and explained. (Private sector)
>
> The standardised audiogram doesn't reflect realistic listening situations and so speech tests may provide a more accurate representation of an individual's hearing difficulties. (Public sector)

Finally, respondents felt that speech testing helped HHPs manage patients' expectations during audiology consultations. One commonly reported example was the mismatch in the audiogram classifications (e.g., mild hearing loss) and the communication difficulties experienced by the patient. Therefore, they believed that speech testing was beneficial for improving patients' understanding of their own hearing abilities. Beyond diagnostic assessment, speech testing was also reported to be beneficial for the counselling process and could lead to improved patient satisfaction.

> It allows you to gain a picture of their actual hearing. A person can have a mild loss but may struggle with speech more so. It is also a good tool to use for counselling and rehab purposes and allows you to set realistic expectations. (Public sector)
>
> Gives you a better understanding of patients' loss and possible problems, for both clinician, patient and family which should allow for better treatment outcome. Should reduce return appts for some patients and lead to better satisfaction for those often listed as difficult. (Public sector)

2) Guiding HA fitting

Speech tests can be used to assess functional HA benefit. HHPs reported making HA adjustments based on speech tests and the results from aided speech testing were used to identify the limitations of HAs. Although HHPs felt speech testing was a useful counselling tool to demonstrate aided vs unaided speech perception performance, they reported a lack of standardisation in assessing HA benefit.

> Gives level of functional hearing difficulty perhaps not revealed by PTA alone. Allows before and after aiding comparison to validate efficacy of hearing aids. (Public sector)
>
> A really useful counselling tool with patients at assessment to explain their processing in noise without visual cues (especially those with a greater SNR loss). A shame it is not a verified test for assessing improvement with hearing aids. (Private sector)
>
> Speech testing is a good tool to measure the benefit from the hearing aid. If speech testing is carried out on the first fit appointment, we can adjust the hearing aid characteristics based on this and address some issues then and there which will improve patient satisfaction and can reduce follow up visits. (Public sector)
>
> It's the only way to understand the functional impact. It can be very surprising how much the speech test scores can vary from the audiogram in patients who are not successful with amplification. (Private sector)

3) Supporting a diagnostic test battery

Speech testing was also reported to be a useful part of the audiological test battery to assist in the diagnosis of specific auditory conditions, especially in those where the patient's functional hearing is not predictable from the audiogram (e.g., auditory processing disorder, non-organic hearing loss).

> Diagnostics, part of APD (Auditory Processing Disorder) test battery, aural rehabilitation (cognitive load and listening effort, directional microphones, noise reduction algorithms, validation of fitting etc.) (Private sector)
>
> We are sometimes asked by ENT to perform speech testing on acoustic neuroma clinics, but do not routinely use them unless there is a complex patient or unexplained problems with hearing, i.e., to assess if there may be an auditory processing issue. (Public sector)

HHPs also reported the use of speech testing in the audiological diagnostic assessment battery for determining CI candidacy (indications for CIs).

> Identifies patients with very poor speech discrimination abilities. Assists with counselling on cochlear implant candidacy. (Public sector)

3.4.3 Summary of results

The scoping review presented in this chapter summarised the speech testing practices of a total of 2820 HHPs working in audiology settings in seven countries. Of the studies that reported speech recognition threshold (SRT) practices (n=10 countries, n=2069 HHPs), 1798 respondents (87%) reported carrying out this testing regularly. Each study presented in the scoping review differed in scope and purpose and utilised different survey questions. The scoping review did not uncover practice patterns from the UK. Therefore, a questionnaire of speech testing practice was developed and completed by 295 HHPs within this thesis. Overall, results found that 44% of UK HHPs carried out speech testing regularly. Barriers to speech testing uptake included lack of clinical time and adequate resources in India, South Africa (see Table 3.1), and the UK, but details of testing methodologies and reasoning was not consistently reported across studies.

3.5 Discussion

The aims of this chapter were to evaluate HHPs’ speech testing practices in routine adult audiology services within the UK and across the world, and better understand the facilitators and barriers to speech testing provision. A scoping review was carried out to understand the global landscape of speech testing practice, but no practice data was available from the UK. Therefore, a new questionnaire study of UK HHP’s speech testing practice was completed (n=295) in this chapter. Separating the UK sample into public and private sectors highlights the influence of various factors in these areas of healthcare and helps facilitate comparison with practice in other countries.

Overall, results for the rate of use of speech tests in UK adult audiology practice (26% during assessment; 18% during HA fitting) are far lower than indicated in the literature on audiology practice data from the US (American Speech-Language-Hearing Association, 2019; Kirkwood, 2005), Canada (DeBow & Green, 2000), Australia

(Myles, 2017), South Africa (Thakor, 2020) and Saudi Arabia (Alanazi, 2017; see Table 2.1). However, these results mask a significant difference in speech testing approaches between the public and private sector, with HHPs in the private sector more likely to perform speech testing than those in the public sector. The type of test used also differed with sector and appointment type. This variability is evident around the world. For instance, speech in noise administration rates in India varies from 4.5% of respondents (Easwar et al., 2013) to 34% of respondents (Nandurkar et al., 2015), and speech in noise measures were not performed by any respondents in a Saudi Arabian study (Alanazi, 2017). In contrast, a study of American audiologists found that 66% incorporated aided speech in noise measures, and 80% performed unaided speech in noise measures at the initial HA fitting (Anderson et al., 2018). Differences in healthcare provision models across the world may partially explain these discrepancies. More specifically, audiology practices within the US are most akin to reports from private sector UK-based HHPs, given that American health services are predominantly reliant on private funding and insurance policies. These findings are further supported by a study demonstrating speech testing as a treatment outcome after HA fitting in private American audiology practices (American Speech-Language-Hearing Association, 2019). It can be argued that the commercial nature of private sector HA provision may influence the provision of speech testing.

Despite the low uptake of speech tests in the UK, respondents reported specific speech test measures and equipment used in clinical practice. Ear-specific transducers were the most commonly used equipment for delivering speech testing, although in many cases a single loudspeaker set-up was also used. Surprisingly, reliance on face-to-face live voice was identified as the third most popular choice for speech testing modality. The prevalence of this method was unexpected given the uncalibrated, highly variable nature of interactive, naturalistic voice testing, which can lead to inconsistencies between HHPs and make it particularly challenging to compare performance between testing conditions and testing centres (Hood & Poole, 1980; Roeser & Clark, 2008). Audiologists in Canada (DeBow & Green, 2000), South Africa (Thakor, 2020) and Australia (Myles, 2017) also reported a high reliance on the use of live voice during speech testing. The increased use of live voice testing may be due to variation in equipment, lack of validated recorded speech materials in appropriate languages/accents and time availability. Very few respondents reported using multi-speaker arrays to conduct speech testing and this could also account for the lack of localisation assessments carried out (just 13% of HHPs carrying out localisation testing). During a typical group conversation, there may be several speakers and background noise sources and the listener will need to both locate where the speaker of interest is and adapt their focus to discriminate between speech and noise. If listening skills assessed within speech testing differ significantly from those required for everyday communication, the real-world applicability of test results may be affected.

Audiology practice surveys performed in Australia, South Africa and India highlighted reasons why HHPs performed speech testing in routine adult audiology practice (Myles, 2017; Nandurkar et al., 2015; Thakor, 2020). These included cross-checking results with pure tone audiometry findings, counselling and managing patient expectations, assessing HA candidacy and use within the diagnostic test battery. In this study, despite the relatively low uptake of speech testing across adult audiology practices in the UK, HHPs reported different beliefs in the potential benefits of speech testing. One of the most common benefits was how speech testing helped patients and their families understand audiological assessment results in everyday speech perception difficulties. Adults with hearing loss have previously reported that HHPs were unaware of their communication needs, and patients could not recall technical clinical information (Watermeyer et al., 2015a). Using more ecologically valid stimuli such as speech could help patients apply their diagnostic results to real world listening scenarios. Previous literature has suggested that enhanced ecological validity can lead towards more integrated and individualised hearing healthcare (Keidser et al., 2020).

Several HHPs indicated that speech testing was beneficial to compare functional performance pre- and post-HA fitting. This included the ability to validate the efficacy of the HA fitting and to adjust the HAs based on their settings. However, some respondents reported a lack of verified methods to measure HA benefits. Previous studies have used speech testing as a sensitive outcome measure to explore the impact of complex HA systems (Glista et al., 2009; Wolfe et al., 2011) and to evaluate hearing device fine tuning (Tonelini et al., 2016). However, current speech testing practice guidance does not include the adjustment of HAs in response to speech testing results (British Society of Audiology, 2019). Clinical HHPs may benefit from further training and guidance to meaningfully interpret and use unaided and aided speech testing results to assess and improve HA fitting and rehabilitation.

Respondents, particularly those from the public sector, reported the importance of using speech testing within the clinical diagnostic test battery. This could be due to the public sector's connection to other medical departments (e.g., tertiary level audiology departments connected to Ear, Nose and Throat and CI centres). In such settings, there may be an additional need for speech testing. Differences in HHP training and education between the private and public sector in the UK may also contribute to corresponding differences in identifying the need for speech testing based on medical rationale. Speech testing is included in the diagnostic test battery for specific conditions (e.g., central auditory processing disorder; American Speech-Language-Hearing Association, 2014). Therefore, it is important HHPs across all sectors remain up to date with information about their use and have access to adequate training and resources to provide appropriate intervention options for patients. Furthermore, as speech testing is performed within the CI candidacy assessment across the world (British Cochlear Implant Group, 2017), raising awareness of speech testing within routine audiology practice could help identify potential candidates earlier and lead to increased uptake.

Despite the overall low uptake of speech testing presented in this study, the lack of benefit of such testing was not considered a common limiting factor. The majority of public-sector HHPs in the UK reported the lack of clinical time as a primary barrier to performing speech testing, despite the availability of assessments designed to be completed within a few minutes (e.g., QuickSIN). In the UK, public health commissioning groups use NICE guidelines to allocate funds and resources (Chundu & Flynn, 2014); the absence of speech testing in such guidelines could influence the time and resources allocated for these activities in public-sector audiology services. Audiologists around the world have reported a lack of government funding for audiology services (Goulios & Patuzzi, 2008). Previous researchers have also found time demands to be the highest stress factor for HHPs (Emanuel, 2021; Severn et al., 2012), but some have suggested these factors may affect more public sector clinicians than independent private clinicians (Mott et al., 2004). Flexible resource management within the private sector is more likely to impact the significant differences between the provision of private- and public-sector speech testing observed in this study and globally.

Beyond the forced-choice barrier options, respondents reported several additional factors limiting speech testing uptake, including the absence of speech testing in departmental protocols and a lack of evidence for how speech testing can be used for individual patients. These factors align with barriers reported worldwide (Table 3.1). Although speech testing is recognised as a functional hearing assessment, the lack of standardisation represents a barrier to its clinical use (Moore et al., 2019), affecting the consistency of speech testing usage between clinicians and services across the world. The use of speech materials are sensitive to a person’s cognitive function (Nuesse et al., 2018), and the choice of using word or sentence stimuli is dependent on clinical requirements and the influence of other factors (e.g., contextual cues in sentence materials; Wilson & McArdle, 2005). Speech tests differ in functionality in a hierarchical manner; some assess the listener’s ability to detect speech stimuli, whilst others assess sentence discrimination. Therefore, HHPs require guidance to choose the most appropriate measure depending on evidence and clinical need. There is also a need for more sensitive triage techniques and cognitive screening measures within audiology to improve the holistic interpretation of results (Shen et al., 2016). Moreover, speech test materials are not available for all languages and accents (Nandurkar et al., 2015; Thakor, 2020).

These barriers were also reported by UK respondents in this study. However, recommendations for the construction of multilingual speech tests are available such that they can be administered in the listener’s native language, even if the tester does not understand that language (Akeroyd et al., 2015). HHPs reported the absence of speech testing in departmental and national guidance in this study, which is in agreement with findings from other countries (Alanazi, 2017). The lack of such guidance may contribute to inconsistencies in practice, including the use of speech testing. A collaboration between health authorities, researchers, hearing device manufacturers, HHPs and service users could lead to the development of accessible toolkits of validated speech test materials, normative data, recommended equipment and practical guidance.

This research is the first of its kind to report on the patterns of speech testing practice in routine adult audiology practices, both within the UK and in consideration of the impact from an international perspective. A notable strength of this work is the inclusion of UK-based public- and private-sector audiology services in an international context to reveal similarities and differences in audiology practices around the world. The provision of healthcare services by private versus public sectors differs on a country-level basis, necessitating a direct comparison of different service delivery approaches on an international scale. However, there are also some limitations within this study. Due to the sampling method, it was not possible to calculate a response rate for this study. Furthermore, although many UK-based HHPs felt speech testing was beneficial in this study, this research did not investigate the reasons and motivations for using speech testing on a case-by-case basis and whether the incorporation of speech testing impacted patient care, outcomes and satisfaction as well as HA use. The present study also did not explore impact of HHPs' educational level on speech testing practice. Finally, despite involving key stakeholders in the development of the questionnaire, there are limitations in the choice and range of questions. Further developments to the questionnaire could ensure that detailed speech testing activities are captured in future studies e.g., information about the type of distractor stimuli, adaptive vs fixed level testing and the presentation of sentences vs single word stimuli. Including a comprehensive list of speech test examples could also help identify speech in quiet and speech in noise testing practice patterns.

Data exploring clinical audiology service provision is often collected by professional bodies or incorporated within grey literature (see **Table 3.1**). It would be beneficial for future work to include the distribution of an international questionnaire of audiology practice, including the use of speech testing, in collaboration with professional bodies and HHPs for dissemination through peer-reviewed publication. Since data collection for this study was conducted before the COVID-19 pandemic, current audiology service provision will reflect increased use of remote care/teleaudiology and a corresponding reduction in speech testing. Future work could also explore how audiology services have developed in response to the pandemic, available remote care options for speech testing and the use and uptake of such testing.

3.6 Conclusion

While pure tone audiometry provides information about a listener’s hearing sensitivity, HHPs reported speech testing to be beneficial in providing patients with relatable information about their functional hearing, guiding HA fitting and for use within the diagnostic test battery. This research demonstrates that the global provision of speech testing is variable, with the UK showing relatively infrequent use of speech testing during the clinical assessment and HA fittings in adult patients by public-sector HHPs. Private sector audiology practices in the UK, however, were more comparable to uptake reported in the US and Canada. A lack of clinical time, training and equipment were identified as primary reasons affecting provision variability in the UK and likely to also account for global heterogeneity in service provision. Given the evolution of new audiological assessment techniques, it is important to gather data on current clinical practice trends. Clinical practice guidance could be developed to enhance the consistency of speech testing methods and recommend relevant training and resources for HHPs around the world. The inclusion of speech testing within the formal scope of practice for audiologists and clinical practice guidance could facilitate the allocation of necessary resources for public-sector HHPs in the UK and beyond.

Within this chapter, a scoping review was carried to investigate speech testing practices in audiology settings around the world. This practice data was not available from the UK context; therefore, a questionnaire of UK HHPs was carried out to fill this gap. Understanding the speech testing landscape is important when considering the development of additional word identification tools, like the Spatial Speech in Noise Test developed in this thesis, as it can help uncover barriers to uptake and clinical requirements.

Assessments of speech perception and localisation abilities are performed infrequently in the UK. However, given the complexity of realistic listening scenarios, the importance of localisation cues and speech discrimination and the perceived benefits of speech perception testing reported in this chapter, it may be beneficial to investigate the use of more efficient, complex assessment methods. Therefore, the experiments described in Chapter 4 and 5 of this thesis will outline the development stages of a Spatial Speech in Noise test (SSiN), a simultaneous assessment of localisation and word identification and its use to assess normal hearing listeners and HA users. Assessing both localisation and word identification abilities in the same task could save time and resources in the clinical environment. Chapter 6 will explore how the SSiN could be used to assess HA features. Chapters 6 and 7 feature the perspectives of HA users, regarding the use of the SSiN, and highlight their own experiences of assessment techniques found within routine clinical audiology.

Chapter 4: Development of a Spatial Speech in Noise Test: Assessing the Impact of the Dual Task Paradigm

Chapter 3 presented the speech testing practice perspectives of current HHPs practicing in the UK. Despite HHPs highlighting the importance of conducting speech testing in audiological practice, these assessments are performed infrequently in UK audiology services. Common barriers to speech testing uptake were also identified, including lack of clinical time and resources. This data is critical when proposing alternative assessment tools as efforts will need to be made to overcome these barriers. Furthermore, literature presented in Chapter 2 highlights how hearing-impaired listeners find dynamic, noisy listening situations the most challenging and researchers have suggested that using more ecologically valid means of assessment within clinical settings, and research studies, would better match the difficulties experienced by listeners.

Therefore, this chapter, along with Chapters 5 and 6, describes the development and evaluation of a Spatial Speech in Noise Task (SSiN) to answer the second research question of this thesis. Overall, this work has the objective of understanding whether the SSiN can be a sensitive simultaneous assessment of relative localisation and word identification performance to assess clinical populations. The SSiN uses dual responses intended to increase cognitive load and measures of reaction time help monitor listening effort. This chapter aims to explore the impact of the SSiN dual task paradigm on performance and further assess its clinical applicability. Following this, Chapters 5 and 6 explores whether the SSiN can be used to assess hearing aid users and advanced hearing aid features. Further developing the SSiN while understanding the current clinical landscape, from the perspectives of patients and clinicians, may help enhance clinical applicability of the task.

4.1 Abstract

Objective: To investigate the impact of the Spatial Speech in Noise Test (SSiN) dual task paradigm on performance.

Design: The SSiN is designed to be a complex ecologically relevant listening task. In experiment 1, younger (< 30 years old) and older (> 60 years old) normal hearing listeners performed the SSiN word identification and relative localisation tasks individually and in the dual task paradigm, with the order of testing counterbalanced.

Study Sample: Two groups of participants were included in this study. The first group consisted of younger adults (*n* = 13), aged 23–40 years (*M* = 26.8; *SD* = 4.11), and the second group consisted of older adults (*n* = 15) aged 62–80 years (*M* = 69.35; *SD* = 6.12).

Results: The relative localisation task (secondary task) in the dual task SSiN resulted in reduced performance compared to the single relative localisation task. Older listeners showed a modest impairment in word identification in the context of the dual task, compared to the word identification single task. All listeners exhibited slower word identification reaction times when performing the dual task compared to the single tasks.

Conclusion: The dual nature of the SSiN task increases cognitive load to reflect difficult listening scenarios. SSiN findings include a listener’s spatial acuity, word identification and spatial release from masking and the use of speech stimuli and multisource, multitalker babble allows for an engaging task that replicates the challenges of real-world listening. Further exploration of the SSiN can lead to a better understanding of its clinical application for different patient populations.

4.2 Introduction

Everyday communication requires the encoding of dynamic, fast-changing speech signals that may arrive from anywhere in space and often occurs in the presence of competing sounds that may also be in the form of speech. Sound localisation involves the ability to detect the position of a sound source and is critical for survival and communication (Schnupp et al., 2011). The ability to localise sound sources offers a critical advantage for separating competing sounds that arise from different locations. However, clinical assessments of spatial hearing are often restricted to localising a single source in frontal azimuth and do not reflect listening challenges in everyday life (Dorman et al., 2016; Grantham et al., 2007; Kerber & Seeber, 2012).

4.2.1 Spatial release from masking assessment

From a young age, normal hearing listeners have improved speech intelligibility when target sounds are spatially separated from competing maskers. This benefit is called spatial release from masking (SRM; Freyman et al., 2001; Zurek, 1993), and reflects both better-ear effects (Best et al., 2006) and the ability to deploy spatial attention mechanisms (Bronkhorst, 2015; Darwin & Hukin, 2000). SRM assessment generally involves measuring the speech reception threshold when speech and maskers are collocated and again when spatially separated, most commonly by 90°. However, realistic sound scenes are often more complex than these SRM test designs. The Listening in Spatialized Noise-Sentences test (LiSN-S) (Cameron & Dillon, 2007) involves the presentation of sentences (via headphones) to establish a speech reception threshold in different spatial configurations of target speech and distractor speech. Target sentences are perceived to come from 0-degrees azimuth (in front of the listener), while distractor stimuli were presented from 0-degrees azimuth or +/-90 degrees azimuth. Glyde et al (2013) used the LiSN-S to test normal hearing- and hearing-impaired listeners and recommended that clinical speech in noise tests should include spatial separations of speech and distractor stimuli to avoid underestimation of speech in noise difficulties. However, alternative test designs would have to be implemented with loudspeakers to “establish the effects of hearing aids in enhancing speech sound identification in spatialised noise” (Mealings et al., 2021).

4.2.2 Listening effort and the dual task assessment

Listening effort is a term used to describe a specific form of mental effort (Pichora-Fuller et al., 2016), and is the “interaction of cognitive resources required to understand speech combined with motivational factors involved with completing a task in a particular environment” (Reinten et al., 2021, p. 1). Speech understanding measures can be used to calculate the proportion of words or phonemes correctly identified by the listener, within a specific condition, but are not reflective of how much effort the listener required to complete the task. Hughes et al (2018) reported how people with hearing loss with good speech intelligibility commented that it was their ‘burdensome effort’ led them to withdraw from social situations (Hughes et al., 2018). Increased listening effort has also been reported to lead to emotional strain (Alhanbali et al., 2018), and early retirement (Danermark & Gellerstedt, 2004). Ohlenforst et al (2017) completed a systematic review to investigate the impact of hearing impairment and hearing aid amplification on listening effort. Although findings from the physiological measurement studies suggested hearing impairment increases listening effort, there was no conclusive data implying hearing aid amplification reduces listening effort. However, the authors found a large variation of research populations, conditions and outcome measures used across studies (Ohlenforst et al., 2017). More recently, Kestens et al (2021) suggested that including listening effort assessment methods in audiological assessment would help audiologists better understand a hearing aid user’s hearing loss induced participation restriction and help hearing aid users accomplish their participation goals (Pichora-Fuller et al., 2016). However, a lack of correlation between listening effort assessment tools has been noted (Gosselin & Gagné, 2011; Hornsby, 2013), and more research investigating the relationship between objective and subjective tools is necessary before recommending specific tools for audiology clinical practice.

There is currently no gold standard measure of listening effort and methods include self-report (including rating scales) (Brons et al., 2014), pupillometry (Naylor et al., 2018), eye tracking, skin conductance (Holube et al., 2016), heart rate variability (Mackersie et al., 2015), reaction time (Houben et al., 2013) and dual task paradigms (Degeest et al., 2021). The dual task paradigm has been used as a behavioural measure of listening effort in normal hearing listeners and those with hearing loss

(Fintor et al., 2022; Gagné et al., 2017; Giuliani et al., 2021; Picou & Ricketts, 2014). During a dual task paradigm, a listener is asked to complete a primary and secondary task simultaneously. It is expected that the necessary mental/cognitive capacity will be used to complete the primary task. In the assessment of listening effort, the primary task of a dual task paradigm has typically consisted of word or sentence recognition in quiet or in background noise (Gagné et al., 2017). The secondary task has been known to take many forms including memory tasks and tactile pattern recognition (Gosselin & Gagné, 2011). A decrease in secondary task performance reflects increased listening effort (Downs, 1982).

4.2.3 Motivations for this study

Given the developments in modern hearing aids (HAs) and the paucity of clinical sound localisation testing, there is a need for more ecologically valid, cognitively demanding tests (Cord et al., 2004; Pichora-Fuller et al., 2016; Walden et al., 2000). This includes tests that better reflect the more cognitively demanding nature of listening and communicating in real world situations. Accordingly, this study explored the potential clinical applications of a Spatial Speech in Noise Test (SSiN; Bizley et al., 2015). The SSiN is designed to be a more challenging assessment technique to reflect realistic listening scenarios by implementing a dual task paradigm. The SSiN tests speech identification and sound localisation in the presence of multi-talker babble and has been refined through piloting of different clinical populations. This study describes improvements made to the SSiN methodology to enhance usability. It also uses the resulting test to assess normal hearing listeners. Listeners completed the SSiN as a dual task where they had to report both word identification and relative localisation information and performed each test independently to investigate the impact of the dual task paradigm on performance. Older and younger adults were tested in this study to determine if age affects SSiN dual task performance.

4.2.4 Development of a Spatial Speech in Noise Test

The SSiN was developed to assess relative localisation and word identification ability in the presence of multi-talker babble. The publication from Bizley et al. (2015) described the first version of the SSiN and reported findings based on normal hearing adults. The SSiN was designed to be suitable for a wide range of participant groups, including children and elderly listeners to be ecologically valid with the use of speech stimuli and speech as the multisource background noise.

The relative localisation aspect of the SSiN evolved from a standalone task that was introduced to measure spatial acuity throughout azimuth (Wood & Bizley, 2015). Wood and Bizley (2015) tested 20 normal hearing participants in an anechoic chamber and used broadband and spectrally restricted stimuli to limit localisation cues to interaural level or timing differences. Listeners performed a two-alternative forced-choice test in which they discriminated whether a target sound originated from the left or right of a preceding reference. Target and reference sounds originated from adjacent speakers, reflecting a 15° location shift. Testing was completed in the presence of a background noise which arose independently from all speakers (-127.5° to +127.5° in 15° increments). Results showed that listeners' relative localisation ability declined with less favourable signal to noise ratios (SNR) and at peripheral locations compared to the midline.

The relative localisation task was then combined with the speech tokens from the CAPT: Chear Auditory Perception Test (Vickers et al., 2018), as the reference and target sounds, and multi-talker babble as the multisource background noise- thus creating the dual task SSiN (Bizley et al., 2015). During the task, participants were required to identify the speech tokens and judge their relative location shift. The SSiN was conducted at individualised SNRs to match the difficulty across listeners at approximately 50% speech reception threshold (Bizley et al., 2015). An adaptive pre-task (threshold task) was conducted to estimate this point. This point on the psychometric function was selected to ensure performance was above chance and avoided ceiling performance. The reported critical difference for the CAPT is 18% (Vickers et al., 2013). Therefore, the 50% correct point also fell between chance performance (25%) plus critical difference and ceiling performance minus critical difference (43%-82%).

Subsequent piloting tested this SSiN method used by Bizley et al. (2015) on bilateral HA users (*n* = 5) with bilateral symmetrical moderate to severe sensorineural hearing loss but found significant performance floor effects in relative localisation (Parmar, 2016). To reduce such floor effects, the task was further refined by increasing speaker separations from 15° to 30° and reducing the number of multi-talker babble locations such that independent babble was presented from two adjacent speakers on either the left or right of space. The refined methodology was trialled on a group of normal hearing participants (*n* = 11) aged 21 to 60, and bilateral cochlear implantees (*n* = 10) aged 8 to 80 (Ahnood, 2018; Parmar et al., 2018a). Results from normal hearing listeners replicate findings from Bizley et al (2015), whereby relative localisation abilities were reduced towards the periphery compared to the midline. Normal hearing listeners showed clear evidence of SRM in the presence of the lateralised noise sources. A similar pattern of results was found for bilateral cochlear implant users, but their relative localisation and word identification performance was poorer than normal hearing listeners, despite performing the task at equivalently difficult SNRs. Although these refinements eradicated relative localisation floor effects for hearing impaired listeners, there was some instability in the threshold task which led to ceiling effects for normal hearing participants.

The SSiN is designed to be an ecologically relevant but more challenging assessment technique to reflect realistic listening scenarios. The dual task paradigm potentially adds a cognitive challenge and requires additional cognitive resources. Therefore, impairment in SSiN secondary task performance and an increase in reaction times may represent markers of listening effort. The effects of measuring the SSiN dual task paradigm on cognitive load are currently undetermined. Therefore, this study had two primary aims: (a) introduce and use a more robust threshold task within the SSiN test battery and (b) compare the performance between both elements of the SSiN when performed as single tasks versus in the dual task context.

4.3 Method

An adapted version of the SSiN described in Bizley et al. (2015) was used in this study.

4.3.1 Ethical considerations

This study received ethical approval from the University College London (UCL) Research Ethics Committee (3865/001). No participant identifiable data is presented in this chapter. Data were stored in compliance with General Data Protection Regulation (EU) 2016/679. All listeners signed an informed consent document and were reimbursed for their efforts.

4.3.2 Testing chamber

Participants sat on a chair in the centre of an anechoic chamber with sound-attenuating foam triangles on all surfaces (dimensions of 24 cm triangular depth and 35 cm total depth) and a suspended floor. They were surrounded by a ring of 18 speakers, which were 122 cm from the centre of the subject's head and at ear level arranged at 15° intervals from -135° to +120°. Participants were given a touch screen tablet for recording responses and were asked to face a marked sign positioned at the midline. In the SSiN task, the following speakers in the frontal hemifield were used as testing locations: +/-90°, +/-60°, +/-30° and 0° (see **Figure 4.1**). Figure 4.1 shows only the speakers that were used in the present study.

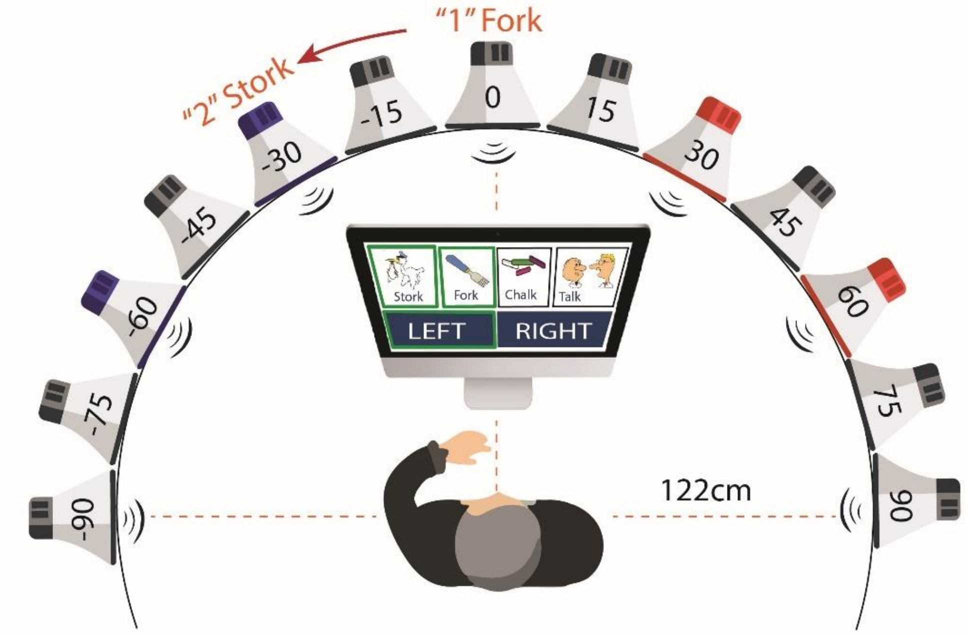


Figure 4.1 **The speaker arrangement for the Spatial Speech in Noise Test.** Speakers are labelled with their azimuthal location (degrees). In the figure above, a reference speech token ("Fork") is presented from one speaker followed by a target speech token ("Stork") from a speaker 30 degrees to the left or right. Testing takes place in the presence of multi-talker babble originating from either the left (blue) or right (red) speakers. Listeners are asked to face the midline throughout testing and to identify both words on the touch screen and the location shift between the words. The touch screen presented in this figure is not to scale. Speakers used for presentation of speech tokens are labelled with the speaker symbol within the speaker ring.

4.3.3 Stimuli

Stimuli were generated and presented at a 48 kHz sampling frequency and consisted of monosyllabic word tokens based on the Chear Auditory Perception Test (CAPT; Vickers et al., 2018) pronounced by a sole British English female. CAPT words were selected because participants over the age of 5 years could understand the vocabulary and these words have been utilised in studies to assess HA fitting algorithms, where they were found to be sensitive to changes to HA fitting parameters (Marriage et al., 2018).

Sixteen speech tokens were used, divided into four groups. Each group targeted a particular type of phonemic discrimination, including complex vowel discrimination, simple vowel discrimination, initial contrastive consonant and the final contrastive consonant (see **Table 4.1**). The utterances were between 445 ms and 885 ms long (*M* ± *SD* = 660 ± 102 ms) with a variable amount of silence at the end (78 ms to 97 ms). Words were presented such that the vowels were sound level matched and in the presence of multi-talker babble generated by overlaying four-word passages from 16 individual talkers drawn from Mark Huckvale's SCRIBE database (www.phon.ucl.ac.uk/resource/scribe/). The first speech token was presented from a speaker and the second was presented after a silent interval of at least 45 ms, from a speaker 30° to the left or right. Multi-talker babble was measured to reach peak intensity of approximately 52 dBSPL in any given trial. On each trial independent samples of babble were presented simultaneously from one of two pairs of speakers (-30° and -60°, +30° and +60°) to generate a diffuse lateralised noise source. The level of uncorrelated multi-talker babble was ramped on and off with a linear ramp over 1 s.

Stimuli were presented by Canton Plus XS.2 speakers (Computers Unlimited, London) via a MOTU 24 I/O analogue device (MOTU, MA, US) and two Knoll MA1250 amplifiers (Knoll Systems, WA, US). Individual speakers were level matched with a CEL-450 sound level meter, and spectral outputs were verified with a condenser microphone positioned at the centre of the chamber where the subject's head would be during presentation of a stimulus. The microphone signal was passed to a Tucker Davis Technologies System 3 RP2.1 signal processor via a Brüel and Kjær 3110-003 measuring amplifier. All speakers were matched in their spectral output that was flat from 400 Hz to 800 Hz, with a smooth, uncorrected 1.2 dB/octave drop off to 10 kHz and a smooth uncorrected drop off of 1.8 dB/octave from 800 Hz to 25 kHz. The MOTU device was controlled by MATLAB (MathWorks) with the Psychophysics Toolbox extension (Brainard, 1997; Kleiner et al., 2007).

4.3.4 Threshold estimation

The new threshold estimation task consisted of a four-alternative forced-choice speech in noise task that presented a single word per trial, randomly drawn from all word groups. The task was a 3 down-1 up adaptive staircase task, taking the average of the last four reversals. During the threshold task, one word was presented from the speaker at 0° in the presence of multi-talker babble which was presented from a pair of speakers either on the left or right of space (-30° and -60°, +30° and +60°) at an overall level of 52 dBSPL. The location of multi-talker babble alternated between trials such that 50% of trials took place with babble on the left, and 50% with babble on the right. Speech tokens were presented at 0° azimuth.

Participants were instructed to select the word they heard from a four-choice list on a touch screen tablet. After each response, the level of speech token was adapted depending on the participant’s response, following a three-up one-down adaptive staircase design. The threshold was determined by taking the average of the last four reversals and targeted the 79.4% point (Levitt, 1971). Each participant completed the task three times and the average threshold obtained from the three measurements was used in the main task.

4.3.5 Testing

For the main task, participants heard two monosyllabic words within the same word group (**Table 4.1**), presented sequentially from speakers separated by 30° in the presence of multi-talker babble. Participants were instructed to identify both words in order and the direction of the location shift between the first word and the second word using the touch screen tablet (see **Figure 4.1**).

The SNR established in the threshold estimation task was used throughout the main task. Within a trial, a reference speech token was presented followed by a silent interval of at least 45 ms ($M = 163 \pm 97$ ms) and the presentation of a target speech token from an adjacent speaker (30° interval). The location of the first word varied randomly from trial to trial, and the location of the multi-talker babble varied randomly between left (-30° and -60°) and right (+30° and +60°) side configurations. Each trial began automatically 1 s after the participant made a response in the preceding task.

Participants performed two repetitions of every word from each pair of locations, yielding 16 trials for each direction judgment and a single presentation of every word at every speaker location. Participants performed a practice trial at a clearly audible SNR and 90° speaker separations before the main task to ensure understanding of instructions. The task consisted of eight blocks of 24 trials and participants were given breaks between each block.

Discrimination	Word List
Complex vowel (Vc)	Pale Pool Pile Peel
Simple vowel (Vs)	Hoot Heat Heart Hurt
Initial consonant (Ci)	Chalk Talk Fork Stork
Final consonant (Cf)	Cheat Cheese Cheap Cheek

Table 4.1 SSiN confusion groups. The word groups are taken from a larger set from Vickers et al (2018).

4.3.6 Participants

Participants included 27 normal hearing listeners grouped by age category (younger or older). Group 1 included 13 participants (11 females; two males) aged 23–40 years (*M* = 26.8; *SD* = 4.11). Group 2 included 15 participants (10 females; four males), aged 62–80 years (*M* = 69.35; *SD* = 6.12). Participants took part in the study if they were 18–30 years of age in Group 1 and 60–80 years of age in Group 2, had no history of hearing loss or ear-related disorders and had no reported cognitive impairment.

4.3.7 Test protocol

Otoscopic examination and pure tone audiometry was conducted for all participants to confirm normal hearing thresholds between 250 Hz and 6 kHz. The mean five-frequency pure tone average for the right and left ears were 17.19 dB HL (*SD* = 11.54) and 16.89 dB HL (*SD* = 10.53) respectively for the older group. For the younger group, the mean five-frequency pure tone average was 18.25 dB HL (*SD* = 9.55) and 17.52

dB HL (*SD* = 10.23) for the right and left ears respectively. The Montreal Cognitive Assessment (MoCA; Lin et al., 2017; Nasreddine et al., 2005) was used to screen cognitive function using the recommended cut-off score of >= 26. Previous studies using the MoCA found that due to the nature of the verbal instructions and questions, the hearing-impaired populations may score lower compared to normal hearing listeners (Utoomprurkporn et al., 2020). For example: participants with hearing loss could mishear target words or numbers during recall tasks. Therefore, a visually based MoCA was used for all participants (Utoomprurkporn et al., 2021). All participants performed three versions of the SSiN: (a) dual task of word identification and relative localisation, (b) word identification task alone and (c) relative localisation task alone. Testing was completed over one to two visits. The order of testing was counterbalanced across participants.

4.3.8 Statistical analysis

Word identification and relative localisation performance data were categorised as correct or incorrect, and analysed using generalized linear mixed effects modelling (GLMM) with a binomial (logit) error distribution. Analysis was based on trial-by-trial responses. For relative localisation, performance was analysed across “mean location”, and this was defined to be the average location between the target and reference word of each trial. Reaction times were calculated relative to the onset of the trial and were analysed using linear mixed modelling (using package *lme4* in R Version 3.6.2) (Bates et al., 2015). Within the SSiN, the second word is presented at least 45 ms (*M* = 163+/-97 ms) after the first word. One model was created for each of three dependent variables: (a) word identification performance, (b) relative localisation performance and (c) reaction time. Age and gender effects were not significant in any analysis and were therefore removed from the models.

All models included a random effect of subject to account for random inter-subject variability in baseline performance or reaction time. Since regression models can be sensitive to variables that are correlated, the variance inflation factors (VIFs) for all predictors used in the model were calculated to check for multicollinearity. Since the VIFs for all predictors were very low (all < 1.02), none were excluded. Normality of residuals in reaction time models was ensured using QQ plots. Performance of model fit was evaluated by calculating the area under the curve (AUC) of ROC (receiver operating characteristic) curves for each model, and sensitivity and specificity were calculated using optimal cut points (Youden, 1950). The azimuthal distance between a speech token presentation and the mean multi-talker babble location was calculated for each trial and added to the analysis to explore SRM.

Post hoc analysis was performed through contrasts of least-square means using the *emmeans* library (Lenth et al., 2018). The *p*-values were corrected for multiple comparisons using the Tukey method. Significant differences are reported using $\alpha = 0.05$.

4.3.8.1 Word identification

Word identification accuracy (coded as correct or incorrect on a word-by-word basis, with two words per trial) was modelled as a function with several fixed effects. These included participant group (older vs younger listeners), task (single vs dual), word group, trial number, word order (i.e., word 1 or word 2 within the trial), categorical speaker locations for speech token presentation (+/-90°, +/-60°, +/-30° and 0°) and speech-noise separation (in degrees). In experiment 1, interactions between task and trial number, task and group, task and word number, task and word group, group and speech-noise separation, group and word group and word number were included. Random linear learning effects within a random clustering factor of participants were estimated.

4.3.8.2 Relative localisation

Relative localisation accuracy was also captured as either correct or incorrect and was modelled as a function of fixed effects, including group, task, mean speaker location, word group and trial number. Random linear learning effects within a random clustering factor of participants were estimated.

4.3.8.3 Reaction time

Reaction time for word identification and relative localisation selections are presented relative to trial onset. Here, reaction time is the time taken for participants to select a word (word identification reaction time) or location shift (relative localisation reaction time), on the touchscreen provided, calculated from trial onset. Reaction time outliers were systematically removed such that reaction times between 0.1 s and 14 s were included in the analysis for word identification. These values were chosen as responses outside of this range would likely be unrelated to the task. For relative localisation selections, reaction times below the minimum reaction time to word 2, and those above 14 s, were systematically removed. The log of reaction times was used to account for positive skew. Reaction times in word identification were modelled using fixed effects of group, task (single vs dual), speech-noise separation, word group, word number and trial number. Experiment 1 interactions included task and word group, task and word number, group and speech-noise separation, group and task, group and word group and group and word number. Reaction times in relative localisation were modelled using fixed effects of group, task, word group, mean speaker location and trial number. Interactions included group and word group, mean location and group, task and trial total, and task and group. Random variability between subjects in baseline reaction times was estimated.

4.4 Results

In this experiment, word identification and relative localisation of normal hearing listeners was assessed either through each of the corresponding SSiN single tasks or the SSiN dual task paradigm. This method was used to determine whether the dual task context has an impact on task performance. It is predicted that if the dual task imposes additional cognitive demands, which limit performance, then performance will be superior in the single task context.

Participants included 27 normal hearing listeners grouped by age category (younger (18-30 years): *n* = 13, or older (60-80 years): *n* = 15). Each participant performed the following tasks: (a) word identification, (b) relative localisation and (c) dual task SSiN (word identification and relative localisation within the same task).

The order of testing was counterbalanced between tasks such that 50% of participants performed the dual task first and 50% performed both single tasks first. In considering the results of this experiment, the main effects will first be outlined in each task before addressing the question of whether the dual task design impacted performance compared to the single task design, and whether any differences were more marked in the older hearing group than in the younger hearing group. The SSiN was conducted at individualised SNRs, established within a threshold task that preceded the main task. Older listeners performed the SSiN at a mean SNR of 1.68 dB (*SD* = 2.29), and younger listeners and younger listeners performed the SSiN at a mean SNR of 2.27 dB (*SD* = 2.50).

4.4.1 Word identification performance

Word identification performance (i.e., percentage of words correctly identified) was modulated by azimuthal location of both the presented words and location of the multi-talker babble (**Figure 4.2**). Performance was most accurate when speech and multi-talker babble were maximally separated (see **Figure 4.2A**).

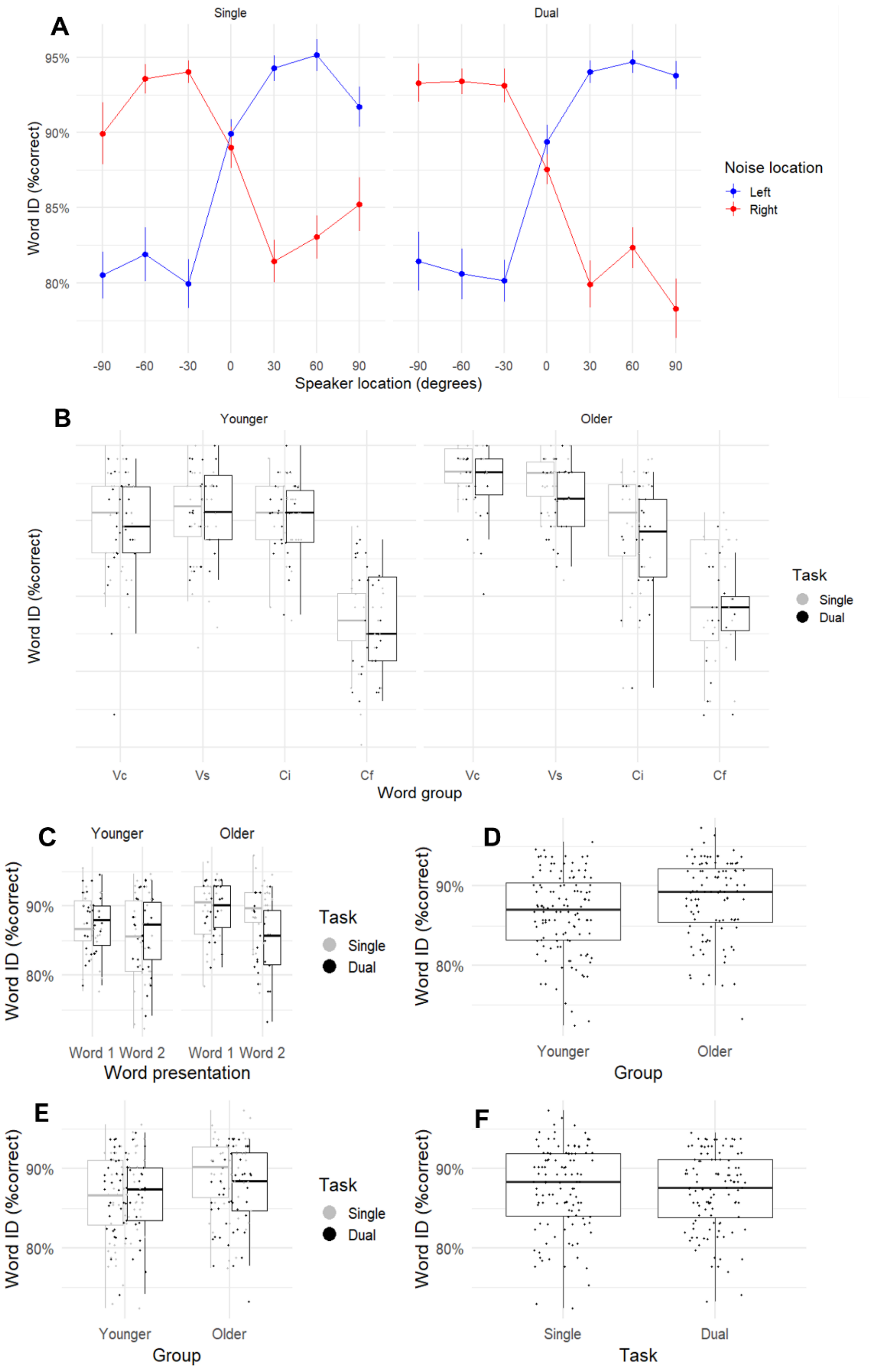


Figure 4.2 Word identification performance for the single and dual SSiN tasks. A) Word Identification Performance Across Speaker Location for Single/Dual Task Chance performance is 25%., B-F: Analysis of factors influencing word identification performance, B) word identification performance (% correct) between word groups, C) word ID performance for first and second word presentations, D) word identification performance between participant groups and tasks and E) word identification performance between tasks.

To determine which factors influenced the ability to accurately identify the speech tokens in the presence of multi-talker babble, analysis was carried out using a generalised linear mixed effects model. The final model accurately predicted word identification performance (sensitivity = 0.689, specificity = 0.701, AUC = 0.755). Significant main effects and interactions of predictors of word identification performance are outlined in **Table 4.2** and include proximity to the noise source (see **Figure 4.2** for word identification performance).

Item	**χ^2**	**df**	**p**
Task (dual/single)	0.299	1	0.584
Group (older/younger)	32.80	1	<0.001*
Speaker Location	190.464	6	<0.001*
Speech-Noise Separation	383.491	1	<0.001*
Word Group	354.45	3	<0.001*
Word Number (first/second)	1.79	1	0.185
Trial Number	3.801	1	0.051
Group × Noise Separation	2.65	1	0.087
Task × Word Group	6.88	3	0.076
Task × Word Number	3.32	1	0.067
Task × Group	11.19	1	<0.001*
Group × Word Group	97.47	3	<0.001*
Group × Word Number	1.86	1	0.173
Test × Trial Number	2.430	1	0.119

* $\alpha = 0.05$.

Table 4.2 Predictors of word identification performance.

Term	Group	Reference	Est	SE	Z	p	OR	95% CI
Task (single/dual)	Dual	Single	0.071	0.13	0.55	0.584	1.07	0.83-1.39
Group (older/younger)	Older	Younger	1.10	0.19	5.73	<0.001*	2.98	2.04-4.35
Speaker location	90° left	Midline	-1.00	0.09	-11.1	<0.001*	0.367	0.35-0.435
	60° left	Midline	-0.25	0.08	-3.25	0.019*	0.78	0.67-0.91
	30° left	Midline	-0.15	0.07	-2.21	0.332	0.86	0.75-0.99
	30° right	Midline	-0.09	0.07	-1.42	0.788	0.91	0.79-1.04
	60° right	Midline	-0.07	0.08	-0.90	0.971	0.93	0.79-1.08
	90° right	Midline	-0.76	0.09	-8.05	<0.001*	0.46	0.39-0.56
Word group	2	1	0.02	0.11	0.19	0.998	1.02	0.83-1.26
	3	1	0.05	0.11	0.47	0.966	1.05	0.85-1.3
	4	1	-1.24	0.09	-13.42	0.000	0.29	0.24-0.35

Table 4.3 Estimates of each of the significant terms to predict word identification accuracy. Estimates include strength and significance (*p*) as well as odds ratio (OR) and its 95% CI.

Critically, there was no overall difference in word identification performance based on task type (single or dual task; see **Figure 4.2**).However, there was an effect of participant group whereby older listeners performed significantly better than younger listeners (see **Table 4.2**). There was also an interaction between task and participant group. Post hoc analysis revealed older listeners performed specifically better when word identification was performed as an independent task compared to younger listeners (Est = -0.453, *p* = 0.015). However, older listeners' word identification performance was hindered in the dual task context compared to the single task (Est = 0.203, *p* = 0.009), and this effect was not apparent in the younger group (Est = -0.07, *p* = 0.563; see **Figure 4.2E**). There was also no significant difference between dual task performance of the older and younger groups (Est = -0.177, *p* = 0.645). In addition to no main effect of task type (single/dual), the interactions between task type and word number and task type and word group were nonsignificant.

4.4.2 Word identification reaction time

In addition to collecting the word identification performance of each listener (% correct), we determined the time taken for listeners to make their response selections on the touch screen (see **Figure 4.3**). Response times to speech have been used in previous literature to investigate listening effort (Houben et al., 2013) and it was expected that reaction time may vary with difficulty level (e.g., due to spatial location of the presented word or the presented word's proximity to noise source). Although SSiN word identification performance did not differ significantly between the single and dual tasks, the dual task design markedly slowed reaction times for word identification selections (see **Figure 4.3).** To investigate the predictors of word identification reaction time, a linear mixed effects model was created ($R^2 = 0.487$); significant predictors of word identification reaction time are outlined in **Table 4.4** and **Table 4.5**. Reaction times for identifying speech tokens were significantly slower during the dual task (*M* = 4.37 s, *SD* = 1.47 s) relative to the single task (*M* = 3.81 s, *SD* = 1.31 s). There was also a significant main effect of the azimuthal distance between speech and noise and speaker location.

Figure 4.3 Log reaction time for word identification selections in the single and dual SSiN tasks. Results are presented for both participant groups (younger and older listeners) across speaker location (degrees).

Item	χ2	df	p
Task (dual/single)	395.94	1	<0.001*
Group (older/younger)	0.21	1	0.650
Speaker Location	88.59	6	<0.001*
Speech-Noise Separation	350.632	1	<0.001*
Word Group	106.75	3	<0.001*
Word Number (first/second)	3465.80	1	<0.001*
Trial Number	0.37	1	0.542
Task × Word Group	19.72	3	<0.001*
Task × Word Number	20.59	1	<0.001*
Group × Noise Separation	31.10	1	<0.001*
Task × Group	50.85	1	<0.001*
Group × Word Group	40.85	3	<0.001*
Group × Word Number	0.00	1	0.986

Table 4.4 Predictors of word identification reaction time. * α = 0.05.

Term	Group	Reference	Est	SE	Z	p
Task	Dual	Single	0.15	0.01	19.90	<0.001*
Location	90° left	Midline	0.05	0.08	7.21	<0.001*
	60° left	Midline	0.03	0.01	5.04	<0.001*
	30° left	Midline	0.02	0.01	3.33	0.015*
	30° right	Midline	0.007	0.01	1.25	0.868
	60° right	Midline	0.022	0.01	3.72	0.004*
	90° right	Midline	0.05	0.01	6.604	<0.001*
Word group	2	1	-0.03	0.01	-3.87	0.001*
	3	1	0.00	0.01	-0.023	1.000
	4	1	0.05	0.01	6.309	<0.001*

Table 4.5 Estimates of each term to predict word identification reaction time. Estimates include strength and significance (*p*).

Although there was no significant effect of participant group (older or younger) on word identification reaction time, there was a significant interaction between task and participant group. Mirroring the effect of participant group on accuracy, post hoc analysis revealed that younger participants' word identification reaction times were less hindered by the dual task (Est = -0.110, $p < 0.001$), relative to older participants (Est = -0.162, $p < 0.001$) (see **Figure 4.5**).

4.4.3 Relative localisation performance

During the SSiN, participants are required to identify the location shift between word 1 and word 2 after they complete the word identification task. This relative localisation assessment is therefore a secondary measure within the SSiN and may consequently add to a listener's cognitive load. **Figure 4.4A** displays the relative localisation performance in the single and the dual tasks, plotted as a function of the mean speaker location (degrees) of the word pairs. Overall, relative localisation performance is optimal at the midline compared to peripheral locations regardless of multi-talker babble location.

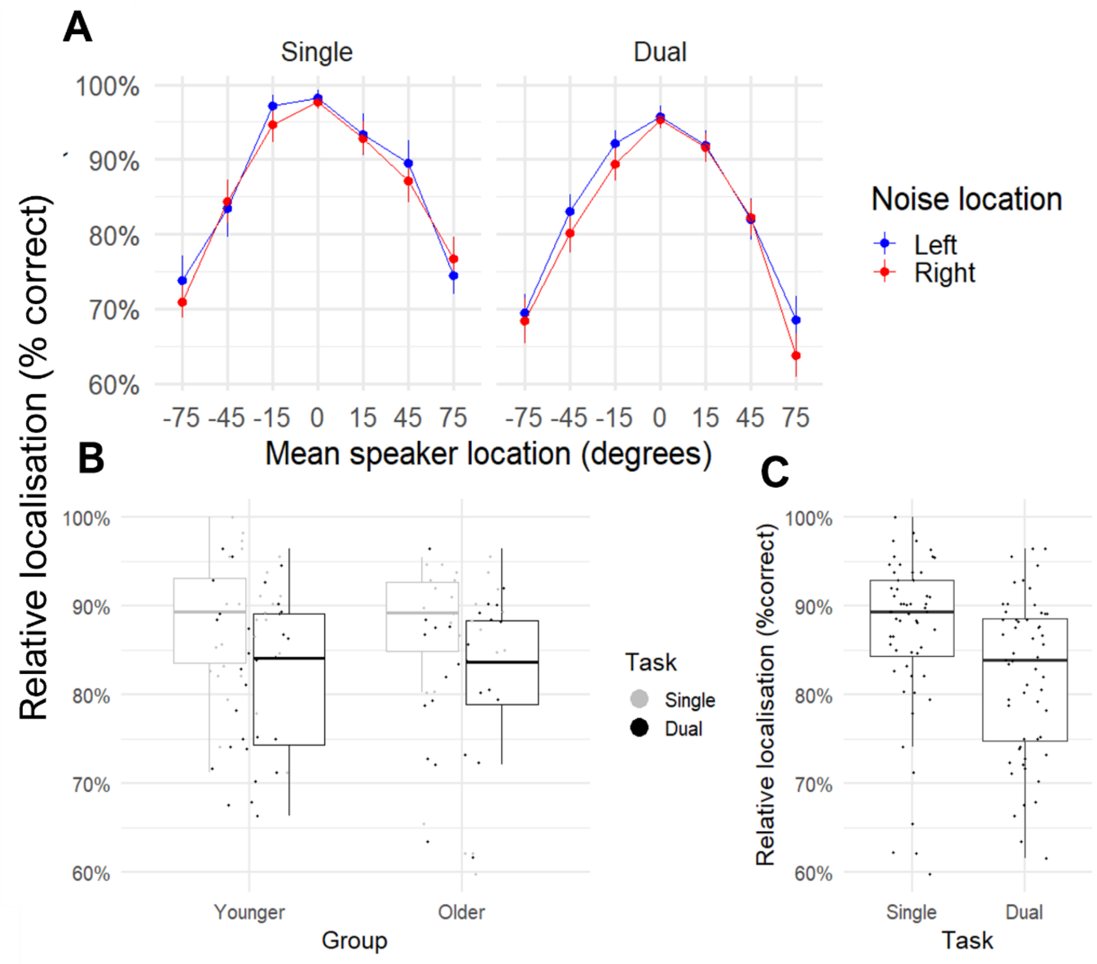


Figure 4.4 Relative localisation performance in the single and dual SSiN tasks. A) relative localisation performance (% correct) as function of mean speaker location (degrees), B) relative localisation between participant groups and tasks and C) relative localisation performance between tasks. Chance performance =50%.

A GLMM was performed to quantify main effects of relative localisation performance (sensitivity = 0.667, specificity = 0.781, AUC = 0.783). Significant predictors of relative localisation performance are outlined in **Table 4.6** and **Table 4.7**. Critically, relative localisation accuracy was significantly lower during the dual task relative to the single task (see **Figure 4.4C**). There was also a significant interaction between test (dual vs single) and participant group (younger and older). Post hoc analysis found that the relative localisation performance of both groups was significantly improved in the single task compared to the dual task. However, there was a difference in effect sizes (younger: Est = 0.562, $p < 0.001$; older: Est = 0.281, $p = 0.001$), as younger listeners tended to perform better in the single relative localisation task compared to older listeners, but there was no significant difference in relative localisation performance between groups in the dual task (see **Table 4.6**).

Item	**χ2**	**Df**	**p**
Task (dual/single)	13.293	1	<0.001*
Group (older/younger)	1.265	1	0.261
Mean speaker location	813.641	6	<0.001*
Word group	11.861	3	0.008*
Task × group	6.805	1	0.009*
Trial number	0.00	1	0.950

* $\alpha = 0.05$.

Table 4.6 Predictors of relative localisation performance.

Term	Group	Reference	Est	SE	Z	p	OR	95% CI
Task	Dual	Single	-0.28	0.07	-3.646	<0.001*	0.75	0.64-0.88
Location	75° left	0°	-2.56	0.14	-18.14	<0.001*	0.08	0.06-0.1
	45° left	0°	-1.76	0.14	-12.28	<0.001*	0.17	0.13-0.22
	15° left	0°	-0.67	0.16	-4.17	<0.001*	0.51	0.38-0.7
	15° right	0°	-0.81	0.16	-5.15	<0.001*	0.45	0.33-0.61
	45° right	0°	-1.56	0.15	-10.77	<0.001*	0.21	0.16-0.28
	75° right	0°	-2.50	0.14	-18.00	<0.001*	0.08	0.06-0.11
Word group	2	1	0.18	0.08	2.40	0.077	1.20	1.03-1.39
	3	1	-0.06	0.07	-0.78	0.862	0.94	0.82-1.09
	4	1	0.10	0.08	1.32	0.552	1.10	0.95-1.28

Table 4.7 Estimates of each significant term to predict relative localisation performance. Estimates include strength and significance (p) as well as odds ratio (OR) and its 95% CI.

Group	Reference	Est	SE	Z	p
Single task-older listeners	Single task-younger listeners	-0.3034	0.2696	-1.125	0.673
Dual task-older listeners	Dual task-younger listeners	-0.0229	0.2670	-0.086	0.998
Single task-older listeners	Dual task-older listeners	0.2812	0.0771	3.646	0.001*
Single task-younger listeners	Dual task-younger listeners	0.5616	0.0750	7.493	<0.001*

Table 4.8 Estimate of interaction term ‘Task x Group’ to predict relative localisation performance. Estimates include strength and significance (p).

4.4.4 Relative localisation reaction time

The reaction time for relative localisation judgment was calculated for the single and dual tasks. Since the localisation judgment is the secondary task in the SSiN, the relative localisation reaction times are not directly comparable between single and dual tasks (slower dual task word identification responses will also contribute to this). Despite this, these data are plotted in **Figure 4.5** to specifically illustrate the relative localisation reaction time differences between participant groups during dual task performance (dark blue shaded plots).

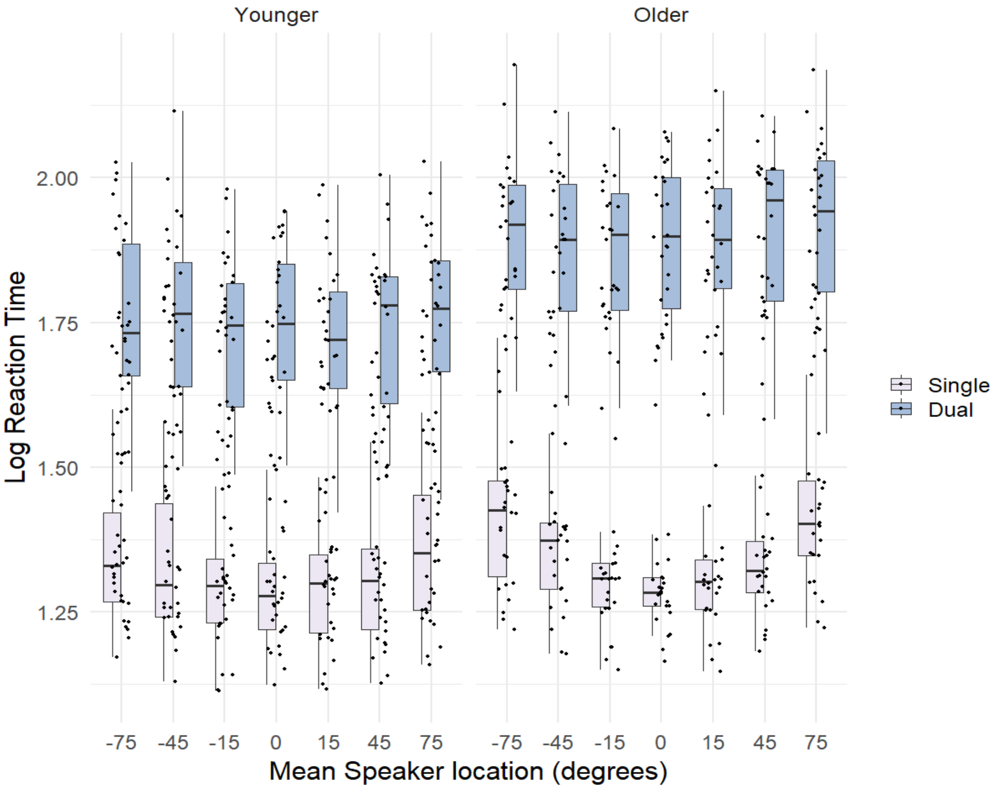


Figure 4.5 Log reaction time for relative localisation across mean speaker location for the single and dual SSiN tasks. Results are presented across mean speaker location (degrees) and are based on relative localisation selections in the single/dual tasks for both participant groups (younger and older listeners).

Relative localisation reaction time was modelled with a good fit ($R^2 = 0.649$) and significant predictors of word localisation reaction time are outlined in **Table 4.9**. Briefly, there was no main effect of mean speaker location or participant group. However, there was a significant interaction between participant group and task. Post hoc analysis revealed older participants had slower reaction times in the dual task compared to younger participants in the dual task (**Table 4.10**), conversely, these group differences in reaction time were not observed in the in the single task context (see **Figure 4.5**).

Item	$\chi 2$	df	p
Task (dual/single)	2989.62	1	<0.001*
Group (younger/older)	0.1588	1	0.6903
Mean Speaker Location	0.2232	1	0.6366
Word Group	36.45	3	<0.001*
Trial Number	18.33	1	<0.001*
Group × Word Group	77.11	3	<0.001*
Group × Mean Location	0.33	1	0.637
Task × Group	294.07	1	<0.001*

Table 4.9 Predictors of relative localisation reaction time. *α = 0.05

Term	Group	Reference	Est	SE	Z	p
Task	Dual	Single	0.363	0.007	54.675	<0.001*
Word group	2	1	-0.023	0.007	-4.032	<0.001*
	3	1	-0.026	0.007	-4.468	<0.001*
	4	1	-0.033	0.006	-5.688	<0.001*

Table 4.10 Estimate of each significant term to predict relative localisation reaction time. Estimates include strength and significance (*p*).

Group	Reference	Est	SE	Z	p
Single task-younger listeners	Single task-older listeners	0.0125	0.045	0.276	0.9927
Dual task-younger listeners	Dual task-older listeners	-0.2285	0.045	-5.051	<0.001*

Table 4.11 Estimate of interaction term "Task x Group" to predict relative localisation reaction time. Estimates include strength and significance (*p*).

4.5 Discussion

The work presented in this chapter was conducted to explore the impact of the dual task paradigm on word identification and relative localisation performance compared to their corresponding single tasks. This study was carried out to better understand potential uses of the SSiN for assessing specific populations and whether the dual task reflected the challenging nature of realistic listening situations.

In this chapter, performing the SSiN as a dual task rather than as its single task components has presented several important, new findings. First, for all listeners, relative localisation performance was reduced in the dual task paradigm compared to when this task was completed alone (without the preceding word identification task). Second, older listeners' word identification performance was reduced in the dual task context. This was not the case for younger listeners. An analysis of reaction times revealed that listeners performed slower in the word identification dual task compared to the single task, even when performance was equivalent (as for younger listeners). Finally, reaction time to the location shift response was slower for older listeners in the dual task compared to younger listeners in the dual task. Despite no cognitive concerns in either group (through self-report or results from the MoCA), performance differences between older and younger listeners indicate the need to consider participants' ages between and within conditions when exploring further uses of the SSiN to assess clinical populations.

Overall, the SSiN dual task paradigm allows for the simultaneous assessment of spatial hearing and speech identification within a dynamic, ecologically valid testing paradigm using speech tokens and multisource babble. The nature of the dual task also mimics important listening scenarios, as individuals need to locate and discriminate speech to follow conversation in complex scenes. Furthermore, more cognitively demanding listening tasks help avoid ceiling effects commonly observed within speech recognition testing and could, therefore, provide scope to measure intervention benefits (e.g., auditory training or HA features).

Although previous researchers have used the SSiN to assess relative localisation and word identification performance (Bizley et al., 2015; Parmar et al., 2018a), the impact of the dual task context on performance was previously undetermined. Therefore, in the present study, normal hearing listeners (both younger and older) were tested to investigate the effect of the dual word identification and relative localisation tasks on performance and reaction time compared to the single tasks.

Listening effort is a term used to describe a specific form of mental effort (Pichora-Fuller et al., 2016), and is the “interaction of cognitive resources required to understand speech combined with motivational factors involved with completing a task in a particular environment” (Reinten et al., 2021, p. 1). Speech understanding measures can be used to calculate the proportion of words or phonemes correctly identified by the listener, within a specific condition, but are not reflective of how much effort the listener required to complete the task. Listening effort has been tested in a number of ways, including self-report (Brons et al., 2013), behavioural measures (Ng et al., 2015) and physiological assessment (Mackersie & Calderon-Moultrie, 2016; Ohlenforst et al., 2018; Zhao et al., 2019). Researchers have found that it is more effortful for older listeners to complete speech in noise tasks compared to younger listeners (Desjardins & Doherty, 2013). Testing both the listener’s speech understanding performance and listening effort could help clinicians better understand overall listening experiences and listening challenges. This may be of particular interest as patients may present with good speech in noise perception scores but find these listening environments especially cognitively demanding.

One behavioural method of investigating listening effort involves the use of dual task paradigms and recording of reaction times (Gagné et al., 2017). The dual task paradigm assumes that there is a limit to the amount of available cognitive resources (Kahneman, 1973). Dual task paradigms have been used to assess listening effort. It is predicted that a decline in the performance within a secondary task indicates there is less spare capacity available for allocation to secondary tasks, as resources have been used up during the primary task. Therefore, speech perception tasks that occur in challenging sound scenes require working memory and attention that would otherwise be used in multi-tasking activities such as dual tasks. When secondary visual and motor tasks have been performed alongside speech perception tasks, response times in the secondary time increase as SNR decreases (Neher et al., 2014; Seeman & Sims, 2015; Wu et al., 2016). In general, the performance of the primary task (speech identification in the SSiN) will likely be unchanged within the dual task but that the performance of the secondary task (relative localisation in the SSiN) in the dual paradigm will be reduced, compared to the corresponding single task (Hick & Tharpe, 2002).

In this study, findings revealed no significant worsening of primary task performance (word identification) between the dual and single task for younger listeners. However, older participants were more hindered by the dual task for word identification performance than younger listeners. Also, overall relative localisation performance was reduced in the dual task compared to the single task. This indicates the increased cognitive load within the SSiN dual testing paradigm, which is expected within more challenging listening scenarios. Furthermore, reaction times within the dual task were slower than the single task. Previous studies have also found slower reaction times when listeners are under higher cognitive load within a dual task paradigm (Hunter, 2021). Therefore, there is potential for the SSiN to be used as a marker for understanding listening effort, by monitoring secondary task performance and reaction times between test conditions, as well as assessing spatial hearing abilities.

When investigating the impact of the dual task paradigm, normal hearing listeners of two age categories were tested: younger listeners (< 30 years of age) and older listeners (> 60 years of age). Participants were only included in the study if they did not report any cognitive dysfunction, all participants carried out the MoCA and obtained a score of 26 or above, indicating no presence of cognitive impairment. Results in this chapter found that older listeners’ word identification performance and reaction times were more hindered in the dual task compared to younger listeners. Therefore, implying the older adults exerted more listening effort than young adults did, even when the SNR was adjusted on an individual basis. Also, that the SSiN dual task is sensitive to between groups age differences. Similarly, Gosselin and Gagne (2011) tested 25 young adults (18-33 years of age) and 25 older adults (64-76 years of age) with normal hearing sensitivity and normal cognitive function (as determined by the MoCA) where both groups performed a primary (sentence recognition) and a secondary task (tactile pattern recognition), separately and concurrently, with individualised SNRs. Results found no significant difference in word recognition task performance between groups when the task was performed in isolation. However, older adults performed poorer in the secondary task compared to their younger counterparts. Furthermore, the reaction times of older adults were significantly longer than young adults for single task word recognition and dual task word recognition (Gosselin & Gagné, 2011).

Additionally, a review of 20 experimental studies (published from 1989) examining the relationship between speech in noise performance and cognitive abilities concluded that the assessment of hearing and cognition are the primary and secondary concern when evaluating speech understanding, respectively (Akeroyd, 2008). Two studies also found that cognition was a useful predictor of hearing aid benefit.

The reaction time differences found between age groups in this study may also exist due to practical factors associated when using touchscreen tablets to provide task responses. Older adults may face personal challenges restricting their reaction times. These include accessibility or usability issues, technical familiarity and the associated frustration (Barnard et al., 2013). On the other hand, younger participants who may be more familiar with the equipment and be accustomed to higher levels of motivation associated with other uses of touchscreens (e.g., video game play). In such scenarios, this experience could reduce reaction time (Glueck & Han, 2020). Therefore, it is important to evaluate the user experience of completing tasks that rely on such technology, like the SSiN, to improve the test design and identify any physical challenges involving the test environment or equipment (Jenkins et al., 2016).

While reaction times for both groups were faster as the azimuthal distance between speech tokens and mean multi-talker babble increased, younger listeners showed significantly more benefit of spatial separation relative to older listeners. Finally, older participants' SSiN word identification performance was significantly better than younger listeners, possibly due to needing to carry out the SSiN at higher mean SNRs, despite normal pure tone thresholds (Fitzgibbons & Gordon-Salant, 2010; Grose et al., 2015). Together, these differences suggest the need for age matched participant groups in future comparison studies using clinical populations. Findings from chapter 3 of this thesis highlighted HHPs' experiences of speech perception testing and the added value such testing adds to the audiological clinical test battery approach, including hearing aid rehabilitation. However, dual task performance and reaction differences found between groups in the present study highlight the importance of including a measure of listening effort in clinical and research settings, due to the attentional and cognitive resources required to understand and follow speech in challenging situations and how these differ with age.

4.6 Conclusion

This chapter's findings reveal that the dual nature of the SSiN increases cognitive load to reflect challenging listening scenarios. Therefore, there is potential for the SSiN to inform clinicians about a patient's listening effort in addition to word identification and relative localisation performance, between testing conditions. The added information about listening effort could help clinicians build a more individualised management plan for patients. Specifically, one of the clinical implications of this chapter's findings is that HHPs may need to be more cautious of basing intervention decisions based solely on speech perception results, as listeners' listening effort may differ when word recognition remain similar. For clinical applications, dual task assessment tools may be more appropriate than self-report techniques (e.g., rating scales and questionnaires), particularly if patients are unable to make reliable listening effort judgements.

To investigate use of the SSiN in other clinical domains and build a set of normative data, Chapter 5 presents a comparison of bilateral HA users and normal hearing listeners. Given that Chapter 3 highlighted the lack of clinical time, equipment and training for speech testing in audiology and the lack of localisation testing in general, it would be beneficial to explore a variety of potential uses of the SSiN. Therefore, Chapter 6 demonstrates the use of the SSiN to assess the benefits of adaptive directionality features in current HA technology and includes a qualitative account of the SSiN user experience. To explore how tests like the SSiN may impact the patient experience, Chapter 7 presents hearing aid user perspectives of audiological assessment.

Chapter 5: Using the SSiN to Assess the Relative Localisation and Word Identification Performance of Hearing Aid Users

In Chapter 4, word identification, relative localisation performance and reaction times in the SSiN dual task paradigm were compared to their respective single tasks. Results indicated the SSiN achieved the goal of increasing cognitive load and the reaction time measures could be used as a proxy of listening effort monitoring, between test conditions.

The test is a better representation of real-world listening challenges for hearing device users; therefore, the next step would be to evaluate the SSiN with hearing impaired listeners and hearing device users. Previous researchers have indicated that hearing aid users have reduced spatial hearing abilities compared to normal hearing listeners. However, Chapter 3 revealed spatial hearing is rarely assessed in the audiological clinical environment and there is a variation in speech testing practices during the hearing aid intervention stage, across health sector in the UK.

Furthermore, there may be utility in improving our understanding of how advanced hearing aid processing handles dynamic listening situations and whether the SSiN could be used as an outcome measure post hearing aid fitting, to help patients better understand the benefits and limitations of hearing aids. Therefore, this chapter uses the SSiN to assess a group of adult bilateral hearing aid users and compares performance to a group of normal hearing listeners. Chapter 6 then uses the SSiN to assess the impact of hearing aid adaptive directionality on word identification and relative localisation performance.

5.1 Abstract

Objective: To use the spatial speech in noise (SSiN) to compare the word identification and relative localisation performance of bilateral hearing aid users to those of normal hearing listeners.

Design: Bilateral hearing aid users and normal hearing listeners performed the SSiN dual task. Generalised linear mixed effects models and linear mixed models were fitted to explore predictors of word identification, relative localisation performance and reaction times.

Study Sample: 38 normal hearing listeners (aged 22–83 years) and 22 bilateral hearing aid users (aged 20–79 years).

Results: Normal hearing listeners and hearing aid users had similar word identification performance when speech and noise were in close proximity. However, normal hearing listeners showed a near-ceiling advantage when speech and noise were separated, which hearing aid users did not demonstrate. Lastly, hearing aid users experienced significantly reduced relative localisation performance and slower reaction times in the relative localisation task compared to normal hearing listeners.

Conclusion: SSiN findings include a listener’s spatial acuity and word identification. The use of speech stimuli and multisource babble allow for an engaging task that replicates real world listening challenges. Bilateral hearing aid users had reduced relative localisation and spatial release from masking abilities compared to normal hearing listeners.

5.2 Introduction

A body of research has shown hearing aid (HA) users to have impaired localisation and poorer spatial speech in noise abilities compared to normal hearing listeners (Brimijoin et al., 2014; Drennan et al., 2001; Keidser et al., 2009; Van den Bogaert et al., 2006). Binaural amplification is recommended for people with bilateral hearing loss to restore audibility and access to vital auditory cues.

HA amplification increases the level of sound for a person with hearing loss. In quiet environments, this can enhance a person’s ability to hear speech, therefore improving communication. However, complex environments often include a mixture of competing speakers and background noise, and more cognitive resources are required to follow the speakers of interest and selectively switch between them if target sources are continuously changing (Shinn-Cunningham & Best, 2008). Within complex listening situations, similar auditory percepts (e.g., frequency content, pitch, temporal features, spatial features) are grouped by the brain to assign labels to the same auditory object. However, for people with hearing loss, this encoding is not as effective due to decreased audibility and impaired abilities to resolve spectro-temporal information (Deeks & Carlyon, 2004). Therefore, hearing impaired people will have difficulty forming auditory groups and switching between groups in complex, fast-changing listening scenarios (Shinn-Cunningham & Best, 2008). Furthermore, interfering sounds can mask important cues of target sounds, and the focus of the communication/conversation can rapidly change, resulting in a loss of contextual cues. Additionally, hearing impaired listeners have more difficulty filtering out unwanted signals and can find dynamic acoustic scenes overwhelming (Noble, 2006).

Hearing aid directional microphone technology is designed to enhance signals from the front of the listener, compared to those arriving from the back or the sides (Keidser et al., 2009; Van den Bogaert et al., 2006). Although, directional microphones can improve the signal to noise ratio by up to 6dB (Ricketts & Dittberner, 2002), their dependence on signal location could negatively impact speech recognition and localisation of signals presented around the listener (e.g group situations or unexpected sounds in busy environments). A review by Akeroyd (2014) found five studies (published between 2005-2014) that reported localisation errors as large or larger in the hearing aided condition compared to the unaided condition. Performance was particularly hindered if the hearing aid was set to a highly directional mode (Best et al., 2010b; Brimijoin et al., 2014; Keidser et al., 2009). Conversely, findings from Picou and Ricketts (2017) did not follow this pattern. The team investigated the effects of hearing aid directionality on sentence recognition, listening effort and localisation. They focussed on three hearing aid directionality conditions: bilateral omnidirectional microphones, bilateral directional microphones and an asymmetric microphone configuration and tested eighteen adults with moderate to severe hearing loss. Listeners were presented with five monosyllabic words from four loudspeakers at -60°, -45°, +45° and +60°. Following a dual task paradigm, listeners were asked to locate the correct speaker the word was presented from and recall as many words as possible after all presentations. Therefore, outcomes included localisation accuracy, localisation speed and word recall. Results found no significant main effect of loudspeaker location or microphone configuration (or their interaction) on localisation performance or localisation speed (Picou & Ricketts, 2017). These results may be due to the listeners being able to move their head freely in the experiment, the limited number of speaker locations and the reduced maximum speaker eccentricity (+/-60°) used in the task. Despite finding no significant main effect on localisation accuracy, the authors reported the directional microphone condition resulted in enhanced word recognition and reduced reaction times during the dual task paradigm.

Given the developments in modern HAs and the paucity of clinical sound localisation testing, there is a requirement for more ecologically valid tests (Cord et al., 2004; Pichora-Fuller et al., 2016; Walden et al., 2000). Assessing the efficacy of HA amplification requires tests that better reflect the more cognitively demanding nature of listening and communicating in real world situations. Accordingly, this study explored the potential clinical applications of a Spatial Speech in Noise Test (SSiN; Bizley et al., 2015). The SSiN test paradigm is designed to be a more challenging assessment technique to reflect realistic listening scenarios by implementing a dual task paradigm. This study compared word identification, relative localisation and reaction times between normal hearing listeners and bilateral HA users.

5.3 Method

The SSiN task conducted in this chapter was identical to the dual task SSiN method presented in the previous experimental chapter.

5.3.1 Ethical considerations

This study received ethical approval from University College London (UCL) Research Ethics Committee (3865/001). No participant identifiable data is presented in this paper. Data was kept in compliance with General Data Protection Regulation (EU) 2016/679. All listeners signed an informed consent document and were reimbursed for their efforts.

5.3.2 Participants

Participants consisted of 38 normal hearing listeners (aged 20–79) and 22 experienced bilateral HA users with bilateral symmetrical (within +/- 15 dB HL from 500–4 kHz) mild to severe sensorineural hearing loss (aged 22–83; see **Figure 5.1**). **Table 5.1** presents the participant demographics. The inclusion criteria were as follows: (a) bilateral HA users with > 2 years' experience of using behind-the-ear HAs and mild to severe symmetrical sensorineural hearing loss or normal hearing in both ears; (b) no recent history of ear surgery or ear infection; (c) no intrusive tinnitus or vertigo; (d) native English speaking and (e) HA users who had been seen by their audiology provider within the last 12 months. Six normal hearing listeners who had performed the dual task first in Chapter 4 (and therefore had no prior knowledge or practice of the test paradigm) were included in the normal hearing dataset in this chapter.

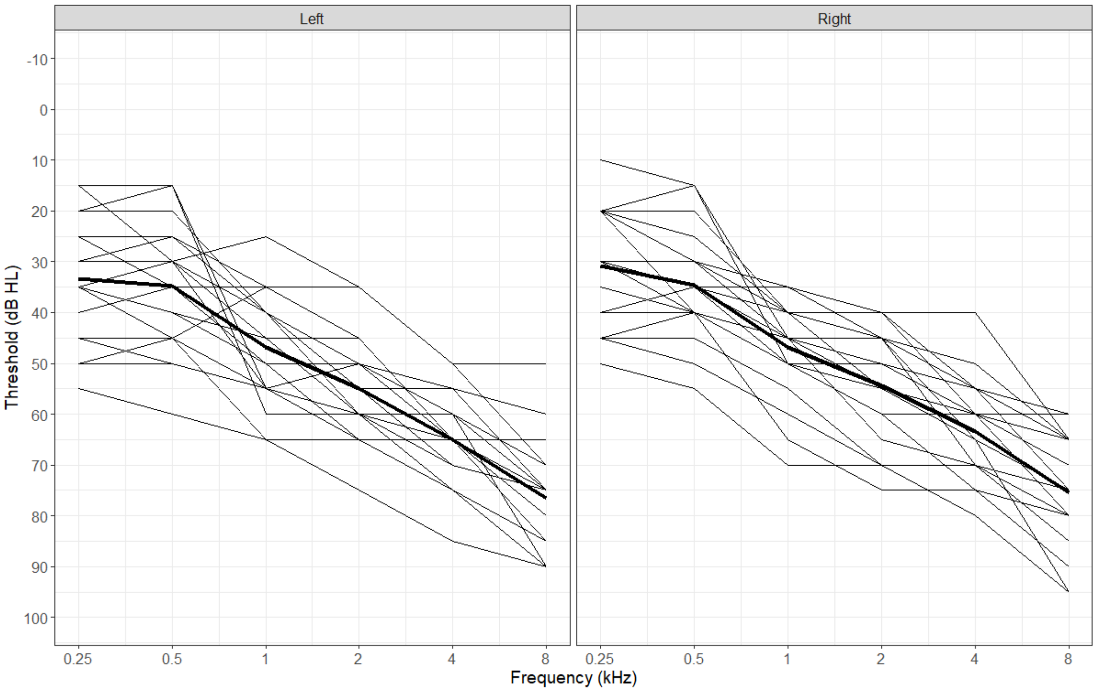


Figure 5.1 Hearing levels (dB HL) of all hearing aid users. The thicker solid black line represents mean hearing thresholds.

	Normal hearing listeners	
	Characteristics	Frequency
Age group	18-30	12
	31-40	4
	41-50	2
	51-60	6
	61-70	4
	71-80	4
	81+	3
Sex	Female	24
	Male	14
	Hearing aid users	
	Characteristics	Frequency
Age group	18-30	1
	31-40	2
	41-50	3
	51-60	4
	61-70	2
	71-80	7
	81+	3
Sex	Female	13
	Male	9

Table 5.1 Participant demographics.

5.3.3 Test protocol

HA users wore their own hearing devices during testing. HA set-up was checked during the test session. All HAs were programmed using the NAL-NL1 prescription algorithm. All HA users obtained their devices from the National Health Service.

The test protocol involved one visit per participant. HA users were recruited from online support groups for people with hearing loss and the UCL Ear Institute participant database. Normal hearing listeners were recruited through local community groups. An advertisement stating the details of the study was circulated amongst members, and those interested contacted the experimenter for further details. After pure tone audiometry, each participant performed the SSiN (dual task) once.

During the test session, a threshold task was followed by the SSiN dual task practice trials and main task. In the SSiN main task, as in Chapter 4, participants heard two monosyllabic words within the same word group (**Figure 5.2**) presented sequentially from speakers separated by 30° in the presence of multi-talker babble. Participants were instructed to identify both words in order and the direction of the location shift between the first word and the second word using the touch screen tablet (**Figure 5.2**). The test environment, stimuli and apparatus used were identical to those described in the previous chapter.

Discrimination	Word List
Complex vowel (Vc)	Pale Pool Pile Peel
Simple vowel (Vs)	Hoot Heat Heart Hurt
Initial consonant (Ci)	Chalk Talk Fork Stork
Final consonant (Cf)	Cheat Cheese Cheap Cheek

Table 5.2 SSiN confusion word groups.

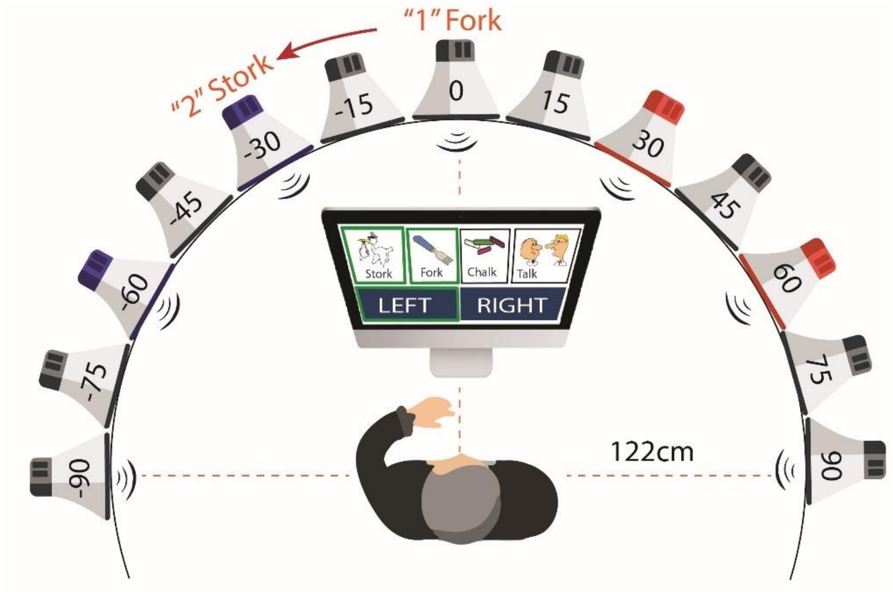


Figure 5.2 The speaker arrangement for the Spatial Speech in Noise Test. Speakers are labelled with their azimuthal location (degrees). In the figure above, a reference speech token ("Fork") is presented from one speaker followed by a target speech token ("Stork") from an adjacent speaker. Testing takes place in the presence of multi-talker babble originating from either the left (blue) or right (red) speakers. Listeners are asked to face the midline throughout testing and to identify both words on the touch screen and the location shift between the words. The touch screen presented in this figure is not to scale. Speakers used for presentation of speech tokens are labelled with the speaker symbol within the speaker ring.

5.3.4 Statistical analysis

Firstly, the association between word identification performance (percent correct) collapsed across location and SNR was tested using linear regression, with performance as the dependent variable, and fixed effects of SNR and group. Inclusion of the group effect improved the model fit (F(1,665)=6.51, p=0.009) and Bayesian Information Criterion (BIC) relative to a model with only SNR, but including an interaction between group and SNR did not, and so the interaction was not included. Word identification and relative localisation performance data were categorized as correct or incorrect and analysed using generalized linear mixed effects modelling with a binomial (logit) error distribution. Reaction times were calculated relative to the onset of the trial and were analysed using linear mixed modelling (both using package *lme4* in R version 3.6.2) (Bates et al., 2015). One model was created for each of three dependent variables: (a) word identification performance, (b) relative localisation performance and (c) reaction time. Age and gender effects were not significant in any analysis and therefore were removed from the models.

All models included a random effect of subject to account for random inter-subject variability in baseline performance or reaction time. Since regression models can be sensitive to variables that are correlated, the variance inflation factors (VIF) for all predictors used in the model were calculated to check for multi-collinearity. The VIFs for all predictors were very low (all below 1.02), and so none were excluded. Normality of residuals in reaction time models was ensured using QQ plots. Performance model fit was evaluated by calculating the area under the curve (AUC) of ROC curves for each model, and sensitivity and specificity were calculated using optimal cut points (Youden, 1950). The azimuthal distance between a speech token presentation and the mean multi-talker babble location was calculated for each trial and added to our analysis to explore spatial release from masking.

Post hoc analysis was performed through contrasts of least-square means using the *emmeans* library (Lenth et al., 2018), and *p*-values were corrected for multiple comparisons using the Tukey method. Significant differences are reported using α = 0.05. Below is a description of each of the three models used.

5.3.4.1 Word identification

Word identification accuracy (coded as correct or incorrect on a word-by-word basis, with two words per trial) was modelled as a function of several fixed effects. These included participant group (normal hearing listeners vs HA users), word group, trial number, word order (i.e., word 1 or word 2 within the trial), categorical speaker locations for speech token presentation (+/-90°, +/-60°, +/-30° and 0°) and speech-noise separation (in degrees). The interaction between group and speech-noise separation was included. Random linear learning effects within a random clustering factor of participants were estimated.

5.3.4.2 Relative localisation

Relative localisation accuracy was also captured as either correct or incorrect and was modelled as a function of fixed effects, including group, mean speaker location, word group and trial number. Random linear learning effects within a random clustering factor of participants were estimated.

5.3.4.3 Reaction time

Reaction time is the time taken for participants to select a word (word identification reaction time) or location shift (relative localisation reaction time), on the touchscreen provided, calculated from trial onset. Reaction time outliers were systematically chosen due to the parameters of the task such that word identification reaction times between 0.1 s and 14 s were included in the analysis. These values were chosen as responses outside this range would likely be unrelated to the task. For relative localisation selections, reaction times below the minimum reaction time to word 2, and those above 14 s, were systematically removed. The log of reaction times was used to account for positive skew of the reaction time distribution. Reaction times for word identification selections were modelled using fixed effects of group, speech-noise separation, word group, word number and trial number. Reaction times for the location shift selection were modelled using fixed effects of group, task, word group, mean speaker location and trial number. Random variability between subjects in baseline reaction times was estimated by including subject as a random effect.

5.4 Results

The SSiN was performed once by each participant (38 normal hearing listeners, 22 bilateral HA users). Prior to completing the main task, each participant performed a threshold task to establish the signal-to-noise ratio over which testing took place (see **Figure 5.3**). Figure 5.3 shows the individualised SNRs as a function of word identification performance (% correct) collapsed across speaker location, for each participant. Word identification performance for the normal hearing group (mean 86.2%, SE=2.44) was higher than for the hearing impaired group (mean 72.6%, SE=3.19), and this difference was significant (F(1,50)=7.51, p=0.008). When controlling for this, there was no significant association between SNR and word identification performance (F(1,50)=1.04, p=0.313), providing evidence that the standardisation of SNRs across participants was effective despite differing hearing thresholds between groups. Test–retest reliability of the SSiN was estimated as in Bizley et al. (2015) using a split-half analysis and collapsing word identification performance across speaker location. Cronbach’s alpha was 0.75, which is deemed acceptable for developing an assessment (Nunnally, 1978).

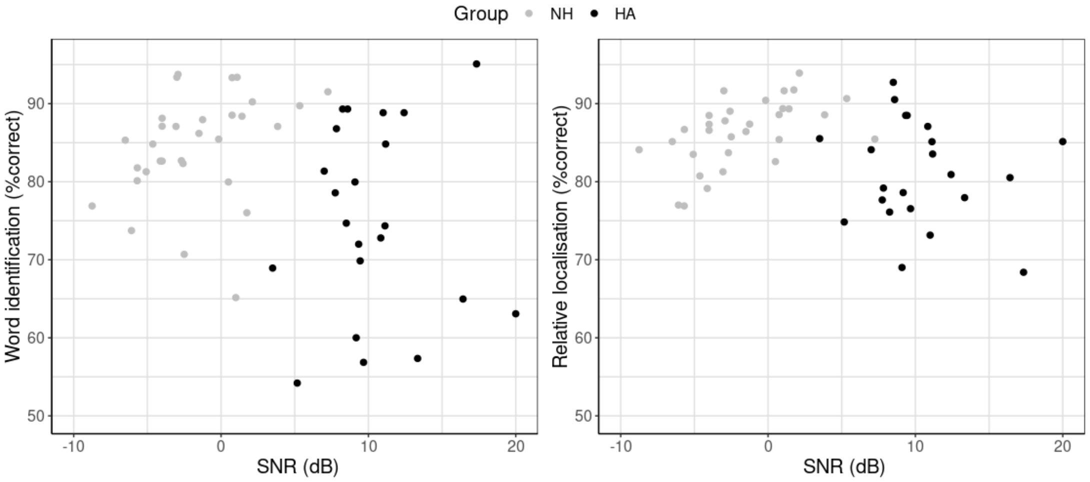


Figure 5.3 Word identification (% correct), relative localisation performance (% correct) and the SNR (dB) used within the SSiN for each participant. Performance % correct scores were collapsed across speaker location and plotted as a function of signal to noise ratio established from the threshold task and used in the main SSiN task.

5.4.1 Word identification performance

The word identification performance of normal hearing listeners and HA users for word 1 and word 2 presentations combined are presented across speaker location (degrees) in **Figure 5.4A,** and performance across word groups is presented in **Figure 5.4B**. Statistical analysis explored predictors of word identification performance including speaker location and azimuthal distance between speech and noise source to explore spatial release from masking between groups.

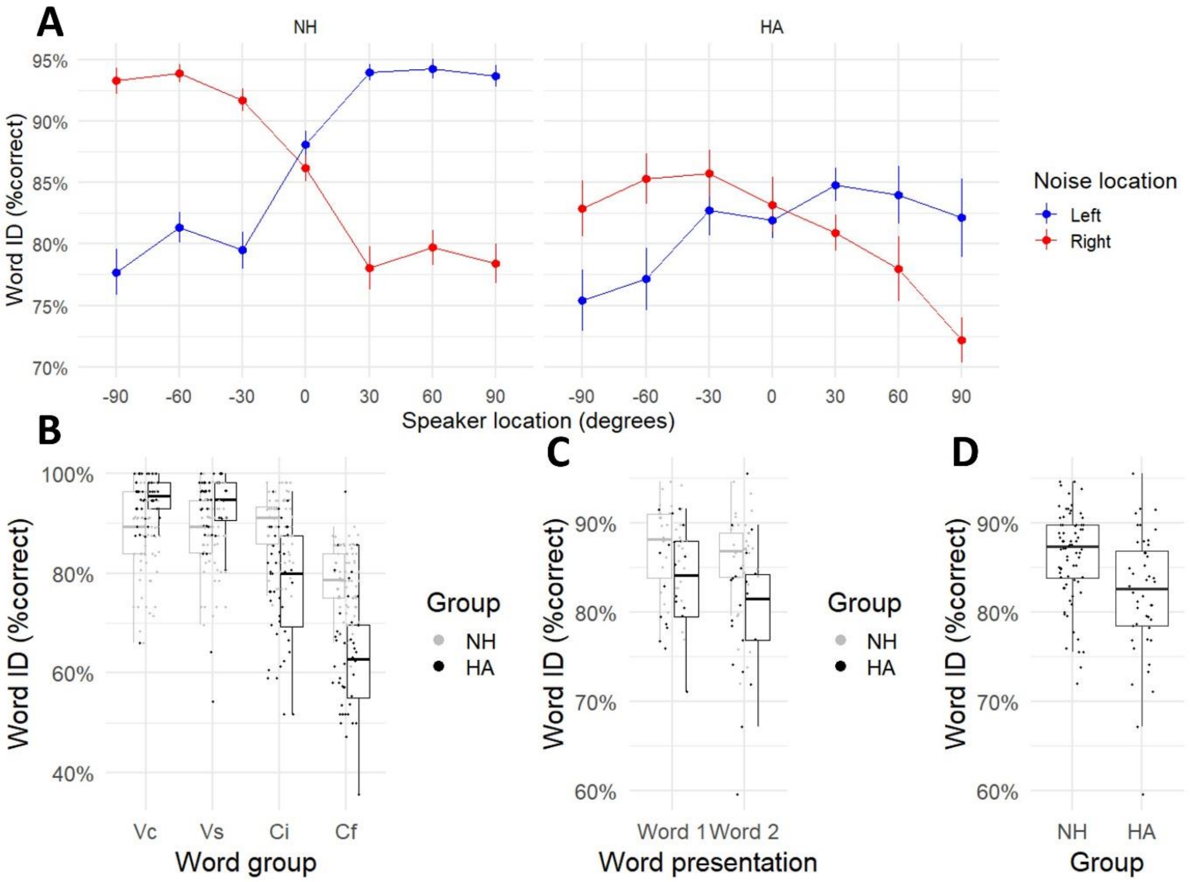


Figure 5.4 SSiN word identification performance for normal hearing listeners and hearing aid users. A) word identification (% correct) across speaker location (degrees) for normal hearing listeners and HA users, word identification performance (% correct) between B) word groups, C) word presentation order and D) participant groups.

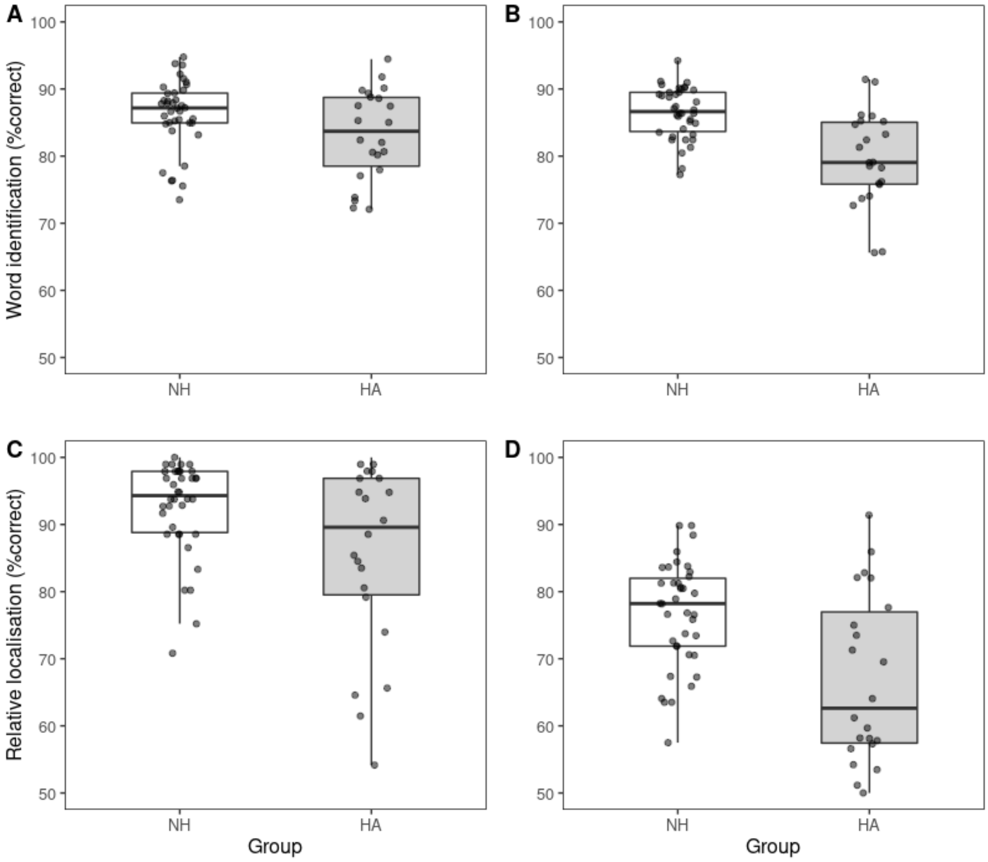


Figure 5.5 Word identification and relative localisation performance at central and peripheral locations for normal hearing listeners and hearing aid users. A) Word identification (% correct) for the NH and HA groups collapsed across central speaker locations (0°, 30° and -30°), B) Word identification (% correct) for the NH and HA groups collapsed across peripheral speaker locations (-90°, -60°, 90°, 60°), C) Relative localisation (% correct) per participant for NH and HA groups collapsed across central mean speaker locations (0°, 15°, -15°), D) Relative localisation (% correct) for the NH and HA conditions collapsed across peripheral mean speaker locations (-75°, -45°, 45°, 75°).

The model terms for word identification performance for normal hearing listeners and HA users (sensitivity = 0.656, specificity = 0.697, AUC = 0.732) are outlined in **Table 5.3**. Overall, there was a borderline effect of participant group (p=0.05) (see **Figure 5.4**). There was a significant difference between how the groups performed in relation to the azimuthal distance between the speech token and the mean multi-talker babble location (see **Figure 5.6**), with HA users' performance much less strongly modulated by the speech-noise source spatial separation than normal hearing listeners. HA users were also significantly poorer at word identification at the most lateral (±90) positions.

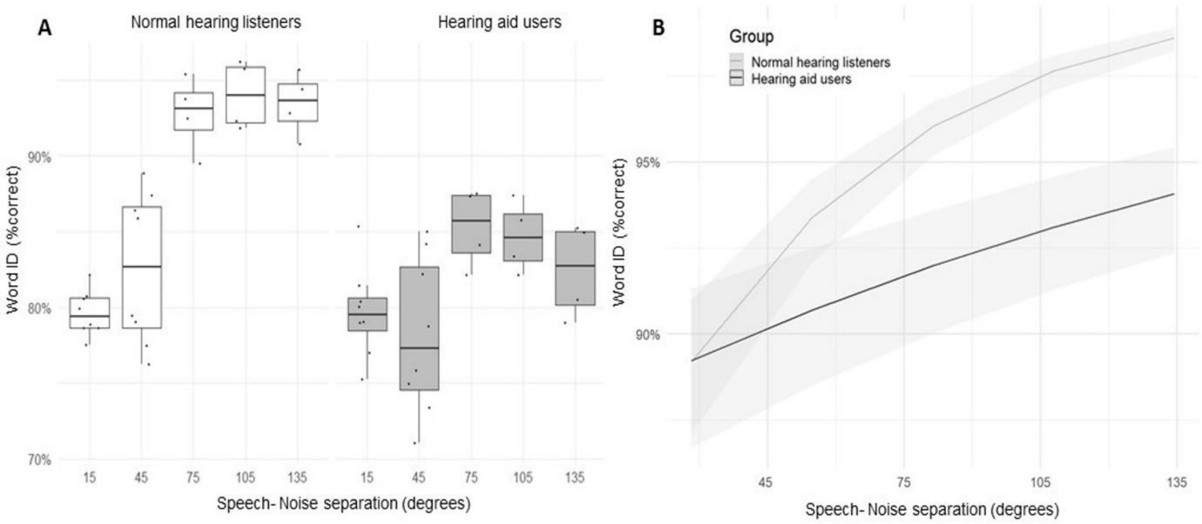


Figure 5.6 Effect of speech-noise azimuthal separation on word identification performance (% correct) for normal hearing listeners and hearing aid users. Word identification performance (% correct) for normal hearing listeners and bilateral HA users as a function of the distance between speech token and the mean location of multi-talker babble (degrees), B) modelled interaction between group and speech-noise separation (degrees) in predicting word identification accuracy (shaded areas: 95% confidence intervals [CIs]). Areas of overlap between the 95% CI of the two groups represents word-noise spatial combinations where performance does not significantly differ between groups.

In the current SSiN methodology, multi-talker babble is presented from either the right or left of azimuthal space, and words can occur anywhere in frontal space. SRM is evident in the cross-over in performance for left-noise and right-noise trials, where contralaterally occurring speech signals are better discriminated than those ipsilateral to the noise. To better understand the SRM, we considered performance according to the angular distance of the speech target and the noise task (see **Figure 5.6A**). As anticipated, this revealed that speech tokens nearer to the noise locations were significantly more difficult to discriminate compared to those spatially separated from the multi-talker babble. An additional figure is presented in **Appendices 9.4** which also shows word identification performance (% correct) as a function of speech-noise azimuthal separation (degrees), but distinguishes between conditions where speech is presented centrally to the mean noise source location, and where speech is presented peripherally to the mean noise source.

For normal hearing listeners' word identification performance within a hemifield, increasing the distance between a speech token's presentation speaker location and the mean location of the multi-talker babble was associated with improved performance. Beyond the hemifield, there was a plateauing of performance as normal hearing listeners reached ceiling performance before the speech and babble are maximally separated. For HA users, performance was similar to normal hearing listeners when speech and babble were presented in the same hemifield but reduced when the babble is fully lateralised to the contralateral side. There was no significant difference between the overall word identification performance between normal hearing listeners and HA users and the performance of the two groups was similar when the stimulus and noise were in close proximity. However, normal hearing listeners showed a near-ceiling advantage when speech and babble were separated that HA users did not demonstrate, representing a statistically significant difference (see **Figure 5.6B**).

Finally, there was a significant effect of word number, and identification of the second word presentation was poorer than the first word. However, there was no interaction between group and word number, indicating both groups presented with similar effects in relation to word order. There was also a significant effect of word group on word identification performance. Post hoc testing revealed that the word groups varying by consonant features (Cf and Ci) were significantly more difficult to discriminate than those varying by vowel (Vc). The target word (second word) was significantly more difficult to discriminate compared to the reference word, and post hoc analysis found that this effect was present similarly in the normal hearing group (Est = 0.204, *p* < .001) and the HA user group (Est = 0.201, *p* < .001).

Item	**χ2**	**df**	**p**
Group (HA/NH)	3.122	1	0.05*
Speaker Location	143.335	6	<0.001*
Speech-Noise Separation	590.573	1	<0.001*
Word Group	1011.651	3	<0.001*
Word Number (first/second)	14.173	1	<0.001*
Trial Number	7.993	1	0.005*
Group × Word Number	0.877	1	0.349
Group × Speech-Noise Separation	146.730	1	<0.001*

Table 5.3 Predictors of word identification performance.

Term	**Group**	**Reference**	**Est**	**SE**	**Z**	**p**	**OR**	**95% CI**
Group	HA	NH	0.25	0.13	1.964	0.050*	1.29	1.01-1.65
Speaker Location	90° Left	Midline	-0.63	0.08	-7.80	<0.001*	0.53	0.45-0.62
	60° Left	Midline	-0.08	0.06	-1.18	0.895	0.92	0.81-1.05
	30° Left	Midline	0.03	0.06	0.44	0.999	1.03	0.91-1.16
	30° Right	Midline	0.01	0.06	0.17	1.000	1.01	0.89-1.38
	60° Right	Midline	-0.11	0.06	-1.64	0.645	0.89	0.79-1.02
	90° Right	Midline	-0.64	0.08	-7.89	<0.001*	0.53	0.45-0.62
Word Group	Vs	Vc	-0.05	0.06	-0.75	0.872	0.95	0.85-1.07
	Ci	Vc	-0.56	0.06	-10.14	<0.001*	0.57	0.52-0.64
	Cf	Vc	-1.33	0.05	-25.89	<0.001*	0.26	0.24-0.29
Word Number	2	1	-0.18	0.04	-3.76	<0.001*	0.82	0.76-0.92

Table 5.4 Estimates of each significant term to predict word identification accuracy. Estimates include strength and significance (p) as well as odds ratio (OR) and its 95% CI.

5.4.2 Word identification reaction time

Figure 5.7 displays the log reaction times for word identification selections for normal hearing listeners and bilateral hearing aid users. These reaction times represent the time taken for participants to select the first and second word, measured from trial onset.

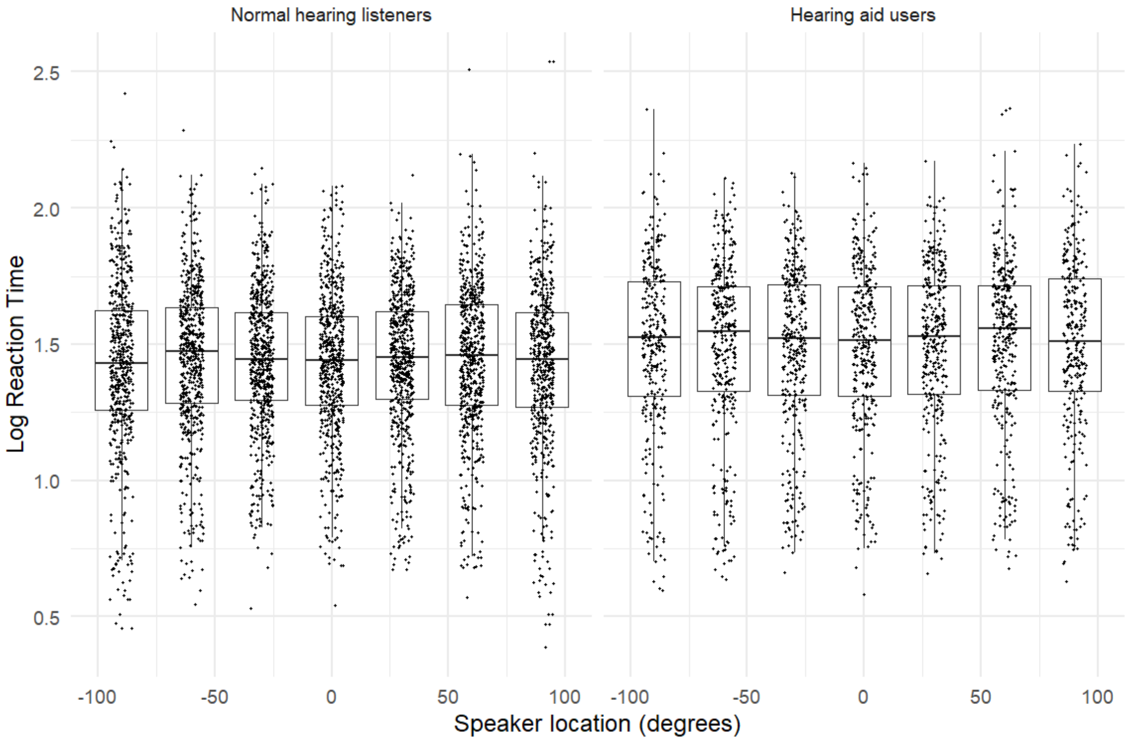


Figure 5.7 Log reaction time for word identification selections across speaker location (degrees) for normal hearing listeners and hearing aid users. Results have been collapsed across word 1 and word 2 presentations.

Reaction time data for word identification was visualised and analysed (**Figure 5.7**) using a linear mixed model ($R^2 = 0.546$). Model estimates and significance are outlined in **Table 5.5**. Overall, there was no significant difference between the word identification reaction times of normal hearing listeners and HA users. There was a significant effect of speech-noise separation and an interaction between this effect and participant group. Mirroring the performance data, normal hearing listeners tended to respond faster when the speech and noise were spatially separated, whilst reaction times remained more consistent across speech-noise separations for HA users. There was also a significant effect of word group, with faster reaction times for the Vs and Ci word groups than the Vc word group. Post hoc analysis found no significant difference between reaction time of normal hearing listeners and HA users in relation to the reference word (Est = -0.0419, *p* = 0.886) or the target word (Est = -0.074, *p* = 0.563). There was a significant effect of trial number, with both groups responding faster over the course of the testing session.

Item	**χ2**	**df**	**p**
Group (HA/NH)	0.454	1	0.50
Speaker Location	86.928	6	<0.001*
Speech-Noise Separation	325.914	1	<0.001*
Word Group	77.380	3	<0.001*
Word Number (first/second)	5188.769	1	<0.001*
Trial Number	13.727	1	<0.001*
Group × Word Group	89.032	3	<0.001*
Group × Word Number	30.703	1	<0.001*
Group × Speech-Noise Separation	75.328	1	<0.001*

Table 5.5 Predictors of word identification reaction time. *α = 0.05

Term	**Group**	**Reference**	**Est**	**SE**	**Z**	**p**
Group	HA	NH	-0.028	0.011	-0.674	0.500
Location	90° Left	Midline	0.043	0.007	6.269	<0.001*
	60° Left	Midline	0.015	0.005	2.818	0.069
	30° Left	Midline	0.001	0.005	0.297	1.000
	30° Right	Midline	0.000	0.005	0.080	1.000
	60° Right	Midline	0.019	0.005	3.504	0.008
	90° Right	Midline	0.042	0.007	6.137	<0.001*
Word Group	Vs	Vc	-0.031	0.005	-6.126	<0.001*
	Ci	Vc	-0.016	0.005	-3.082	0.011*
	Cf	Vc	0.011	0.005	2.081	0.159

Table 5.6 Estimates of each significant term to predict word identification reaction time. Estimates include strength and significance (*p*).

5.4.3 Relative Localisation performance

As in normal hearing listeners, relative localisation was superior at the midline for HA users (**Figure 5.8**). Generalised linear mixed effect modelling was used to present predictors of relative localisation performance in this cohort.

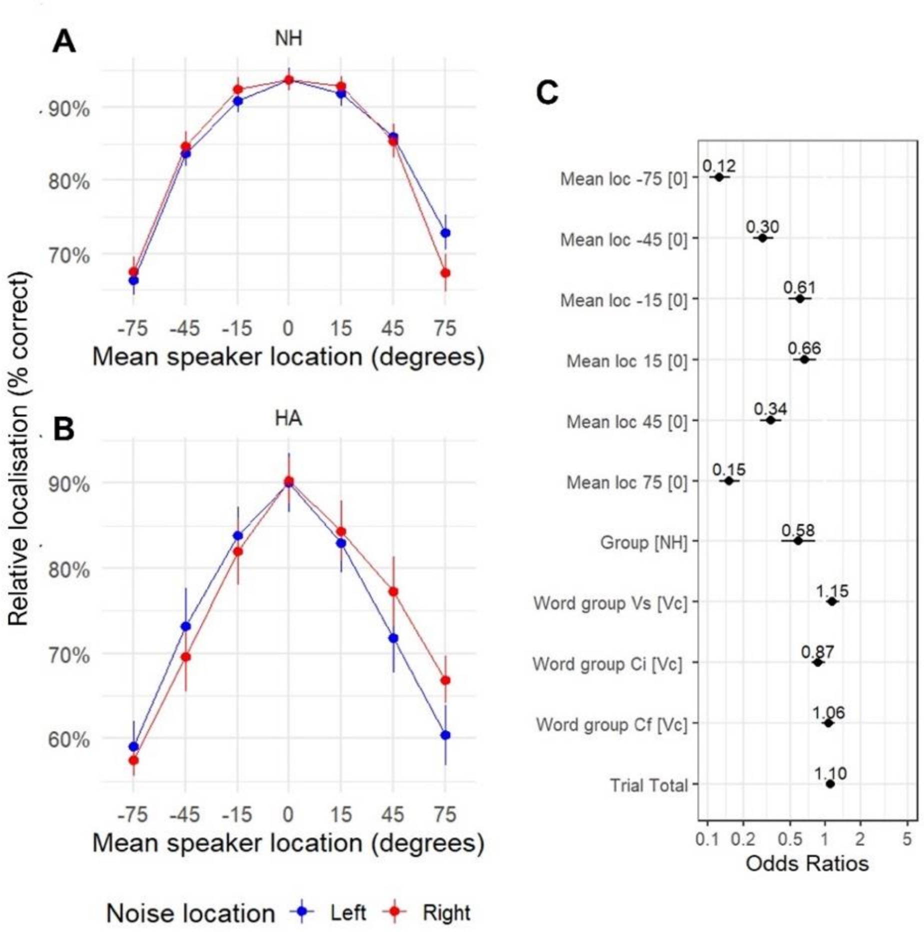


Figure 5.8 Relative localisation performance for normal hearing listeners and hearing aid users. A) Relative localisation performance of normal hearing listeners and B) relative localisation performance of hearing aid users- chance performance is 50%, error bars represent standard error, C) odds ratio (OR) for each term in the prediction of relative localisation performance.

The model's ROC curve yielded an AUC of 0.761 (sensitivity = 0.627, specificity = 0.783). Model terms and significance are outlined in **Table 4**. Overall, HA users' relative localisation performance was significantly poorer than that of normal hearing listeners. Performance was significantly reduced at peripheral locations compared to the midline. There was a positive learning effect throughout the session.

Item	χ2	df	p
Group (HA/NH)	9.901	1	0.002*
Mean Speaker Location	856.664	6	<0.001*
Word Group	19.599	3	<0.001*
Trial Number	4.510	1	0.034*

* α = 0.05.

Table 5.7 Predictors of relative localisation performance.

Term	Group	Reference	Est	SE	Z	p	OR	95% CI
Group	HA	NH	-0.537	0.171	-3.147	0.002*	0.585	0.418-0.817
Mean Speaker Location	75° Left	Midline	-2.080	0.101	-20.534	<0.001*	0.125	0.102-0.152
	45° Left	Midline	-1.221	0.105	-11.547	<0.001*	0.295	0.240-0.363
	15° Left	Midline	-0.493	0.114	-4.321	<0.001*	0.611	0.489-0.764
	15° Right	Midline	-0.410	0.115	-3.555	0.007*	0.663	0.529-0.832
	45° Right	Midline	-1.071	0.107	-10.032	<0.001*	0.343	0.278-0.422
	75° Right	Midline	-1.835	0.102	-18.510	<0.001*	0.152	0.124-0.185
Word Group	Vs	Vc	0.138	0.067	2.073	0.163	1.148	1.008-1.309
	Ci	Vc	-0.142	0.065	-2.201	0.123	0.868	0.764-0.985
	Cf	Vc	0.055	0.066	0.838	0.836	1.057	0.929-1.203

Table 5.8 Estimates of each significant term to predict relative localisation accuracy. Estimates include strength and significance (*p*) as well as odds ratio (OR) and its 95% CI.

5.4.4 Relative localisation reaction time

Figure 5.9 displays the log reaction time for the location shift selection across azimuthal location for both groups. This reaction time measure represents time taken to identify the location shift between the target and reference word presentations and participants would select either ‘left’ or ‘right’ in response. The reaction times for these location shift selections, from trial onset, are presented across mean speaker location.

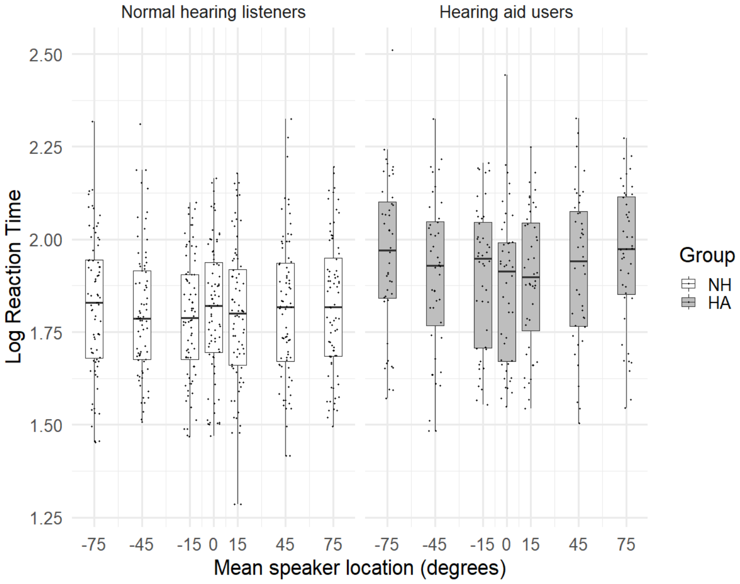


Figure 5.9 Log reaction time for location shift responses across mean speaker location (degrees) for normal hearing listeners and hearing aid users.

The model predicting reaction time for relative localisation identification showed satisfactory performance ($R^2 = 0.35$). HA users were significantly slower than normal hearing listeners in identifying the location shift between reference and target words. Reaction time varied significantly with mean speaker location and were incrementally slower at mean speaker locations farther from centre (see **Figure 5.9**). Reaction times became longer throughout the duration of the task for both groups.

Item	$\chi 2$	df	p
Group (HA/NH)	5.128	1	0.024*
Mean Speaker Location	49.671	6	<0.001*
Word Group	49.651	3	<0.001*
Trial Number	137.106	1	<0.001*

Table 5.9 Predictors of relative localisation reaction time.

Term	Group	Reference	Est	SE	Z	p
Group	HA	NH	0.102	0.045	2.265	0.024*
Location	75° Left	Midline	0.041	0.008	5.278	<0.001*
	45° Left	Midline	0.019	0.008	2.385	0.205
	15° Left	Midline	0.007	0.008	0.895	0.973
	15° Right	Midline	0.011	0.008	1.404	0.800
	45° Right	Midline	0.020	0.008	2.525	0.150
	75° Right	Midline	0.040	0.008	5.157	<0.001*
Word Group	2	1	-0.006	0.006	-0.951	0.777
	3	1	0.006	0.006	1.090	0.696
	4	1	0.033	0.006	4.268	<0.001*

Table 5.10 Estimates of each significant term to predict relative localisation reaction time.

5.5 Discussion

The goal of this study was to explore the clinical application of the SSiN, which Bizley et al. (2015) initially developed. The dual task allows for the simultaneous assessment of spatial hearing and speech identification within a dynamic, ecologically valid testing paradigm using speech tokens and multisource babble. The nature of the dual task also mimics important listening scenarios, as individuals need to locate and discriminate speech to follow the conversation in complex scenes. Furthermore, more cognitively demanding listening tasks help avoid ceiling effects commonly observed within speech recognition testing and could therefore provide scope to measure intervention benefit (e.g., auditory training or HA features). This study compared SSiN performance between a group of bilateral HA users and a group of normal hearing listeners.

According to Bizley et al. (2015), the SSiN has the potential to assess the relative localisation and word identification performance across azimuthal space of clinical populations. In this study, SSiN performance findings consisted of 38 normal hearing listeners and 22 bilateral HA users to further confirm usability. The goal of this experiment was to explore whether the SSiN was usable for this clinical population and compare results between groups. Results from normal hearing listeners replicated those in the dual stream task in the previous chapter and the spatial hearing effects reported in the original SSiN study by Bizley et al. (2015). Relative localisation performance was superior at the midline compared to peripheral locations. Findings in this study demonstrated improved word identification scores when target words were spatially separated from background babble. With the implementation of a more robust threshold seeking task, experienced HA users completed the SSiN without the floor and ceiling effects found in our pilot experiments (Parmar, 2016). Findings from this chapter revealed that HA users tended to have poorer word identification performance compared to normal hearing listeners despite difficulty matching ($p=0.05$) and they did not benefit from spatially separating speech and noise to the same extent as normal hearing listeners. Furthermore, hearing aid users' reaction times were significantly slower than normal hearing listeners, implying they experienced more effortful listening.

In addition, results from the SSiN showed that HA users had significantly reduced relative localisation performance compared to normal hearing listeners. The independent processing present in bilateral HAs can disrupt the interaural level differences and interaural timing differences needed for binaural listening. Attempts have been made to synchronise HA processing and maintain these interaural cues;

however, bilateral HA users often face impaired horizontal sound localisation within behavioural listening tasks (Van den Bogaert et al., 2006). Clinically, audiologists programme and verify HA output, but the focus tends to be on how each HA performs for each ear, with less consideration of the impact on binaural cues (Gorodensky et al., 2019). Testing spatial hearing abilities may help clinicians and patients understand the performance of hearing devices in complex listening scenarios, including their limitations, and explore the benefit of advanced features designed to enhance spatial hearing. There is also scope for using the SSiN as a tool to monitor the impact of binaural auditory training of younger hearing-impaired listeners or younger device users who are still developing their spatial hearing abilities.

Both HA users and normal hearing listeners had significantly reduced word identification performance for the second word (target word) compared to the first word (reference word). However, this was not the case when the SSiN dual task or single word identification task was used to assess normal hearing listeners in the previous chapter (Chapter 4). This study presents a larger dataset, which may have enhanced sensitivity to such factors. One reason for the difference in identification performance between word 1 and word 2 could be an auditory attentional blink, where the identification of the first target impairs the processing of a second target when the second target is presented within several hundred milliseconds after the first target (Shen & Mondor, 2006; Vachon & Tremblay, 2005). Further use of the task could explore this in more detail by adapting the gap between target and reference word presentations.

This study used the SSiN to assess a larger number of normal hearing listeners ($n = 38$) compared to the original use of the task (Bizley et al., 2015; $n = 10$). In addition, Bizley et al. (2015) reported a trend for reaction times to be modulated by space, which has been solidified based on findings in this study. Relative localisation reaction times were significantly slower for stimuli presented at the periphery compared to those in the midline, indicating faster responses in locations with enhanced performance.

Previous spatial hearing researchers have reported ceiling effects when testing hearing impaired listeners’ left-right discrimination or weak correlations between the degree of hearing loss and localisation performance (Lovett et al., 2015). Pilot experiments have found floor effects in localisation performance when testing the SSiN on HA users (Parmar, 2016). To avoid floor effects in localisation performance, tasks have included a method of individualising the SNR for testing (Picou & Ricketts, 2017). The current threshold estimation task was efficient in individualising the speech level used within the main SSiN task to ensure participants perform within a set area of the psychometric function. Furthermore, our pilot work found that HA users performed the relative localisation task below chance performance. Researchers have indicated the need to increase speaker separations for clinical populations given cochlear implant users' spatial hearing abilities vary from those of normal hearing listeners by up to 28° (typical error magnitude; Bizley et al., 2015). Van den Bogaert et al. (2006) reported HA users mean error to be between 16° and 18° depending on the microphone configuration. Speaker separations of 30° were used in this study, without revealing ceiling or floor effects in the HA user group, but this can be adapted to best suit the respective patient group.

The trial total was included in the analysis to investigate how performance and reaction time changes throughout the SSiN task. In total, the current version of the SSiN consists of 224 trials presented across eight testing blocks. Participants were given breaks between each block. However, word identification and relative localisation performance significantly improved for HA users and normal hearing listeners throughout the course of the task. Moreover, relative localisation reaction times became significantly faster for both groups. This indicates the potential learning effects of the test paradigm and the specific words presented. In addition, word identification reaction time was reduced across the length of the task, which may indicate fatigue. Future research could include trialling a reduction in the number of trials, e.g., reducing the number of speaker locations/pairs, to avoid such learning and fatigue effects. A shorter task would increase clinical usability as Chapter 3 revealed that limited clinical time in audiology is a primary barrier affecting the use of additional hearing assessments. Lastly, a shorter test duration would make the SSiN more suitable for paediatric populations.

All HA users wore their own HAs during the study and although the devices were checked for functionality, no in-situ verification was performed. In addition, efforts were made to age match the normal hearing and HA user groups. Given the testing parameters needed to assess the impact of noise reduction and directional microphone schemes in current HAs, future research could include trialling higher levels of background babble. This will also better mimic real world listening situations ecologically, as currently the noise level is lower than that expected in average social situations (overall multi-talker babble was presented at approximately 52 dBSPL in this study's test) but is utilised to test HA users' overall performance rather than the activation of significant compressions schemes or advanced features. The test in this study only presented background babble and target sounds from the frontal hemisphere. In real world listening situations, background noise naturally appears from behind the listener, and further use of the SSiN could include a rear noise source to take this into account. Currently, the SSiN takes place within an anechoic chamber. The selection of speakers was made to ensure that it could utilise an AB-York Crescent of Sound (Kitterick et al., 2011), which can be found in some clinical settings in the UK. Limited access to such facilities reduces the test's utility within clinical settings. However, a virtual implementation of this task would enable the SSiN to be performed from a clinic or even a patient's own home.

5.6 Conclusion

SSiN findings include a listener's spatial acuity, word identification and reaction times. There is also scope for the speech-noise azimuthal separation to be analysed with respect to performance, to assess spatial release from masking (SRM). The task uses smaller speaker separation than other clinically available spatial hearing assessments and uses speech as the target stimuli and multi -source babble as the distractor stimuli, to better mimic the challenges of real-world listening. Bilateral HA users had reduced word identification, relative localisation and SRM abilities compared to normal hearing listeners. Future research could include a reduced SSiN test duration to enhance suitability within clinical testing environments and for special patient populations. Furthermore, additional measures of cognition including working memory and processing speed could be used alongside the SSiN to better understand the factors affecting performance.

Although this study used the SSiN to assess HA user performance for comparison with normal hearing listeners, there are also benefits to understanding how the task can be used in a clinical setting. This could include exploring the impact of using an individual’s results from the SSiN to raise awareness of specific patient difficulties and aid counselling in auditory rehabilitation. In addition, there is potential to use the SSiN as an outcome measure or candidacy tool when considering whether a patient would benefit from advanced HA features, such as directionality and noise reduction systems. Additional research is needed whilst controlling for HA type to investigate whether the SSiN is sensitive to changes in advanced HA features. Therefore, Chapter 6 is presented in three phases as follows: Phase 1 includes findings from HA users, fitted with the same HA, who complete the SSiN with two directionality systems: omnidirectional and adaptive directionality. Phase 2 provides a qualitative account of the participants’ perspectives and experiences completing the SSiN, including a list of primary improvement indicators to consider for future SSiN use. Lastly, Phase 3 includes technical HA measurements to present how HA output is modulated in response to the SSiN test paradigm.

Chapter 6: Using the SSiN to investigate effects of advanced hearing aid features

Chapter 5 explored the use of the SSiN to assess clinical populations and compared performance of normal hearing listeners (*n* = 38) with that of bilateral hearing aid users (*n* = 22). Hearing aid users were found to benefit less from spatially separating speech and noise in the SSiN and have reduced localisation performance, compared to normal hearing listeners. All participants were able to complete the SSiN without significant floor or ceiling effects therefore, indicating that the amendments to the task successfully improved its implementation for this population. Assessing spatial hearing in hearing aid users may assist clinicians in the candidacy assessment for advanced hearing aid features like adaptive directionality or noise reduction systems. It may also be helpful for patients to better understand the benefits and limitations of hearing aid technology in challenging listening situations.

Although Chapter 3 reported a lack of clinical time as a key barrier for HHPs to carry out speech testing, combining the assessment of relative localisation and word identification abilities could improve efficiency rather than testing these domains separately. As findings in Chapter 5 confirmed usability of the SSiN of hearing aid users, the purpose of Chapter 6 is to further investigate its clinical applications. Specifically, this chapter will use the SSiN to assess the benefit of hearing aid adaptive directionality (this version of the SSiN will be referred to as the SSiN-HA hereafter). This chapter takes an action research approach to involve researchers, hearing aid manufacturers and services users in the development and evaluation of the SSiN-HA to better understand it’s clinical usability.

This chapter is presented in three phases:

Phase 1 Using the SSiN-HA to assess adaptive directionality: The aim of this phase was to work with external researchers and hearing aid manufacturers to explore the data presented in Chapter 5 and propose ways the SSiN can be used to assess hearing aid features. Based on the discussions, the SSiN-HA was created and a collaboration with a global hearing aid manufacturer was initiated to control for hearing aid type. The SSiN-HA was then used to compare adaptive directionality with omnidirectional systems in a specific hearing aid model. Results were presented at international conferences which led to the recommendation of completing a larger trial, adding a rear noise source and carrying out hearing aid technical measurements within the SSiN-HA paradigm.

Phase 2 Qualitative review of SSiN-HA usability: The aim of this phase was to understand the user experience of participants undertaking the SSiN-HA. This phase involves two components. Firstly, a questionnaire was carried out and this was followed by an online focus group. Both components were completed by hearing aid users who had recently performed the SSiN-HA. This qualitative review highlighted practical limitations of the SSiN-HA including issues with the touchscreen tablet and some of the presented stimuli.

Phase 3 Hearing aid technical measurements*:* The original plan for phase 3 of this chapter was to implement changes to the SSiN-HA based on phase 1 and 2 and re-evaluate the task using a larger behavioural trial. However, testing was cancelled due to the COVID-19 pandemic. Instead, the feedback from phase 1 was actioned to complete hearing aid technical measurements in response to the SSiN-HA testing paradigm.

6.1 Introduction

Following an Action Research approach, findings from Chapter 5 were presented to multiple hearing aid manufacturers to arrange a collaborative effort to understand the clinical usability of the SSiN. One of the limitations within Chapter 5 was that all participants wore their own hearing aids rather than controlling for hearing aid type. The hearing aid manufacturer Oticon agreed to collaborate with this study by supplying hearing aids to trial the sensitivity of the SSiN to Oticon's speech enhancement, adaptive directionality feature, Open Sound Navigator™ (OSN). Within this chapter, a version of the SSiN, the SSiN-HA, was created to investigate whether the SSiN-HA could be used to assess effectiveness of OSN on relative localisation, word identification performance and reaction times, compared to the unaided and omnidirectional (OMNI) conditions. Hearing aid technical measurements were also carried out to investigate how these advanced features impact hearing aid output. Finally, participants completed a questionnaire and focus group to detail their SSiN-HA testing experience.

Due to the variety of self-reported preferences for noise reduction and directionality, hearing aid manufacturers include generic features for both systems in the hearing aid programming software (Eiler et al., 2008). Generally, the hearing healthcare professional decides whether such settings should be activated at the hearing aid fitting appointment. More recently, mobile applications have given some element of choice to the patient as they are able to make fine tuning adjustments to their hearing aids in specific listening situations (Maidment et al., 2019). However, this process lacks consistency, and the activation of certain features in the clinic may often be based on whether the patient is able to effectively describe their hearing difficulties to the audiologist, whether they are aware of the features available to them and whether there is clinical time available for this trial-and-error approach.

An assessment of candidacy or benefit of hearing aid features may help audiology professionals discuss the appropriateness and limitations of them rather than relying on self-report. Over time this could also reduce the number of unnecessary visits a patient would need to have with the audiologist, one of the main reasons why people consider self-fitting hearing aids (Convery et al., 2011).

6.1.1 Hearing aid processing and Oticon's Open Sound Navigator

Oticon's Open Sound Navigator (OSN) is an adaptive directionality and speech enhancement algorithm that was released by Oticon in 2016 to preserve speech and reduce noise from complex environments (Le Goff et al., 2016). One of its objectives is to apply directionality and noise reduction after the analysis of the competing sounds. The system was created to preserve speech and attempts to detect any speech like modulations in 16 frequency bands. If speech is detected in a frequency band, the algorithm is deactivated in that band. Therefore, OSN should preserve speech regardless of the listener's position in the environment. OSN combines fully adaptive directionality and fast-acting noise reduction. For the directionality, the feature has a two-microphone channel to achieve the omnidirectional response and a back facing cardioid microphone to establish the level and location of the speech and noise sources in the environment. The noise is estimated and the directionality system uses a minimum variance distortion-less response beamformer to use spatial filtering to reduce the loudest noise source between the speech signals and increase the signal to noise ratio (Kjems & Jensen, 2012). According to Le Goff et al (2016), the noise reduction estimate is updated 500 times per second in 16 independent frequency bands and allows for noise reduction between words. The literature suggests OSN reduces listening effort Ohlenforst et al. (2018) and the adaptive directionality is advantageous over the fixed directionality feature, particularly for incidental learning and when a listener is not able to reliably face the target speech (Browning et al., 2019).

Research studies have evaluated OSN for hearing aid users. Ohlenforst et al. (2018) demonstrated how OSN can reduce listening effort during speech recognition in stationary noise and with a 4-talker masker, and that this was sometimes independent of the SNR. The study used pupillometry methods to examine peak pupil dilation and found that the activation of OSN resulted in smaller peak pupil dilation compared to the no-OSN condition—indicating reduced listening effort. Wendt et al. (2017) also used pupillometry, and two different performance levels: SNR corresponding to 50% performance correct and SNR corresponding to 95% (4-talker babble), to test OSN-on vs OSN-off. The peak pupil dilation differed with the difficultly level where 50% performance level resulted in increased peak pupil dilation, indicating increased listening effort, compared to the 95% performance level. However, peak pupil dilation decreased in both difficulty conditions, when OSN was activated. This indicates that noise reduction systems like OSN may be beneficial to patients to reduce listening effort even in situations when speech intelligibility is near ceiling performance.

Browning et al. (2019) examined the impact of OSN in the paediatric population. There is a limited evidence base regarding the use of noise reduction and adaptive directionality for children with hearing aids. However, the literature suggests the use of these algorithms does not affect speech recognition for children (Crukley & Scollie, 2014; Stelmachowicz et al., 2010). Traditional directionality depends significantly on the listeners positioning compared to the speaker. However, natural positioning for the paediatric population or adults with additional needs can be more unpredictable compared to adult listeners. If the child does not know to face the speech signal of interest, then fixed directionality mode will lead to poorer performance than the omnidirectional setting (Ricketts et al., 2007). Therefore, adaptive directionality and noise reduction systems, to avoid the attenuation of speech signals, are of particular importance. Results from Browning et al. (2019) found that, when compared to OMNI, OSN improved speech recognition in steady noise even when children were not facing the target speech. When background noise was speech, OSN and OMNI settings performed similarly (Browning et al., 2019). Therefore, OSN may give children a benefit over the use of fixed directionality as results are not dependent on their positioning.

6.1.2 Hearing aid technical measurements

Noise reduction and directionality systems are present in all modern hearing aids and most make use of the modulation pattern of speech to distinguish between speech and noise signals. There are no specific clinical guidelines or methods of measuring noise reduction or directionality performance and generally the specific description of how a commercial hearing aid systems work is not available to clinicians. Although the evidence suggests dynamic noise reduction algorithms do not improve speech intelligibility, there is a body of research that reports improvements in listening effort (Sarampalis et al., 2009), and improved listening comfort (Mueller et al., 2006).

Different methods of calculating hearing aid output SNR have been proposed. When developing new tasks of speech perception for hearing aid users, it is important to also explore how the task parameters may be sensitive to hearing aid processing differences.

Henning and Bentler (2005) compared speech and noise signals after individually presenting these to the hearing aid. However, the hearing aid compression systems and noise reduction feature would react differently in cases when speech and noise were presented separately compared to when they are presented together, therefore limiting this methods' applicability (Henning & Bentler, 2005). The approach used by Hagerman and Olofsson (2004) separates the speech and noise mixture at the output of the hearing aid (Naylor & Johannesson, 2009; Olsen et al., 2005). This phase inversion approach has been used to measure output SNR in response to varying input SNRs and compression schemes (Naylor & Johannesson, 2009), directionality (Wu & Bentler, 2007; Wu & Bentler, 2009) and dynamic noise reduction (Hagerman & Olofsson, 2004). A study by Wu and Stangl (2013) measured hearing aid output SNR using a KEMAR manikin to investigate whether these measurements could predict a listener's acceptable noise level (ANL: the maximum noise level that the listener is willing to accept when listening to speech), across different hearing aid processing systems. Speech signals were presented at 0° and speech shaped noise was presented at either 0° or 180° and different input SNRs (-5 dB–20 dB). The study found a close relationship between aided ANL and calculated hearing aid output SNR. They also suggested that future clinicians could potentially use output SNR as a clinical measure to choose between hearing aid algorithms (Wu & Stangl, 2013).

Hagerman and Olofsson (2004) tested five different hearing aids to study the effect of noise reduction algorithms. Their findings showed up to a +5 dB enhancement when comparing input and output SNR. Brons et al. (2015) investigated the effects of compression and noise reduction, both together and separately on dynamic gain patterns and changes in speech and noise levels. They used an input SNR of +4 dB as this is associated with the regular listening situations experienced by people with hearing loss (Smeds et al., 2015). Speech and multi-talker babble were presented from a loudspeaker directly in front of the head and torso simulator. Speech and noise recordings were made for four different hearing aid conditions: linear with noise reduction off, linear with noise reduction on, compressive with noise reduction on, compressive with noise reduction off (Brons et al., 2015). Findings revealed a difference between compression and noise reduction processing between hearing aids, but overall effects of noise reduction and compression did not cancel each other out when combined. Although there was no improvement in speech intelligibility, combined compression and noise reduction reduced noise annoyance. These findings indicate the importance of completing hearing aid output measurements alongside collecting behavioural speech perception data, when developing hearing aid assessment tools.

6.1.3 Action research in healthcare

Action research is a process that effectively aids knowledge sharing and problem solving across disciplines and contexts. In healthcare, this process has been used for the development of clinical and health promotion tools (Flicker et al., 2008) and health service delivery mechanisms (Pratt & Hyder, 2018), among many other areas. The Action research process is bottom up and involves multiple stakeholders including the target population, and researchers so that an identified problem can be tackled through an actively collaborative approach (Montgomery et al., 2015).

Bradbury and Reason (2003) outline the key principles of action research and these include how the work is “grounded in lived experience, developed in partnership, addresses significant problems, working with, rather than simply studying, people and developing new ways to see the world” (Bradbury & Reason, 2003). However, there are different models of the action research process. Cordeiro and Soares (2018) completed a scoping review to explore the use of action research in healthcare related studies. The authors commented that the number of action research studies in this context has steadily increased since 2000 and that specific methodologies vary across the world (Cordeiro & Soares, 2018). The term ‘action research’ was first used by Lewin in the 1940s (Hart & Bond, 1995). The action research approach encourages collaboration between researchers, clinicians, patients and the public to facilitate change and bridge the ‘theory -practice gap’ (Tanna, 2005). Action research involves several steps that are often referred to in an action research cycle. The first steps include observing the current research problem and specifying the objectives. The steps that follow are designed to reach the objectives, but intermediate steps are available for reflection and evaluation. Given the cyclical nature of action research, this may also include modification of the original objectives. Meyer (1993) furthered Lewin's original work and summarised the four step approach to include planning, action, observation and reflection (Meyer, 1993). The Kemmis and McTaggart (2000) action research cycle (Figure 6.1) is well documented and involves research planning, action, and observation (data collection and analysis), and a reflection phase. During the reflection phase, researchers can decide whether the cycle needs to repeat so that modifications can be tried and tested (Kemmis & McTaggart, 2000). In hearing healthcare and research, action research has been used for developing tools for hearing impaired listeners to effectively access health services (Constantinou et al., 2017), building intervention for healthcare staff to increase their communication skills and awareness of deaf individuals (Bodenmann et al., 2021) and the development of auditory training games (Vickers et al., 2021).

6.1.4 Motivation for this study

The literature suggests OSN can improve speech understanding and reduce listening effort and this feature is currently available within the UK hearing healthcare system (both public and private sector). Therefore, OSN was chosen to trial the SSiN-HA's sensitivity in assessing such features and investigates the task's clinical potential further. Hearing aids are rapidly developing, and studies have shown the benefits and limitations of advanced features like noise reduction and directionality systems for hearing aid users. However, clinically relevant assessment tools to efficiently understand the benefit of such systems for specific patients could be a valuable addition to audiology settings. Results from Chapters 4 and 5 reported the use of the SSiN on clinical populations. This chapter takes an action research approach to involve researchers and hearing aid users to further develop the SSiN-HA, with the aim of demonstrating its use in assessing hearing aid adaptive directionality (OSN).

6.2 Method

6.2.1 Ethical approval

This study was approved by UCL Ethics committee (project no. 3866/001). Data was kept in compliance with General Data Protection Regulation (EU) 2016/679. The audio recordings of the interviews and focus group were destroyed after transcription. Participants were anonymised in the transcription and any mention of specific service providers were removed. Each participant gave written consent to take part in the study.

6.2.2 Action research approach

Action research, or participatory design, involves action, evaluation and critical reflection and the implementation of evidence-based changes to practice (Lewin, 1946). It is a collaborative process, informed by user involvement (Koshy et al., 2010). In the present study, to investigate how the SSiN-HA could be used to assess clinical populations, researchers, audiologists, hearing aid manufacturers and hearing aid users have been involved in providing feedback. In healthcare, it has become increasingly important to involve patients in the development and evaluation of clinical interventions, including those involving audiology rehabilitation (Hallewell et al., 2021). **Figure 6.1** shows an adapted version of the action research spiral (Kemmis & McTaggart, 2000), with details of this chapter’s action research approach overlaid (detailed description of the steps followed can be found in section 9.5).

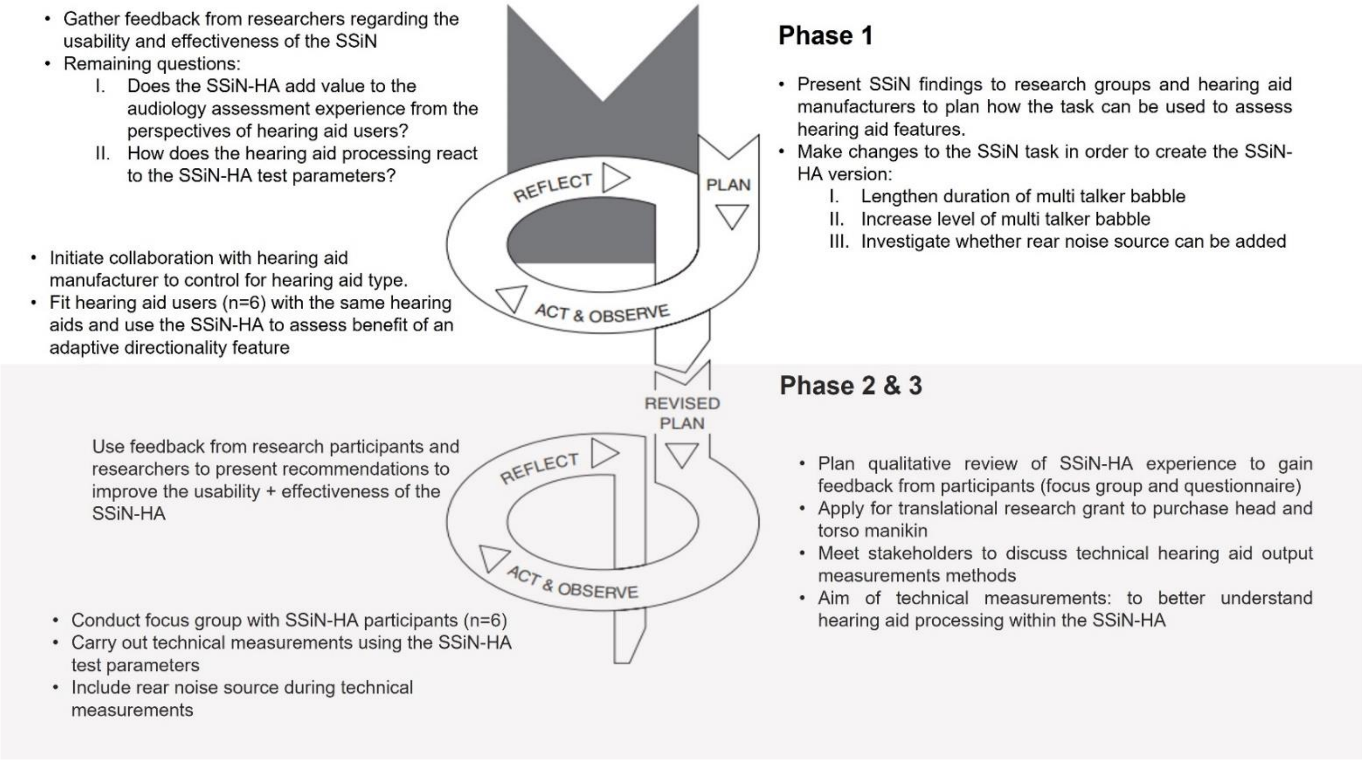


Figure 6.1 Action research spiral. This visualisation shows the action research approach applied in the present chapter, across three phases. Adapted from previous action research literature (Kemmis & McTaggart, 2000).

6.2.3 Development of the SSiN-HA to assess hearing aid advanced features

After presenting the findings of Chapter 5 to researchers and hearing aid manufacturers (Parmar et al., 2018b), the following amendments were made to the SSiN in order to enhance ecological validity and investigate whether the task can be used to assess benefit of Open Sound Navigator on word identification and relative localisation performance:

1) **Multi-talker babble duration** was altered to present continuously through a block instead of ramping on and off on each trial—this would help the hearing aid reach a stable rate of processing without disruption between trials
2) **Multi-talker babble level** was increased to an overall level of 70 dBSPL to simulate realistic noisy environments (SSiN presented in chapter 4 and 5 used multi-talker babble level of 52 dBSPL)

The remaining suggestion was to include a rear noise source in addition to the babble presentations from the frontal hemisphere as this would further enhance how the task relates to realistic noisy listening situations, e.g., in a busy restaurant. However, due to equipment constraints this addition was not possible within the behavioural task without having to reorient the listener relative to the speaker ring. Despite this, a rear noise source was included in the hearing aid technical measurements (Phase 3 of this chapter) as the head and torso manikin (KEMAR) could be turned in different directions to simulate a rear noise source. The SSiN-HA was tested on three normal hearing listeners to ensure usability and comfort.

6.2.4 Participants

Experienced bilateral hearing aid users (*n* = 6) aged 50–85, with mild to moderate symmetrical sensorineural hearing loss in both ears took part in this study. Audiograms of each participant are presented in **Figure 6.2**. Participants were included if they were native English-speaking adults over the 40 years of age with adult-onset hearing loss. They had symmetrical moderate (to severe) sensorineural hearing loss bilaterally and over two years of hearing aid use. They were included if they had no known cognitive or neurological disorders. Demographic information including sex, age, occupation and educational level of all participants is presented in **Table 6.1**. All six participants took part in the SSiN-HA trials in phase 1 and the qualitative study in phase 2. Self-rated unaided and aided hearing ability is also reported in Table 6.1. This subjective rating was used for participants to give their overall hearing ability in one measure in an attempt to be more time efficient in the testing session compared to completing a formal questionnaire e.g. Glasgow Hearing Aid Benefit Profile (Gatehouse, 1999).

Pseudo anonymised identifier	Sex	Age	Years of hearing aid use	Educational level	Self-rated unaided hearing ability	Self-rated aided hearing ability	SSiN-HA SNR (dB)
701	F	68	8	Post graduate qualification	64	29	7.5
702	M	74	15	Trades qualification	30	79	5.6
703	M	59	9	Secondary school	30	70	11.13
704	F	49	19	University degree	50	90	12.5
705	M	81	17	University degree	11	89	9.3
707	F	70	5	Post graduate qualification	77	88	10.5

Table 6.1 Participant demographics. Note: Hearing ability is rated on a scale from 1 = great difficulty to 100 = no difficulty.

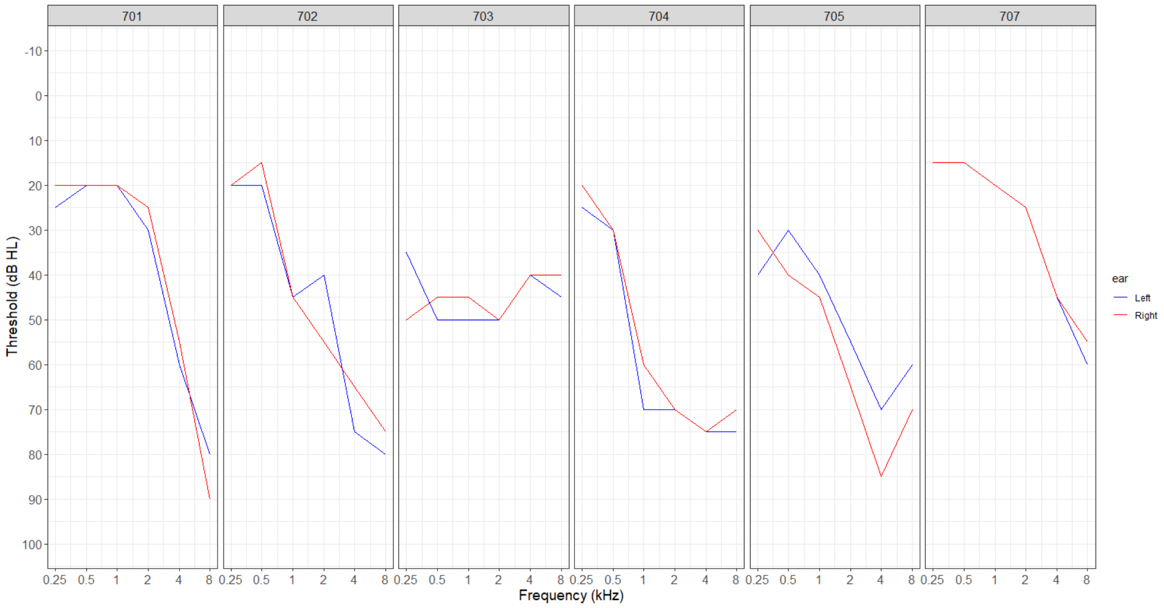


Figure 6.2 Audiograms for each hearing aid user.

6.2.5 Phase 1: SSiN to compare adaptive directionality and omnidirectional microphone settings

6.2.5.1 Study design

A prospective, doubled blind trial to explore the sensitivity of the SSiN-HA in assessing hearing aid adaptive directionality.

6.2.5.2 Hearing assessment and hearing aid fitting

Audiological assessment included otoscopic examination and pure tone audiometry. Participants had Montreal Cognitive Assessment (MoCA) scores higher than 26 as this is the cited cut off for mild cognitive impairment (Nasreddine et al., 2005).

Participants were fitted bilaterally with Oticon Opn S receiver-in-the-canal hearing aids coupled with occluded domes. Hearing aid fitting and verification was carried out using the Otometrics Freefit device. During verification, the International Speech Test Signal (ISTS) (BS EN 60118-15) was used to verify gain targets for soft, average and loud inputs at 50, 65 and 80 dBSPL, respectively. Prescriptive targets were based on participants' real ear measures and audiometric thresholds using the National Acoustic Laboratory – Non-Linear 2 (NAL NL 2) method (see Appendices). Real ear probe measurements were used to ensure gain levels were within set tolerances stated in guidance from the British Society of Audiology (2018).

Participants were given an acclimatisation period of 4–6 weeks to wear the hearing aids before being invited back to complete the study test battery. The hearing aids were fitted with the default OMNI microphone mode for everyday listening. Participants were able to contact the author (a registered audiologist) if they needed follow up appointments post hearing aid fitting. Once invited back, an additional programme was created on the hearing aids. The initial programmed settings were duplicated on the hearing aid software to ensure the second programme had identical gain characteristics as the first. One programme was set to OMNI, and one was set to Open Sound Navigator (OSN). Programmes could be selected by using a paired smartphone app or the programme switch on the back of the hearing aid. In the OMNI setting, noise reduction was deactivated and "pinna omni" was selected in the hearing aid software.

In the OSN setting, noise reduction and automatic directionality were activated. OSN was set to the strongest setting within the Oticon Genie Software by setting “Noise Reduction Simple” to -3 dB, “Open Sound Transition” to high and “Noise Reduction Complex” to -9 dB. Both programmes were otherwise identical and feedback suppression and volume controls were deactivated. The configuration of these two programmes matched that of Browning et al. (2019), and it was hypothesised that they would give the largest noticeable difference in output signal to noise ratio (dBSNR) within the SSiN-HA testing paradigm. To ensure double blind testing, a technician otherwise uninvolved in this work assigned each test condition (either OSN or OMNI) randomly to a number and this information was only released to the author upon completion of data collection.

6.2.5.3 SSiN-HA testing

The set-up of the anechoic chamber, threshold task and SSiN practice trials in the present study was the same as those described in Chapter 4 and 5. The only differences to the main SSiN task were as follows:

- *Duration of babble:* Continuous multi-talker babble within a testing block, rather than babble ramping on and off between trials. Multi-talker babble was presented from the same locations as presented in Chapter 4 and 5 (either +30° and +60°or -30° and -60°) for a duration of 24 trials.
- *Level of babble*: Overall level of multi-talker babble was increased to 70 dB SPL.

Participants carried out the SSiN-HA twice, once with each hearing aid setting: a) OSN activated and b) omnidirectional (pinna omni without noise reduction), over two separate testing days in order to avoid fatigue. Both tests were completed using the same SNR (established within the original threshold task).

6.2.5.4 Statistical modelling

As in the statistical analysis used in the previous chapter, each outcome variable of the SSiN-HA (word identification and relative localisation) was tested in two parts, to include performance and reaction time. Both elements of the test were analysed separately, with statistical models constructed for both performance and reaction time measured. Performance was captured as correct or incorrect and evaluated using logistic regression modelling. Reaction time is the time taken for participants to select a word (word identification reaction time) or location shift (relative localisation reaction time), on the touchscreen provided, calculated from trial onset. Reaction time was evaluated as the natural logarithm of response time in seconds, using linear regression. For word identification selections, response times above 14 s or below 100 ms were systematically removed as outliers. For relative localisation selections, reaction times below the minimum reaction time to word 2 (1.8 s), and those above 14 s, were systematically removed. Both were tested using generalized linear mixed modelling package *lme4* v1.1-26 in R version 3.6.2.

Word identification performance was tested in association with fixed effects of hearing aid condition (OSN vs. OMNI), speaker location, the azimuthal distance between word and noise (degrees), word group, word number (word 1 or word 2 in a trial), and trial number. Additionally, the following interactions were included: hearing aid condition and trial number, hearing aid condition and word number. Random baseline differences between subjects were modelled for each of accuracy and response time. The word identification reaction time model included hearing aid condition, speaker location, word-noise separation (degrees), word group, word number and trial total. An interaction between hearing aid condition and trial total and hearing aid condition and word number were also included.

Relative localisation measures (accuracy and response time) were tested in association with fixed effects of hearing aid condition, mean speaker location (degrees), word group and trial number. Interactions were included between hearing aid condition and trial total. Random baseline differences between subjects were modelled for each of accuracy and response time. Multicollinearity was deemed negligible given low variance inflation factor (VIF) for all predictors. Normality of residuals in reaction time models was ensured using QQ plots. Model performance was evaluated by calculating the area under the curve (AUC) of ROC curves for accuracy models, and goodness-of-fit (R^2) for response time models. Between-condition effect sizes were calculated using Cohen’s d from the model estimate of group differences.

6.2.6 Phase 2: Qualitative review of SSiN-HA experience

Phase 2 of this chapter is a qualitative study to collect participants' perspectives and experiences of carrying out the SSiN-HA. All six participants from phase 1 took part in phase 2.

6.2.6.1 Data collection methods

A questionnaire was created with a mixture of open and closed questions and administered directly after the participants completed phase 1 testing. The questionnaire was developed to explore SSiN usability, including using the test environment and the task itself. The questionnaire was trialled with members of the research team and 2 hearing aid users. The following questions were used:

- What did you think about the words that were used in the spatial speech test? Please include comments on the content, volume, variety, number of words and duration of each
- What did you think about the background noise used in the spatial speech test? Please include comments on the volume, type and whether it reflects typical noise you hear in social situations
- What did you think of the touchscreen used in the task? Please include comments on the pictures, layout and usability of the touchscreen
- Do you feel the instructions of the task were clear and easy to understand?
- What did you think about the testing room?
- How do you think the spatial speech test could be incorporated into audiology testing?
- How challenging did you find the task to be? Please answer from 1 to 10 with 10 being the most challenging and leave any notes below if you wish to give more detail
- Do you feel the current tests used in audiology clinics meet your needs and allow you to make decisions about your hearing aid provision?

To allow participants to discuss the SSiN-HA testing paradigm freely, without the restriction of questionnaire questions, an online focus group was carried out. Focus groups have been extensively used in health research as the process tends to help participants identify and clarify their views (Kitzinger, 1995). Additionally, the process of sharing experiences and voicing opinions occurs in a unique way within a group due to the group dynamics. This may lead to participants contributing things they may not have if they were completing a one-to-one interview or questionnaires (Carey, 1994). The focus group was guided by predetermined topic guide with open ended questions, e.g., “Describe your experience completing the SSiN-HA?” and follow up probing questions including those that asked about the test set up and design, comparison of this task to those carried out in usual audiology care and whether participants had any suggestions for the further development of the SSiN-HA.

6.2.6.2 Data analysis

For both the open questions of the questionnaire and the online focus group, iterative-inductive thematic analysis was used to identify, analyse and report patterns (themes) within data (Braun & Clarke, 2006). The present thematic analysis uses a descriptive approach with a focus on lived experience and was conducted in three stages:

1) data familiarisation: line-by-line data coding

2) data organisation: transforming “free codes” into related areas to have general themes

3) defining themes and report writing

The coded data were organised into general themes regarding the experience of carrying out the SSiN-HA that arose from the focus group. NVivo qualitative research software (Version 12) was used for data handling, organisation, and coding. Direct quotes are included as representations of key themes and are accompanied by participant demographics to provide experiential context. The author was the facilitator of the focus group and carried out coding of the transcripts.

6.2.7 Phase 3: Hearing aid technical measurements

6.2.7.1 Test environment

For SNR function measures, signal generation, routing, and presentation were achieved using the same equipment as that used in phase 1. A GRAS 45BB KEMAR Head & Torso Simulator fitted with pinna simulators, ear canal extensions, and IEC 60318-4 Ear Simulators, closely mimics the acoustic properties of the human ear. The KEMAR (see **Figure 6.4**) meets the international standards as specified by IEC: 60318-7 (International Electrotechnical Commission, 2017) and ANSI: S3.36, S3.2 (American National Standards Institute, 2012).

Pre-amplification for KEMAR's CCP microphones was provided by a Listen SoundConnect 2. This was interfaced to a PC running MATLAB via an RME BabyFace Pro FS audio interface, which in turn was digitally interfaced to a MOTU 24Ao audio interface. This arrangement enables the synchronous playback and recording of multichannel stimulus and binaural response essential to correct operation of the SNR measurement technique employed. KEMAR was positioned on a small stool, facing the midline, in the centre of an anechoic chamber with sound-attenuating foam triangles on all surfaces.

6.2.7.2 Speakers and calibration information

Stimuli were presented by Canton Plus XS.2 speakers (Computers Unlimited, London) via a MOTU 24Ao audio interface (MOTU, MA, USA) and 2 Knoll MA1250 amplifiers (Knoll Systems, WA, USA). The individual speakers were matched for level and frequency response using a Presonus PRM1 precision reference microphone placed at the centre of the chamber where the KEMAR head would be during the presentation of a stimulus. The microphone signal was passed to an RME Audio Babyface Pro FS audio interface, acting as a microphone pre-amplifier and input expander for the MOTU 24Ao audio interface. Through application of FIR compensation filters, each speaker was matched for flat frequency response from 400 to 800 Hz, with a smooth 1.2 dB/octave drop off from 400 to 10 Hz, and a smooth drop off of 1.8 dB/octave from 800 Hz to 25 kHz. Audio processing and MOTU device interfacing was performed using MATLAB (MathWorks) in conjunction with the MATLAB Audio Toolbox extension.

6.2.7.3 Hearing aid set up

Oticon OPN S Receiver in the ear hearing aids were programmed to the mean audiometric thresholds of the hearing aid user group tested in phase 1 (**Figure 6.2**). The OMNI and OSN hearing aid programming was also identical to settings used in phase 1 of this study. Real ear measurements were completed on the KEMAR using an acrylic custom occluded ear mould so ensure the acoustic characteristics of the manikin ear were accounted for. The hearing aids were fitted according to NAL-NL2 using real ear measurements with the Otometrics Freefit, using the ISTS Signal (Holube et al., 2010).

The hearing aids were tested in two speaker configurations: experiment 1 involved co-located speech and babble from 0° and spatially separated with speech at 0° and babble from 180° (**Figure 6.5**). This set up was used to reflect a simple testing design that may be found in clinical settings. Experiment 2 involved the same speech and babble locations as used in the SSiN-HA behavioural experiment described in phase 1 of this chapter (**Figure 6.6**). Speech token and multi-talker babble signal used in experiment 1 and 2 were identical to those used in the SSiN-HA behavioural task.

6.2.7.4 Output SNR analysis

A modified version of the Hagerman and Olofsson (2004) phase inversion method was used to calculate hearing aid output SNR (dB) from experiment 1 and 2 (see **Figure 6.3**). Two speech and noise mixtures are presented to the hearing aid, one with the noise phase inverted. One recording for each of the two input signals was made and the speech and noise signal was extracted after adding and subtracting these recordings. To ensure time alignment was precise for these calculations to be carried out, the playback and recording audio interfaces were identical to ensure synchronisation, the presentations were part of a continuous recording, and the exact duration of each presentation was known and constant. The extracted speech and noise signal can be used to calculate the output SNR (Hagerman & Olofsson, 2004). A summary of the method used in the present study is displayed in **Figure 6.3**. The noise floor (epsilon = ϵ) of each measurement is calculated by using an additional presentation in which both the signal and noise are phase inverted. The validity criterion chosen for each measurement was that the noise floor should be at least 10 dB below the quieter of the two presented, speech or noise, signals (International Organisation for Standardization, 2004). Speech intelligibility index (SII) weighting was applied to the output SNR measurements to reflect how different frequency regions contribute to speech understanding (Santurette et al., 2021; Wu & Stangl, 2013). SII-weighted output SNRs were calculated from output signals of KEMAR without hearing aids (unaided) and for each hearing aid condition. The separated signal and noise were each filtered into 1/3 octave bands and the SNR calculated for each band, The full bandwidth SNR was then calculated as the sum of the band SNRs after weighting each as per ANSI/ASA S3.5 (1997) classifications. Data from experiment 1 were presented as the average hearing aid output SNR collapsed across the right and left KEMAR ears.

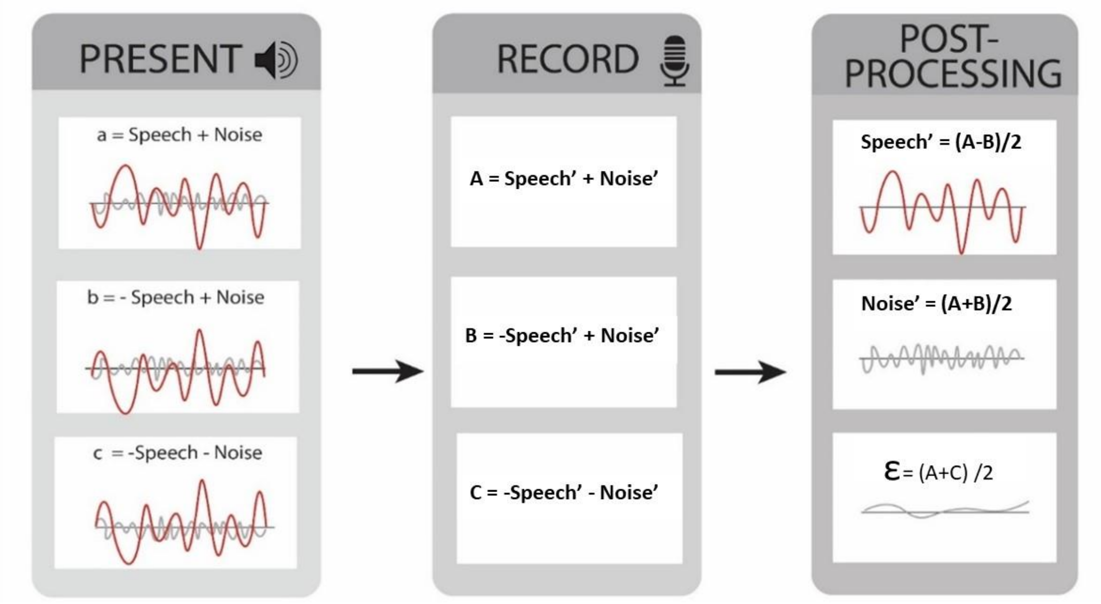


Figure 6.3 Phase inversion technique to calculate hearing aid output SNR. Adapted from Hagarman and Oloffson (2004). The noise floor (epsilon = ϵ) of each measurement is calculated by using an additional presentation in which both the signal and noise are phase inverted.

Figure 6.4 The Anthropometric Pinnae of the KEMAR. An occluded ear mould was coupled to the hearing aid.

6.2.7.5 Test protocol

Here, experiment 1 involved far fewer speaker locations than those used in the SSiN-HA, and this resulted in a shorter testing period. Therefore experiment 1 was carried out as a scoping exercise to investigate the effects of a variety of different hearing aid conditions including input SNRs, directionality features (full directional, OMNI and OSN) and amplitude compression. This data was then used to inform the choice of hearing aid conditions and parameters used in experiment 2. Furthermore, experiment 1 consisted of a simple speaker set-up that is more routinely found in the clinical setting.

6.2.7.5.1 Experiment 1: Speech front, noise back

Speech tokens from all four word groups used in phase 1 of this chapter were presented from 0° azimuth whilst multi-talker babble was presented from 180° or 0° (see **Figure 6.5**). The hearing aids were tested with and without amplitude compression activated. To deactivate amplitude compression, the manufacturer's propriety hearing aid software was used to set the compression ratios to 1:1 at each frequency band. Hearing aid recordings were obtained at an input SNR of +5 dB; with speech at 65 dBSPL and babble at 60 dBSPL (following methodology from Browning et al. (2019), -10 dB SNR; with speech at 60 dBSPL and babble at 70 dBSPL and +10 dB SNR; with speech at 60 dBSPL and babble at 50 dBSPL. These SNRs were chosen to represent a range of listening difficulty levels and replicate those used previously in the literature and encompass the range of SNRs used by listeners in Phase 1 of this chapter. During the test session, multi-talker babble was played continuously, and the length of each speech token was 0.9 s–1.2 s with an average gap of 2 s between words. Recordings of the speech and noise signals were made in the unaided condition and three different aided conditions.

The three hearing aid conditions were 1) OSN, 2) OMNI, 3) and full directional (FD), each tested with and without amplitude compression activated.

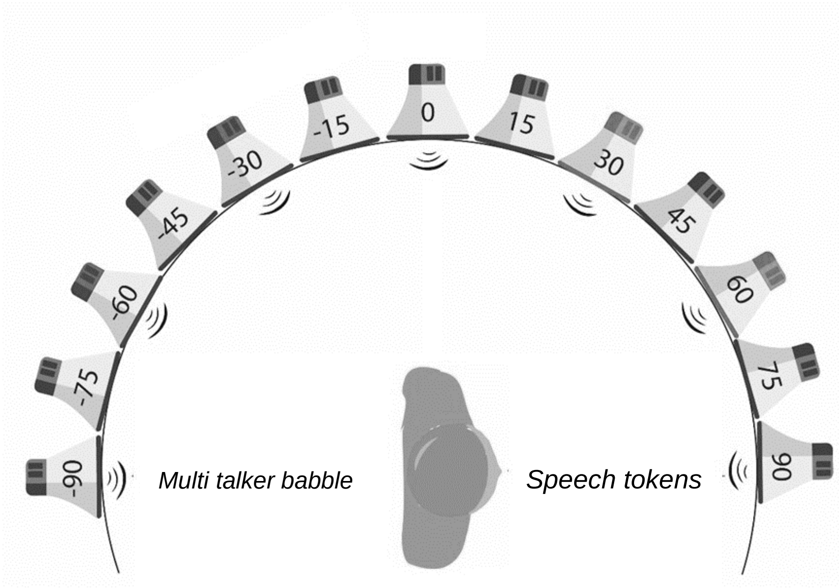


Figure 6.5 Speaker array and KEMAR set up for experiment 1: hearing aid technical measurements in front-back paradigm.

6.2.7.5.2 Experiment 2: SSiN paradigm

SSiN-HA speech tokens, in the presence of multi-talker babble, were presented sequentially from pairs of speakers to best replicate the testing paradigm of the spatial speech test (see **Figure 6.6**). Each word pair was presented from every pair of speakers used in the SiN-HA, separated by 30°. All word groups were presented from the speaker locations denoted in **Figure 6.6.** Two input SNRs: -10 dB and +5 dB were used. These were chosen to reflect a challenging listening situation (-10 dB) and one that was positive (+5 dB) to reflect the SNRs used in the behavioural task in phase 1 of this chapter (mean: 9.4 dB, range: 5.6–12.5 dB). In total, each word pair (12 word pairs x 4 word groups), was presented from every possible combination of speaker pair (7 speaker locations), for both noise locations (right and left) and for two input SNRs (+5 dB SNR and -10 dB SNR). This was carried out over 1152 trials (a duration of 6 hours of recording per condition). For each trial uncorrelated multi-talker babble was presented from a pair of speakers (either -60° and -30° or +30° and +60°)**.** The multi-talker babble was presented at an overall level of 50 dBSPL and 70 dBSPL (combined level from both speakers) to represent input SNR of +5 dB and -10 dB respectively. Recordings of the speech and noise signals were made in the unaided condition as well as two hearing aid conditions, using the OPN S hearing aids coupled to occluded meatal tip ear moulds. The hearing aid conditions were 1) OSN and 2) OMNI (as described in the **Section 6.2.5.2**). To include of all combinations and conditions described above, the final dataset consisted of 27668 hearing aid output recordings.

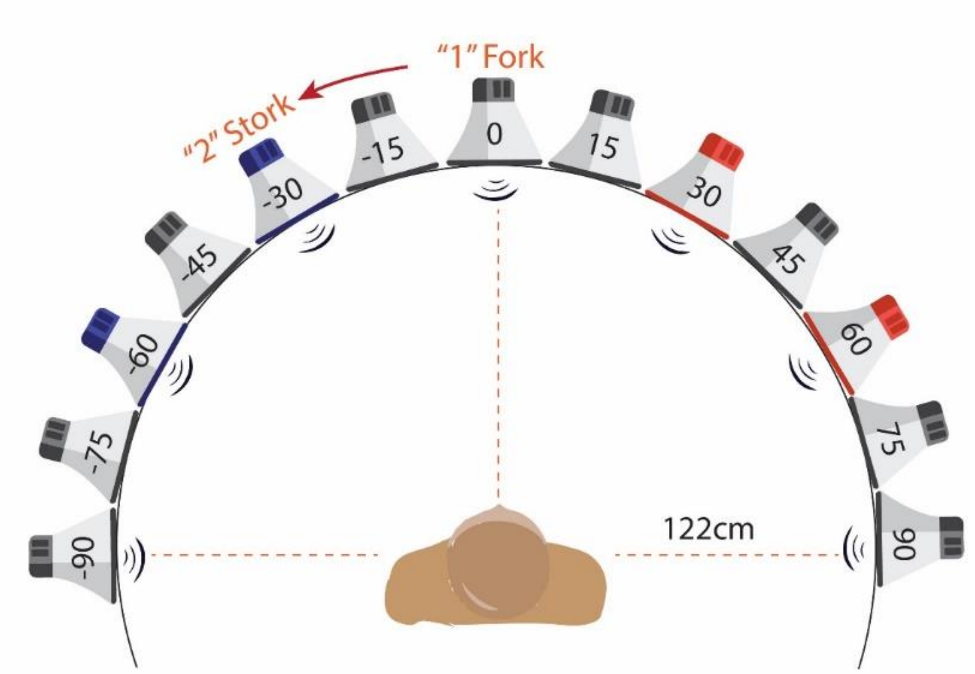


Figure 6.6 Speaker array and KEMAR set up for experiment 2: hearing aid technical measurements in the SSiN paradigm.

After gathering feedback from previous SSiN testing phases with hearing aid users and researchers in phase 1 if this study, a key suggestion was the inclusion of a rear noise source. Therefore, in addition to the frontal noise sources used in the behavioural SSiN-HA task from phase 1, the SSiN-HA technical measurements were carried out with the presentation of multi-talker babble from two locations behind the listener, either 120° and 150° or -120° and -150° (see **Figure 6.7**).

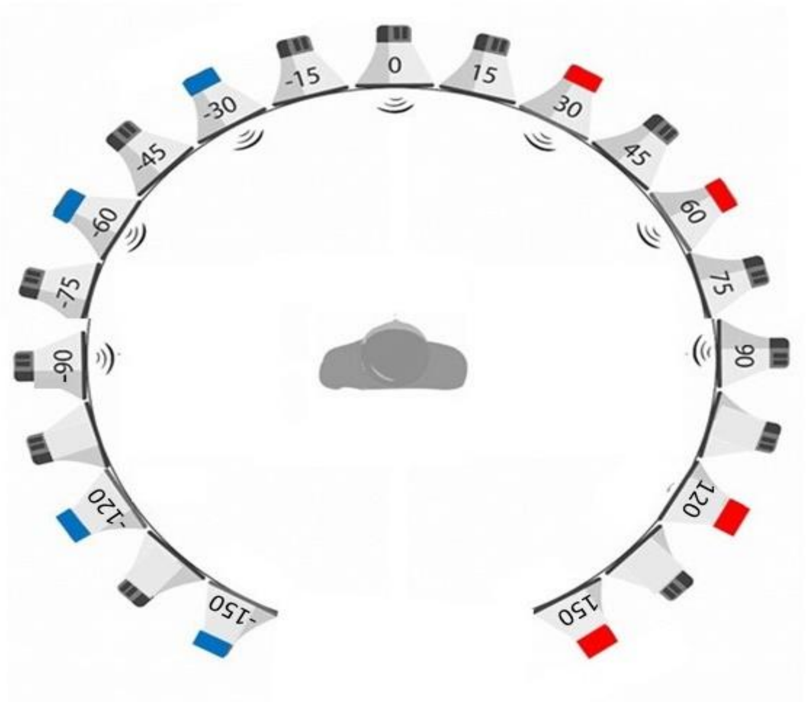


Figure 6.7 Speaker array and KEMAR set up including rear multi-talker babble sources to extend the testing of the SSiN. The red and blue speakers indicate noise location; however, due to limited number of loudspeakers in the anechoic chamber, KEMAR was reoriented to achieve this test design.

6.2.7.5.3 Data analysis

Statistical analysis was completed using *R* version 3.6.2, using linear mixed modelling. SII weighted output SNR was the dependent variable in both presented models. In experiment 1, one model was performed on each sub-experiment, a) noise and speech collocated, b) speech and noise presented spatially separated. The primary predictor variable of interest was hearing aid type, including OMNI, OSN, and FD, each with linear and compression processing, as well as unaided. Additional predictors included input SNR (-10 dB, +5 dB, or +10 dB), word group, and an interaction between hearing aid type and input SNR. All predictors were categorical.

In experiment 2, linear mixed modeling was used to predict SII weighted output SNR with the SSiN-HA test paradigm. Predictive variables were hearing aid type (unaided, OMNI or OSN), word number (first or second), word group, azimuthal distance between word and mean babble location, input SNR and speaker location. Interactions between hearing aid type and word-noise distance, hearing aid type and input SNR, hearing aid and speaker location were included in the analysis. Post hoc testing was completed using the *R* package *emmeans*, using Tukey’s HSD for pairwise comparisons.

6.3 Results

Phase 1 of this study explored the use of the SSiN-HA to compare adaptive directionality (OSN) and OMNI hearing aid features for six experienced hearing aid users. The same participants then completed a qualitative review of the SSiN-HA (questionnaire and focus group) in phase 2. Two experiments were carried out in phase 3 of this chapter to present the hearing aid output SNR in response to a simple two speaker set up and the SSiN-HA paradigm.

6.3.1 Phase 1: SSiN to compare adaptive directionality and omnidirectional microphone settings

The sample consisted of six experienced hearing aid users, each wearing bilateral Oticon OPN S receiver in the canal hearing aids with occluded soft domes. After an acclimatisation period of 4–6 weeks, each participant was invited to two separate testing sessions. Each participant completed the SSiN-HA with their hearing aids set to the OSN condition, and in the OMNI condition, as defined in the methods. In this double-blind study, the order of testing was randomised between participants and neither the participant, nor the main experimenter knew the condition being tested during the session.

6.3.1.1 Word identification performance

Word identification performance (% correct) across azimuthal location (degrees) for OSN and OMNI conditions are presented in **Figure 6.8A**. Mean differences between OMNI and OSN word identification performance at either central or peripheral locations is presented in **Figure 6.9A** and **6.9B**. To investigate predictors of word identification performance, a generalised linear mixed effects model was conducted (AUC = 0.742, sensitivity = 0.709, specificity = 0.658) and significant predictors are outlined in **Table 6.2** Overall, there was no significant difference in word identification performance between OSN and OMNI conditions (**Table 6.2**). Post hoc testing of specific speaker locations is shown in **Table 6.3**.

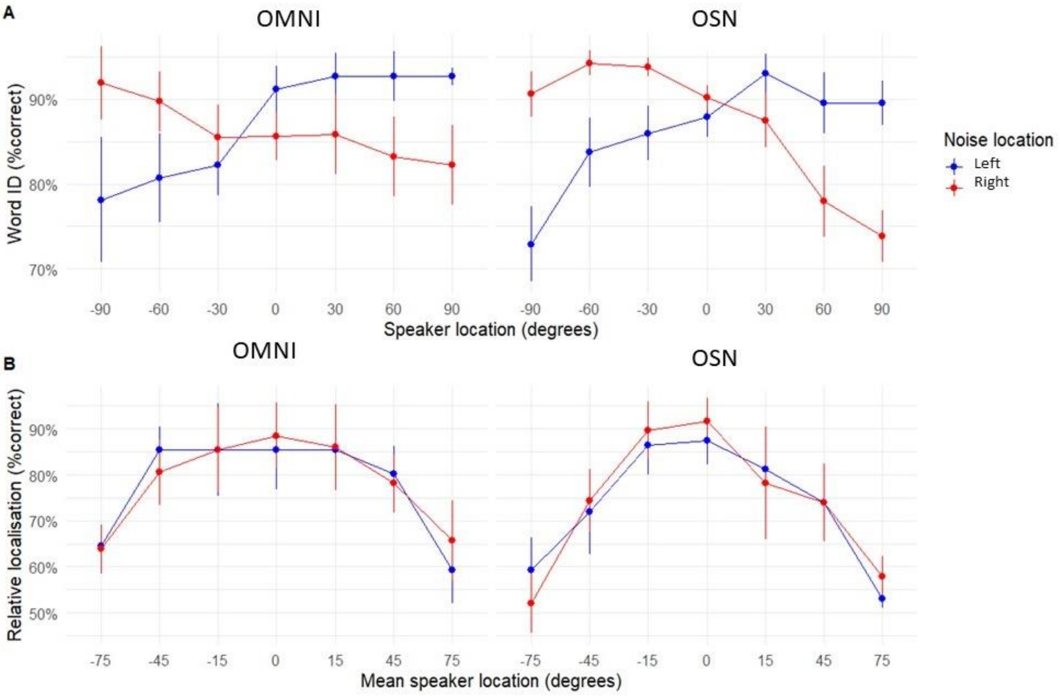


Figure 6.8 Word identification (% correct) and relative localisation performance (% correct) for OSN and OMNI conditions. A) Word identification performance (%) across speaker location (degrees) in the OSN and OMNI condition, B) relative localisation performance (%) across mean speaker location (degrees) for both conditions. Error bars indicate standard error. Relative localisation chance performance = 50%.

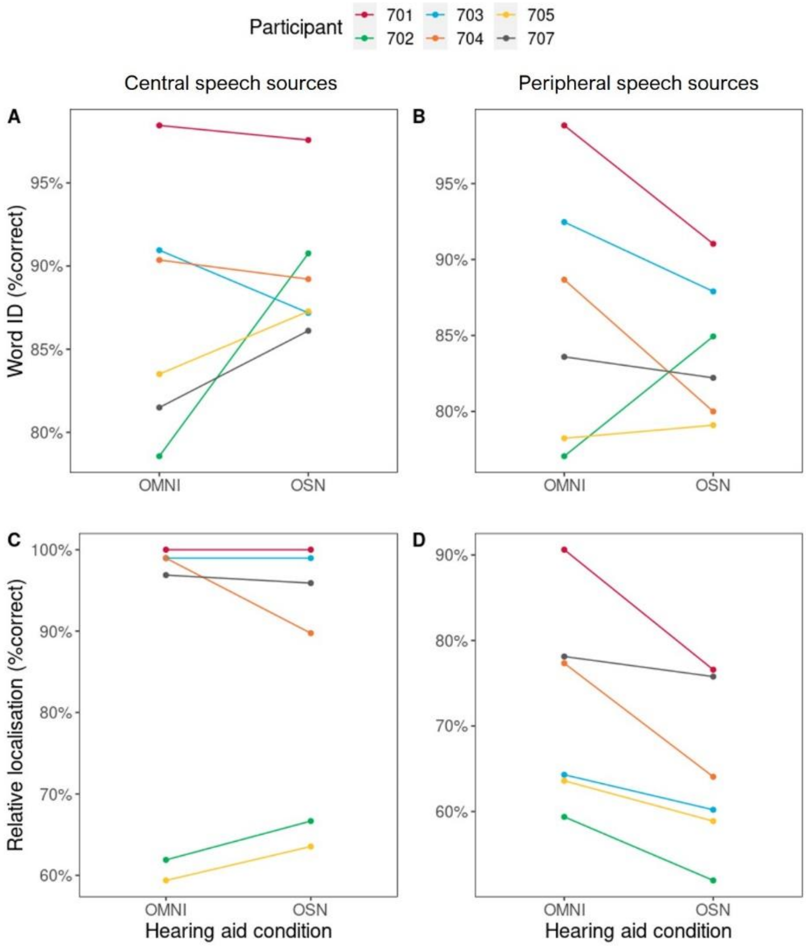


Figure 6.9 Word identification and relative localisation performance at central and peripheral locations for OMNI and OSN conditions, for each participant. A) Mean word identification % correct per participant for the OMNI and OSN conditions collapsed across central speaker locations (0°, 30° and -30°), B) mean word identification % correct per participant for the OMNI and OSN conditions collapsed across peripheral speaker locations (-90°, -60°, 90°, 60°), C) mean relative localisation % correct per participant for the OMNI and OSN conditions collapsed across central mean speaker locations (0°, 15°, -15°), D) mean relative localisation % correct per participant for the OMNI and OSN conditions collapsed across peripheral mean speaker locations (-75°, -45°, 45°, 75°).

	X2	DF	p	
Group (OSN vs OMNI)	2.589	1	0.108	
Speaker location	50.651	6	<0.001	*
Speech-Noise separation	81.513	1	<0.001	*
Word Group	205.712	3	<0.001	*
Word Number (first/second)	4.370	1	0.037	*
Trial Number	0.021	1	0.883	
Group x Trial Number	7.250	1	0.007	*
Group × Word Number	0.009	1	0.923	

Table 6.2 Predictors of word identification performance. Asterisks denote significance (α = 0.05).

Term	Group	Reference	Estimate	St Error	Z	p	OR	95% CI
Group	OSN	OMNI	-0.309	0.192	-1.60	0.108	0.734	0.50 – 1.07
Speaker location	90° Left	Midline	-0.931	0.192	-4.84	<0.001*	0.394	0.27 – 0.57
	60° Left	Midline	-0.253	0.164	-1.54	0.711	0.776	0.56 – 1.07
	30° Left	Midline	-0.140	0.1479	-0.93	0.965	0.869	0.65 –1.17
	30° Right	Midline	0.146	0.155	0.94	0.964	1.158	0.85 – 1.57
	60° Right	Midline	-0.327	0.162	-2.01	0.400	0.721	0.52 – 0.99
	90° Right	Midline	-0.814	0.197	-4.14	<0.001*	0.443	0.30 – 0.65
Word group	Vs	Vc	-0.424	0.153	-2.76	0.028*	0.655	0.48 – 0.88
	Ci	Vc	-0.855	0.145	-5.90	<0.001*	0.425	0.32 – 0.57
	Cf	Vc	-1.666	0.136	-12.27	<0.001*	0.189	0.15 – 0.25
Word number	2	1	-0.252	0.120	-2.09	0.037*	0.778	0.61 – 0.98

Table 6.3 Predictors of word identification. Estimate strength and significance of effects for each significant term are presented.

As in Chapter 4 and 5, word identification performance was significantly better as the azimuthal distance between the word and background babble increased. Performance was significantly poorer for the second word of a trial, relative to the first. Lastly, although there was no main effect of trial number, there was a significant interaction between trial number and hearing aid condition, with OSN showing a trend towards improved performance across the trials which the OMNI condition did not show (**Figure 6.10**).

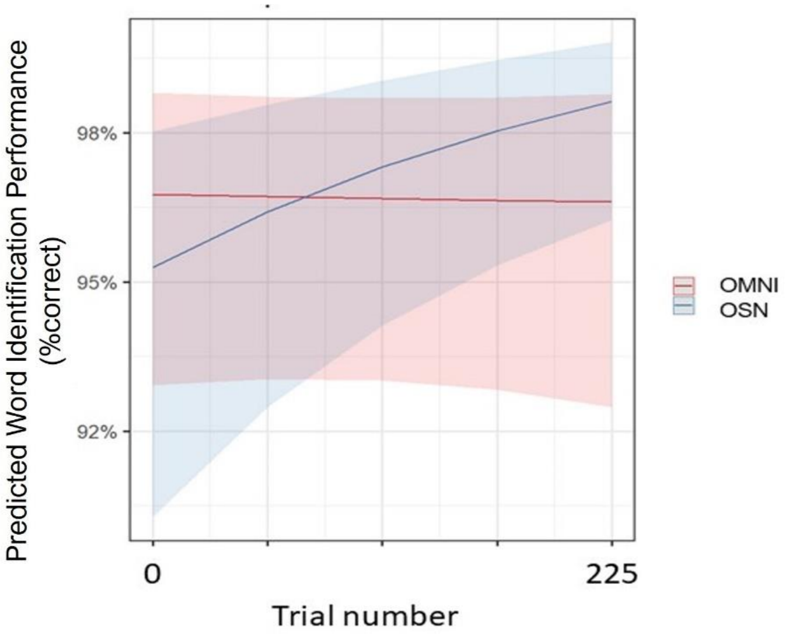


Figure 6.10 Predicted word identification performance as a function of trial number in the OMNI and OSN conditions. Shaded areas indicate 95% confidence intervals.

6.3.1.2 *Word identification reaction time*

Word identification reaction time, in the OMNI and OSN conditions, is presented across azimuthal location (degrees) in **Figure 6.11** Word identification reaction time was modelled to investigate predictors, including the effect of hearing aid condition (R^2

= 0.603). Word identification reaction times were significantly faster in the OSN condition, compared to the OMNI condition, with an effect size of d = 0.238.

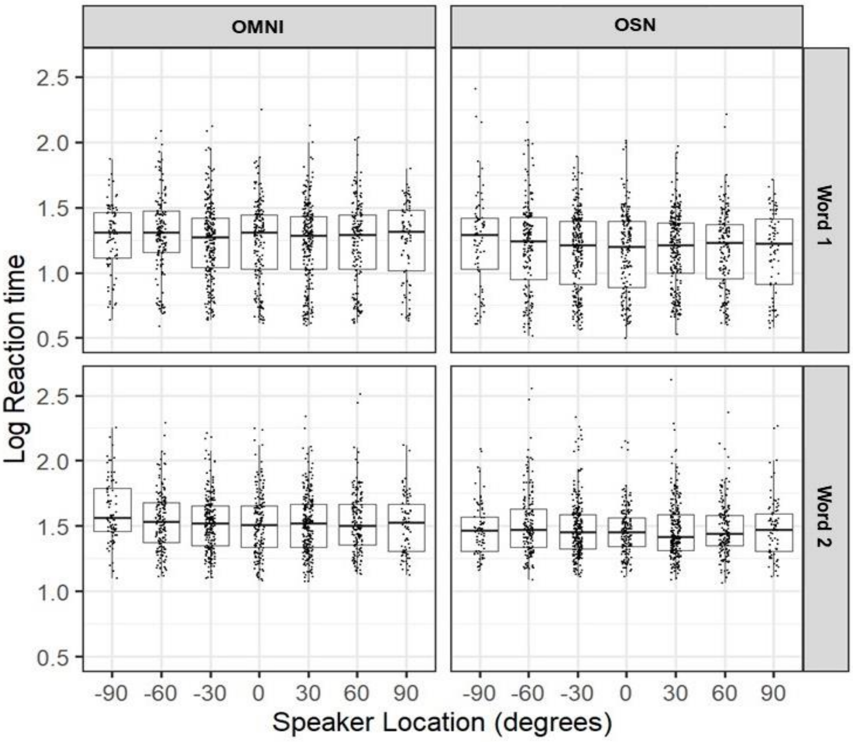


Figure 6.11 Reaction time for word 1 and word 2 correct responses in the OMNI and OSN conditions. Results plotted across azimuthal location.

Significant predictors are outlined in **Table 6.4**, with post hoc testing of specific speaker locations shown in **Table 6.5**. Performance and response time at each speaker location for each condition are shown in **Figure 6.11**. The mean reaction times in the OSN condition were 43 ms and 53 ms faster for the first and second word presentations, respectively, compared to the OMNI condition. Responses were also significantly faster at central speakers, relative to each of 90° and 60° left of the midline. Responses were significantly faster as the distance between words and noise increased. There was a significant effect of trial number and significant interaction between hearing aid condition and trial total, with a trend for reaction time to decrease throughout the task but more so in the OSN condition compared to the OMNI condition.

	χ2	DF	p	
Group (OSN vs OMNI)	6.148	1	0.013	*
Speaker location	80.812	6	<0.001	*
Word-noise separation	43.632	1	<0.001	*
Word Group	91.526	3	<0.001	*
Trial Number	5.548	1	0.018	*
Trial Number × Group	7.475	1	0.006	*

Table 6.4 Predictors of word identification reaction time. Asterisks denote significance (α = 0.05).

Term	Group	Reference	Estimate	St Error	Z	p
Group	OSN	OMNI	-0.028	0.011	-2.480	0.013*
Word number	2	1	0.280	0.006	50.357	<0.001*
Location	90° Left	Midline	0.090	0.013	6.852	<0.001*
	60° Left	Midline	0.053	0.001	5.053	<0.001*
	30° Left	Midline	0.007	0.009	0.778	0.989
	30° Right	Midline	0.001	0.009	0.006	1.000
	60° Right	Midline	0.028	0.010	2.641	0.110
	90° Right	Midline	0.036	0.013	2.719	0.090
Word group	Vs	Vc	0.017	0.008	2.215	0.119
	Ci	Vc	0.013	0.008	1.643	0.354
	Cf	Vc	0.070	0.008	8.857	<0.001*

Table 6.5 Predictors of word identification reaction time. Estimate strength and significance of effects, for each significant term are presented.

6.3.1.3 Relative localisation performance

In addition to investigating predictors of word identification performance and reaction time, we modelled relative localisation performance (AUC = 0.771, sensitivity = 0.577, specificity = 0.874). Here, relative localisation performance was significantly poorer in the OSN condition compared to the OMNI condition (**Figure 6.12**).There was significant main effect of speaker location, where performance was poorer at the peripheral locations compared to the midline, this pattern was present for both conditions. Lastly, accuracy significantly improved with trial number, in both conditions. Significant predictors are outlined in **Table 6.6**, with post hoc testing of specific speaker locations shown in **Table 6.7**.

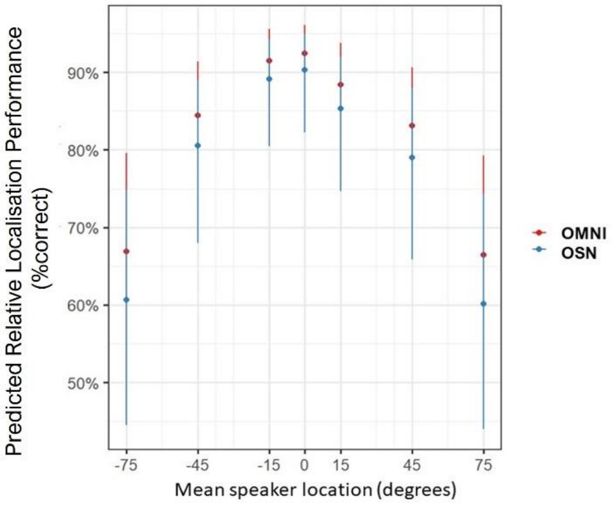


Figure 6.12 Predicted relative localisation performance in the OMNI and OSN hearing aid conditions. Plotted against mean speaker location (degrees). Error bars indicate 95% confidence intervals.

	χ2	DF	p	
Group (OSN vs OMNI)	4.234	1	0.040	*
Mean speaker location	184.396	6	<0.001	*
Word Group	2.326	3	0.507	
Trial Number	4.091	1	0.043	*
Group x Trial Number	0.535	1	0.465	

Table 6.6 Predictors of relative localisation performance. Asterisks denote significance ($\alpha = 0.05$).

Term	Group	Reference	Estimate	St Error	Z	p	OR	95% CI
Group	OSN	OMNI	-0.398	0.193	-2.058	0.040*	0.672	0.46 – 0.98
Mean speaker location	75° Left	Midline	-1.797	0.199	-9.037	<0.001*	0.166	0.11 – 0.25
	45° Left	Midline	-0.808	0.209	-3.864	0.002*	0.446	0.29 – 0.67
	15° Left	Midline	-0.125	0.226	-0.551	0.998	0.883	0.57 – 1.38
	15° Right	Midline	-0.471	0.216	-2.182	0.302	0.625	0.41 – 0.95
	45° Right	Midline	-0.906	0.207	-4.372	<0.001*	0.404	0.27 – 0.61
	75° Right	Midline	-1.817	0.199	-9.133	<0.001*	0.162	0.11 – 0.24

Table 6.7 Predictors of relative localisation performance. Estimate strength and significance of effects for each significant term are presented.

6.3.1.4 Relative localisation reaction time

Relative localisation reaction time was modelled with moderate fit ($R^2 = 0.315$). This reaction time measure was the time taken for participants to respond with the location shift between reference and target words (either left or right). Response times were significantly faster for the OSN condition relative to the OMNI condition (mean difference = 39 ms, SE = 7 ms), with an effect size of d = 0.207 (see **Figure 6.13**)

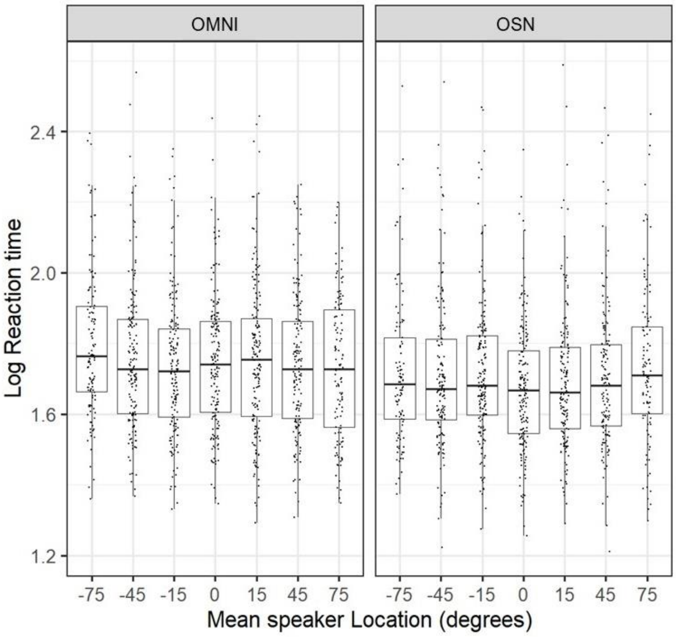


Figure 6.13 Log reaction time for relative localisation selections in the OMNI and OSN conditions. Results plotted as a function of mean speaker locations (degrees).

Significant predictors are outlined in **Table 6.8**, with post hoc testing of specific speaker locations shown in **Table 6.9**. There was no significant interaction between hearing aid condition and mean speaker location. Furthermore, despite the main effect of condition, post hoc testing did not show significant differences between conditions at any individual speakers. Lastly, responses became significantly slower with trial number.

	$\chi 2$	**DF**	**p**	
Group (OSN vs OMNI)	6.390	1	0.011	*
Mean speaker location	20.611	6	0.002	*
Word Group	30.241	3	<0.001	*
Trial Number	38.044	1	<0.001	*
Trial Number × Group	0.170	1	0.680	
Mean speaker location x Group	7.259	6	0.298	

Table 6.8 Predictors of relative localisation reaction time. Asterisks denote significance ($\alpha = 0.05$).

Term	**Group**	**Reference**	**Estimate**	**St Error**	**Z**	**p**
Group	OSN	OMNI	-0.052	0.024	-2.207	0.011*
Location	75° Left	Midline	0.064	0.020	3.272	0.019*
	45° Left	Midline	0.024	0.020	1.243	0.877
	15° Left	Midline	-0.009	0.020	-0.448	0.999
	15° Right	Midline	0.019	0.020	0.944	0.965
	45° Right	Midline	0.011	0.020	0.556	0.998
	75° Right	Midline	0.007	0.020	0.361	1.000
Word group	Vs	Vc	0.019	0.011	1.790	0.278
	Ci	Vc	0.011	0.011	1.066	0.710
	Cf	Vc	0.053	0.011	4.999	<0.001*

Table 6.9 Estimate strength and significance of effects for each significant term are presented.

6.3.1.5 Summary of results

Phase 1 used the SSiN-HA to compare OMNI and the OSN features within one hearing aid model. This double-blind study involved six experienced hearing aid users that were given 4–6 weeks to acclimatise to the new hearing aids. They were then invited back to the research centre to complete the SSiN-HA twice, once with OSN activated and once with OMNI activated. At the group level, was no significant difference in word identification performance, across azimuth, between OMNI and OSN conditions. OSN was detrimental to relative localisation performance compared to OMNI. However, reaction times were significantly faster in the OSN condition for both word identification selections and relative localisation selections.

These findings are based on a small sample size of six participants. **Figure 6.9** summarises the mean performance differences between OSN and OMNI, detected using the SSiN-HA, for each listener. Considering the mean word identification performance differences showcased in **Figure 6.9A**, and the associated group mean difference of 2.8%, a sample size calculation was completed to establish the number of participants required to determine whether the results are reliable. Power analysis suggests that 66 participants in each condition would be required to reliably depict the group differences seen in word identification performance (87.1% vs 89.9%, SD = 5.7%, Power = 0.80, alpha = 0.05). OSN led to significantly poorer relative localisation performance compared to the OMNI condition. If a greater performance difference between conditions (5%) is included in power analysis, 21 participants would be required in each condition.

Figure 6.9C and **6.9D** summarise relative localisation performance between conditions, for central and peripheral speaker locations. Power analysis based on the mean relative localisation performance difference between OMNI and OSN conditions at peripheral locations (6.05%, SD = 11%, Power = 0.80, alpha = 0.05) suggests a sample size (*n* = 60) is needed to reliably detect a change of this magnitude. This is similar to the value derived from word identification performance differences. While the present results from phase 1 of this study are encouraging, the sample (*n* = 6) is underpowered and should be increased to refute Type I error.

To provide insight into the SSiN-HA user experience, all six participants were invited to complete a questionnaire and take part in a focus group in phase 2 of this study. The aim was to generate potential SSiN-HA improvement indicators and compare the task to assessment techniques currently available in audiology clinics.

6.3.2 Phase 2: Qualitative review of SSiN-HA

All participants in phase 1 completed the questionnaire independently, directly after carrying out the SSiN-HA (see methods for questionnaire questions). Themes generated from the analysis included: 1) levels of task difficulty, 2) test environment, 3) real world application.

6.3.2.1 Questionnaire

Levels of task difficulty

Participants discussed elements of the SSiN-HA that they felt added to the challenging nature of the task or, conversely, things that made the task easier. Some also reported that the repetition in the task meant that words became familiar as the test went on and this familiarity sped up their responses. Others commented that the words were difficult to tell apart and therefore appropriate for the task.

> With usage, the words became reasonably familiar (which speeded up the response). Some words had a characteristic element (e.g., sibilance) which made them easier to distinguish. The words were all familiar, but without the graphics I would have really struggled (i.e., would have had difficulty in many cases in—say—repeating them). (AB, 81 years old)
>
> The number of different words seemed low. (AB, 81 years old)
>
> The variety between the four sets seemed planned and reasonable in terms of the different letters and endings used (KL, 70 years old)
>
> In real life the brain “hears” words in context and usually correctly guesses what the word is without necessarily a conscious hearing of the word itself. (EF, 49 years old)
>
> The choice of words given in this test are difficult to tell apart so are a sufficient perhaps—indication of difficult words to distinguish. (GH, 68 years old)
>
> You really had to concentrate to identify this group of words. (CD, 59 years old)

Test environment

Participants mentioned specific aspects of the test environment that were either satisfactory or needed improvement. Specifically, the touchscreen was difficult to use as participants reported they had to press the buttons with force in order for their selection to be recognised. Some participants mentioned how they sat in the chair and the potential impact of changing position. Other participants mentioned the need for regular breaks and that they would not be comfortable completing a task longer than half an hour.

> I did find I was pressing quite hard and so changed from using my index finger to my thumb and then changed the way I was holding the screen too. (AB, 81 years old)
>
> The touchscreen needed a fairly firm touch which took a few goes to get used to and even then I felt that I needed to check after each press that it had registered thus adding another part to the task. The layout seemed ok and I didn’t really register the pictures. (GH, 68 years old)
>
> Quite clear once I’d got my head around the “movement of the second sound relative to the first one.” (CD, 59 years old)

Real world application

Participants reported how much concentration was needed throughout the task and how this could lead to fatigue. Some participants mentioned some applications of this task and wanting to try it with their old hearing aids to make comparisons. Others reported how audiology testing traditionally does not reflect real world situations.

> I would be very interested to do the test with my old hearing aids so as to appreciate the difference between the devices. (LM, 74 years old)
>
> I have never understood how listening to sounds through headphones in a soundproofed room has any bearing on “real world” hearing situations. I have left an audiology hearing test before now and, while traveling home, realised that the settings are not how I would expect them to be. (CD, 59 years old)

6.3.2.2 Focus group

Participants described the process of carrying out the SSiN-HA and compared the task to those they have experienced within the audiology service provision pathway. Three key themes were identified: 1) real world applicability, 2) human factors, 3) equipment and test set up.

Real world applicability

Participants reported the specific benefits of the SSiN-HA test compared to the traditional audiology tests they were accustomed to. Particularly the use of speech tokens in the SSiN-HA was found to be beneficial compared to the regular use of pure tone testing in audiology.

> I certainly found it useful because the test concentrated on a speech element and not on tones and beeps, which to me is doesn't relate in the real world, because I can't hear those things. Anyway, my biggest issue has always been speech. (EF, 49 years old)

> I think it was just so different to any audiology test setup before, related to speech which is my main problem in day-to-day life. (KL, 70 years old)

> If that was some way that modern hearing centres could incorporate tests like that, because most of the time it is about speed. It's about hearing people so that we can communicate, and people don't talk and clicks and beeps and tones. (EF, 49 years old)

Another area of interest was the use of background babble and the dual nature of the task which includes the relative localisation testing. These added a more difficulty to the task and participants commented that this made the task more comparable to day-to-day challenging listening situations.

> So the tests were a little bit more realistic, because you had the background noise, you have to get the direction, you have to actually distinguish the words, which is something that I struggled with. (EF, 49 years old)

> Oh, I wish this could happen more often. Because I feel as though this is really testing me. And I'm really beginning to understand what goes on with my hearing in difficult situations. (LM, 74 years old)

> I think I could hear, but the main challenge was distinguishing where the second word was coming from. I thought I found that quite challenging but challenging is actually good. (KL, 70 years old)

Human factors

Focus group participants also mentioned that although the SSiN-HA testing experience was positive, they did feel fatigued due to the duration and concentration required. Also, due to the difficulty of the task, participants reported their discomfort in having to guess some of the answers.

> I thought the whole thing was very positive, it was quite draining. It's tiring. (KL, 70 years old)

> It was a slight worry at the time because I felt I was guessing some of the time. So, I suppose it sort of bothered me, it bothered me that I might be getting the results wrong. (AB, 81 years old)

Equipment and test set up

Comments were made about the physical testing space and equipment used within the SSiN-HA.

> Quite an experience being in that anechoic room aiming for the chair as I walked in. I'm not quite sure where my feet would go, because I was a bit nervous in there to start with. (AB, 81 years old)

6.3.2.3 Summary of results

Phase 2 of this study involved participants who had completed the SSiN-HA in phase 1. Overall, participants expressed positive experiences in carrying out the SSiN-HA as it was more challenging than assessment methods they had experienced in clinical audiology. Participants also reported some key areas to improve the SSiN-HA, e.g., shortening testing duration. A larger trial was planned to improve the SSiN-HA based on participant comments and results from phase 1 of this study. However, the COVID-19 pandemic disrupted in-person data collection. To investigate how the hearing aid processing responded to the SSiN-HA test paradigm, technical measurements using a head and torso manikin (KEMAR) were carried out in phase 3 of this study. Due to equipment limitations in the anechoic chamber, the introduction of a rear noise source within the behavioural SSiN-HA would have relied upon reorienting the listeners relative to the speaker array and increasing test duration. However, the additional trials and reorientation was possible within the technical measurements in phase 3, using the KEMAR. The use of KEMAR also allowed for the testing of additional hearing aid features and speaker set ups to reflect those that are clinically available.

6.3.3 Phase 3: Hearing aid technical measurements

Here, hearing aid technical measurements are presented from two test protocols. Experiment 1: hearing aid output measurements from speech and noise collocated at 0° and with speech at 0° and noise at 180°. This testing protocol was chosen to reflect a speaker set up that is more likely to be available within a clinical setting. Also, the limited number of speakers resulted in a shorter test duration so that more hearing aid conditions (e.g., amplitude compression) could be tested. Data in experiment 1 was used to decide upon the conditions tested in experiment 2. Experiment 2: hearing aid output measurements during the SSiN-HA test paradigm. Experiment 2 was completed to investigate how the hearing aids respond to the SSiN-HA experimental design used in phase 1 of this study.

6.3.3.1 Results: experiment 1

Hearing aid recordings were carried out with either speech and noise collocated at 0° or with speech at 0° and noise at 180°. SII weighted hearing aid output SNR was calculated for each recording. Throughout the recordings, KEMAR was faced towards 0° azimuth. All hearing aid features were tested once with amplitude compression activated and once with amplitude compression deactivated (linear processing).

6.3.3.1.1 Speech and noise collocated

Linear mixed modelling ($R^2 = 0.853$) was used to understand predictors of hearing aid output SNR (SII weighted). When speech and noise were collocated, there was no significant effect of hearing aid condition (Unaided, OMNI, OSN), with amplitude compression activated or with linear processing (**Table 6.10**, **Figure 6.14**). There was also no significant effect of word group. Although there was a significant effect of input SNR there was no significant interaction between hearing aid condition and input SNR, indicating similar performance unaided and with the three directionality settings within the three different input SNRs (-10 dB, +5 dB and +10 dB).

Effect	**F**	**DF**	**p**
Hearing aid	1.342	6	0.2373
Input SNR	319.74	2	< 0.001*
Word group	62.8	3	0.113
Hearing aid x Input SNR	1.0556	12	0.397

Note. Significance is shown using asterisks (*, $p < 0.05$).

Table 6.10 Significance of main effects in predicting SII SNR when speech and noise are collocated.

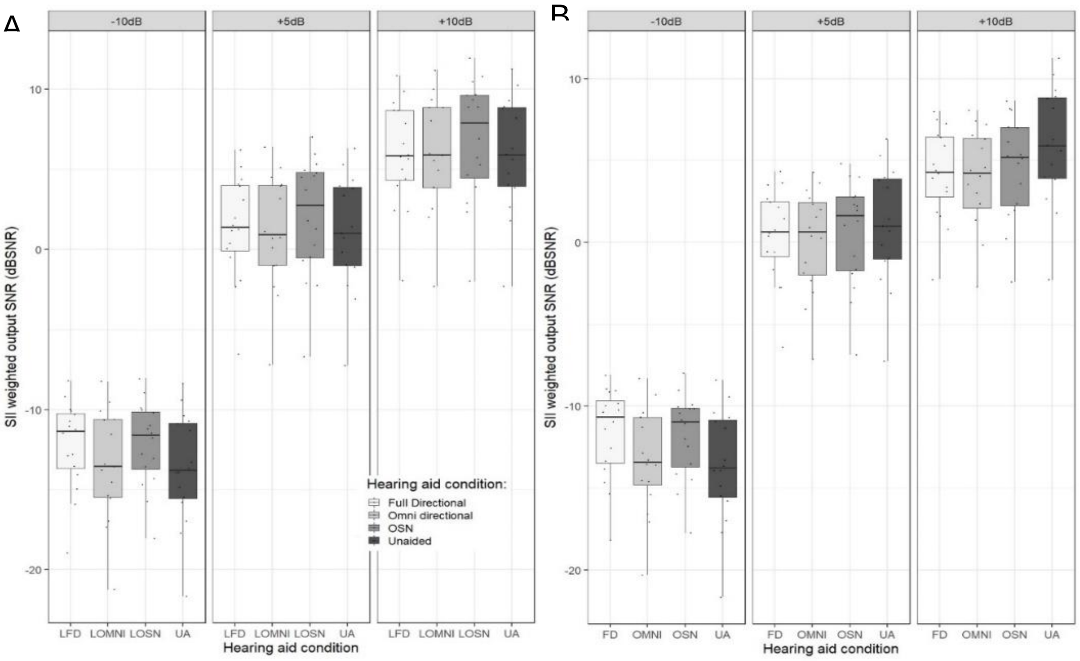


Figure 6.14 SII weighted output for hearing aid and unaided conditions in response to co-located speech and noise presentations. A) SII weighted output SNR for hearing aid directionality conditions with amplitude compression deactivated (linear processing), B) SII weighted output SNR with amplitude compression activated. For both conditions results are presented at three input SNRS: -10 dB, +5 dB, +10 dB and the unaided condition is presented for comparison.

6.3.3.1.2 Speech front-noise back

In this second analysis, linear mixed modelling ($R^2 = 0.825$) was also used to predict SII weighted hearing aid output SNR (dB) when speech was presented from 0° azimuth and multi-talker babble was presented from 180° (behind KEMAR). Overall, OSN and FD significantly improved output SNR compared to the unaided condition, but OMNI did not (**Table 6.12**, **Figure 6.15**). Also, the FD setting was significantly better than OSN. Post hoc analysis found no significant difference between amplitude compression activated and linear processing for hearing aid settings OSN and OMNI. However, FD linear processing resulted in significantly better output SNR compared to FD with amplitude compression activated (**Table 6.12**).

Effect	**F**	**DF**	**p**
Hearing aid	23.95	6	<0.001*
Input SNR	577.496	2	< 0.001*
Word group	0.8091	3	0.489

Note. Significance is shown using asterisks (*, p < 0.05).

Table 6.11 Significance of main effects in predicting SII SNR when speech and noise are spatially separated.

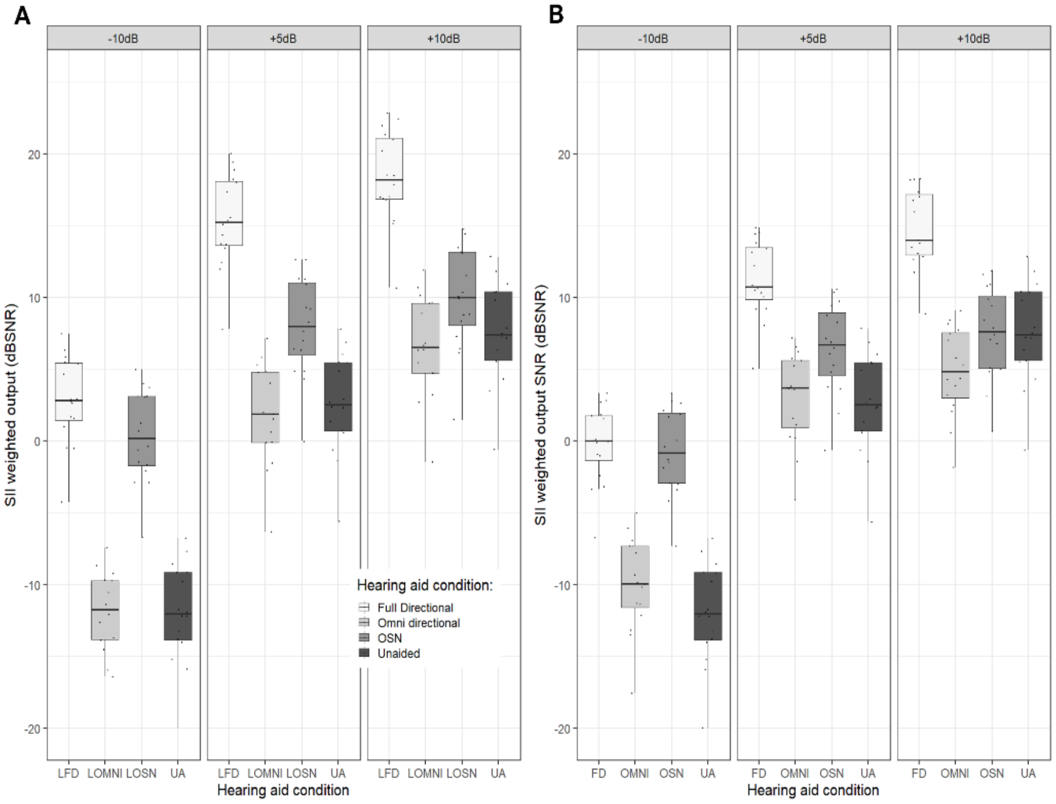


Figure 6.15 SII weighted output SNR for hearing aid and unaided conditions in response to speech and noise presentations spatially separated. A) SII weighted output SNR for hearing aid directionality conditions with amplitude compression deactivated (linear processing), B) SII weighted output SNR with amplitude compression activated. For both conditions results are presented at three input SNRs: -10 dB, +5 dB, +10 dB. The unaided condition is presented for comparison.

Effect	Group - Contrast	Estimate	SE	DF	t	p
Hearing aid	Unaided - Omni Compression	-0.45	0.51	338	0.88	0.975
	Unaided vs. Omni Linear	-0.33	0.51	338	0.64	0.996
	Unaided vs. OSN Compression	2.52	0.51	338	-4.92	< 0.001*
	Unaided vs. OSN Linear	3.89	0.51	338	-7.60	< 0.001*
	Unaided vs. FD Compression	4.56	0.51	338	-8.90	< 0.001*
	Unaided vs. FD Linear	6.69	0.51	338	-13.07	< 0.001*
	Omni Compression vs. Omni Linear	0.13	0.59	338	-0.21	1.000
	OSN Compression vs. OSN Linear	1.37	0.59	338	-2.32	0.234
	OSN Compression - FD Compression	-4.29	0.86	338	-4.97	<0.001*
	Omni Compression - FD Compression	-9.38	0.86	338	-10.85	<0.001*
	Omni Compression - OSN Compression	-5.08	0.76	338	-6.67	<0.001*
	FD Compression vs. FD Linear	-3.46	0.86	338	-4.00	<0.001*

Table 6.12 Post hoc testing with estimates showing a between-group differences for experiment 1. In experiment 1 speech was presented from the midline and multi-talker babble presented behind KEMAR. Significance is shown using asterisks (*, $p < 0.05$).

6.3.3.2 Experiment 2: SSiN-HA paradigm

Given that there was no significant difference between linear processing and processing using amplitude compression for the OMNI and OSN hearing aid recordings presented in experiment 1, the conditions tested in experiment 2 only involve amplitude compression being activated. This also helped bring the technical hearing aid measurements in the SSiN-HA paradigm closer to the methodology used in phase 1 of this chapter as all participants performed the SSiN-HA task with amplitude compression activated on their hearing aids. Experiment 2 was carried out to better understand the hearing aid processing that occurs in the SSiN-HA paradigm to further explore the SSiN-HA's clinical relevance. Speech tokens were presented in pairs, from adjacent speakers 30° apart, to replicate the dynamic nature of the SSiN-HA behavioural task.

Hearing aid output measurements corresponding to speech presentations from all SSiN-HA speaker locations is presented in **Figures 6.16**, **6.17**, and **6.18**. These visualisations suggest that the use of OSN leads to a change in hearing aid output, compared to that of the unaided and omni conditions, when certain test conditions are applied, e.g., -10 dB input SNR with rear noise source. To observe this more closely, subplots of specific conditions were created. **Figure 6.19** shows a subset of the data for specific speech and noise locations to compare hearing aid conditions more closely. In **Figure 6.19**, subplots include: **6.19A** and **6.19D** to present results in response to speech presented at the midline – the location that the KEMAR is facing, while all other subplots present results when speech was presented from a maximally offset position (90°). For the speech presentations from 90°, multi-talker babble is either generated on the same side as the speech or on the opposite side. **Figure 6.19** also demonstrates the impact of whether multi-talker babble is presented in front or behind the KEMAR.

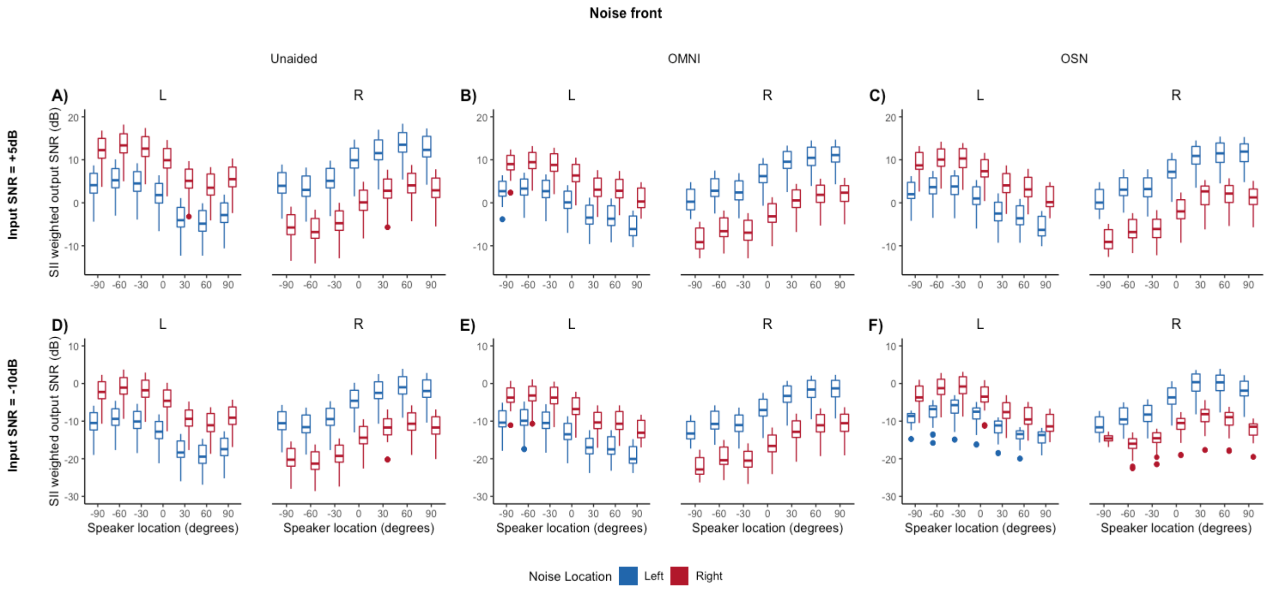


Figure 6.16 SII weighted output SNR from hearing aid conditions (OMNI and OSN) and the unaided condition with multi-talker babble presented in front of KEMAR. Results from experiment 2. During testing, multi-talker babble was presented from the frontal speaker locations. Results are plotted as a function of speaker location (degrees). A, B and C of this figure are results from an input SNR of +5 dB; D, E and F presented results from an input SNR of -10 dB.

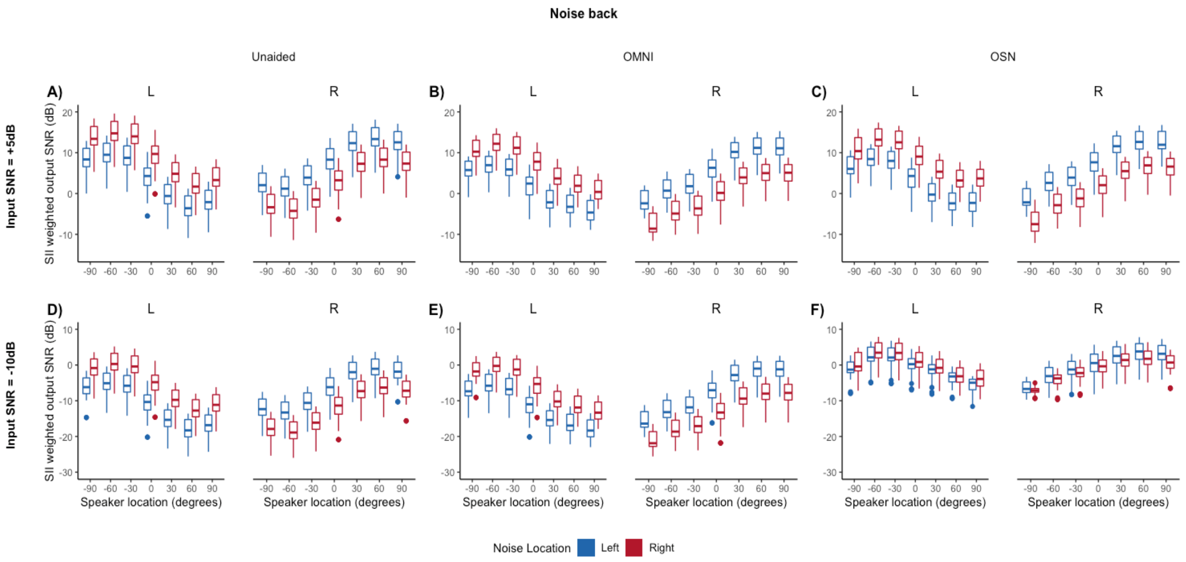


Figure 6.17 SII weighted output SNR from hearing aid conditions (OMNI and OSN) and the unaided condition with multi-talker babble presented from behind KEMAR. Results from experiment 2. Data are plotted as a function of speaker location and for two input SNRs (+5 dB and -10 dB). Multi-talker babble is presented from behind the KEMAR.

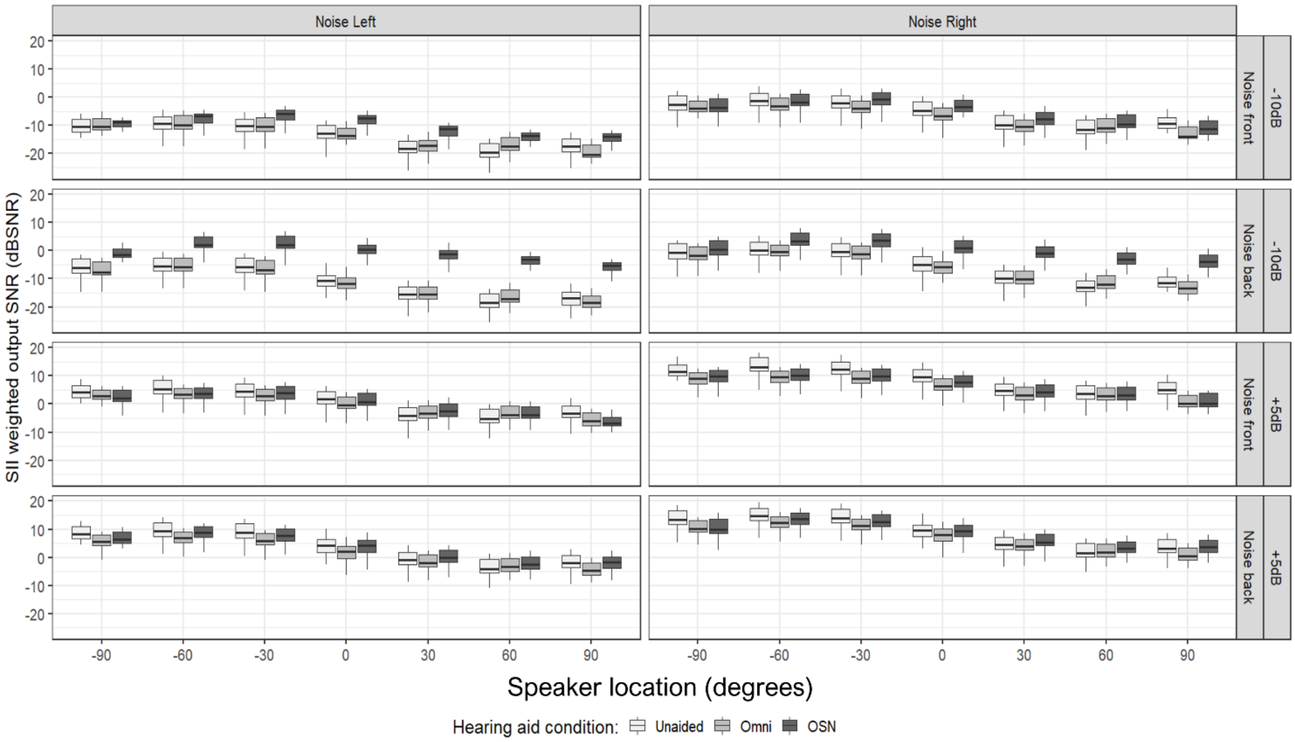


Figure 6.18 SII weighted output SNR recorded through the left KEMAR ear, for each hearing aid condition and the unaided condition. Results from experiment 2. Data are presented across speaker location and separately for each noise position and input SNR.

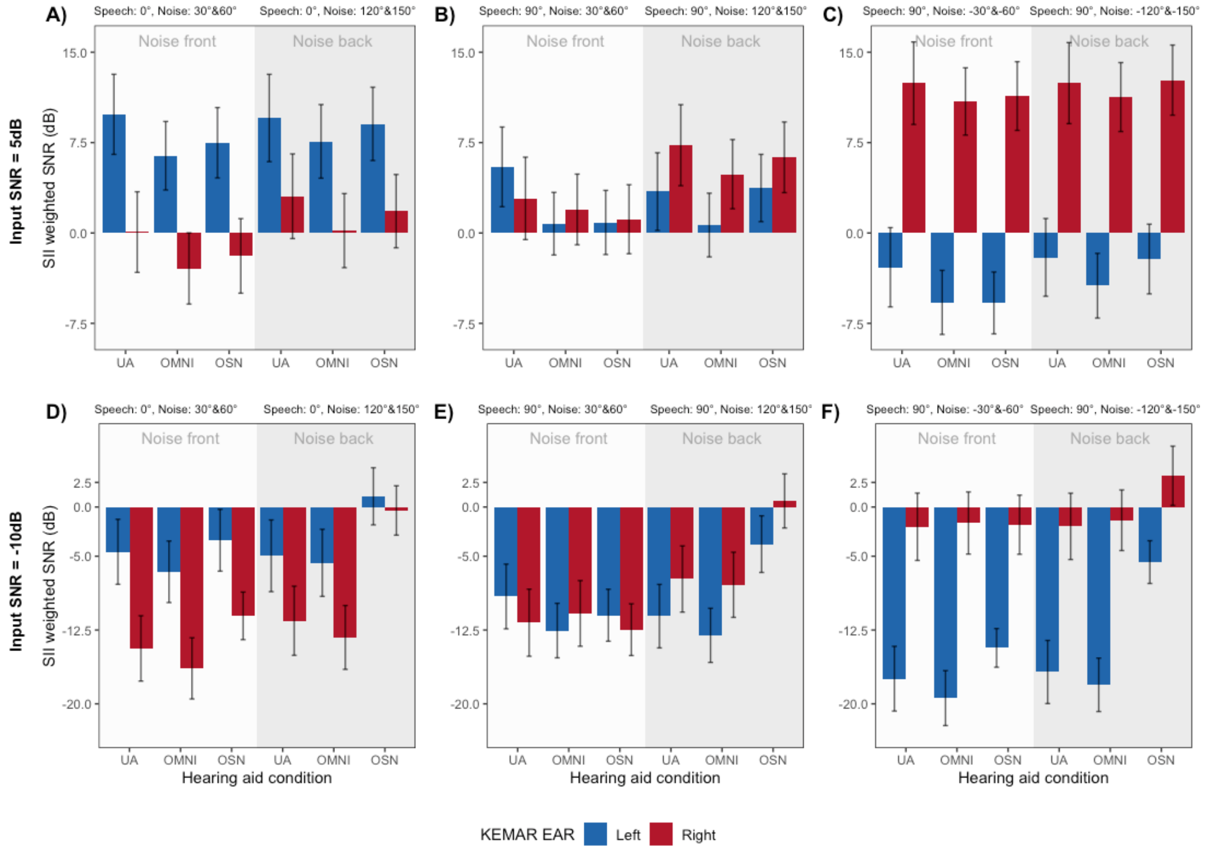


Figure 6.19 A subset of data from experiment 2. Mean SII weighted SNR is presented for each hearing aid condition, including where multi-talker babble was presented in the frontal position and behind the KEMAR. KEMAR faced 0 degrees azimuth throughout the recordings.

SII weighted output SNR showed significant associations with numerous predictors ($R^2 = 0.534$). The significance of all main effects in association with SII SNR are shown in **Table 6.13**, with specific comparisons outlined in **Table 6.14**. SII SNR significantly differed between unaided, OMNI and OSN conditions. OSN results in the best SII weighted output SNR and OMNI resulted in the worst. SII output SNR was also significantly better at higher input SNRs, and when noise was presented from behind KEMAR.

While OSN showed superior performance regardless of noise location (front or back), its benefits were particularly strong when noise was presented from behind, relative to either OMNI or unaided (**Figure 6.18** and **Figure 6.19**). Additionally, OSN provided the most benefit when input SNR was more challenging (-10 dBSNR), while performing more similarly to OMNI and unaided at higher input volumes (+5 dBSNR). Overall, the hearing aid output for the second word of a word pair was significantly better than the first. When output SNR was collapsed across speaker locations the mean SNR in response to the second word was on average 0.31 dB greater than the first word in the OSN condition. This pattern was also present in the OMNI and unaided condition (0.39 dB difference in the OMNI condition and 0.28 dB difference in the unaided condition).

Lastly, SII weighted output SNR was highest for words presented centrally (0°) and decreased towards more peripheral presentations. This pattern across space significantly differed between each of OSN, OMNI, and unaided. For example, the OSN performance gains for words presented centrally relative to more peripherally were strongest, and these spatial differences were less distinct for each of OMNI and unaided.

	DF1	**DF2**	**F**	**p**
Hearing aid	2	27616	49.98	< 0.001 *
Distance from noise	1	27616	2.43	0.119
Input SNR	1	27616	13032.68	< 0.001 *
Speaker location	6	27616	9.39	< 0.001 *
Word group	3	27616	54.58	< 0.001 *
Word number (1st or 2nd)	1	27616	4.14	0.042 *
Noise location (Front or back)	1	27616	84.53	< 0.001 *
Hearing aid × Noise location	2	27616	271.51	< 0.001 *
Hearing aid × Input SNR	2	27616	698.74	< 0.001 *
Hearing aid × Speaker location	12	27616	8.27	< 0.001 *

Table 6.13 Main effects and interactions in predicting SII SNR in experiment 2.

Comparison	Contrast	OR (95% CI)	t	DF	p
Hearing aid	Unaided vs. Omni	4.13 (3.43 – 4.97)	14.99	27616	< 0.001 *
	Unaided vs. OSN	0.13 (0.11 – 0.16)	-21.64	27616	< 0.001 *
	Omni vs. OSN	0.03 (0.03 – 0.04)	-36.64	27616	< 0.001 *
Volume	-10 dB vs. 5 dB	0.01 (0.00 – 0.01)	-162.27	27616	< 0.001 *
Azimuth	-90° vs. 0°	0.12 (0.09 – 0.17)	-12.95	27616	< 0.001 *
	-60° vs. 0°	0.49 (0.38 – 0.63)	-5.57	27616	< 0.001 *
	-30° vs. 0°	0.71 (0.56 – 0.92)	-2.66	27616	0.110
	0° vs. 30°	1.34 (1.04 – 1.71)	2.27	27616	0.259
	0° vs. 60°	1.76 (1.37 – 2.26)	4.44	27616	< 0.001 *
	0° vs. 90°	3.33 (2.42 – 4.57)	7.41	27616	< 0.001 *
Word group	1 vs. 2	0.44 (0.36 – 0.54)	-7.80	27616	< 0.001 *
	1 vs. 3	1.32 (1.08 – 1.62)	2.67	27616	0.038 *
	1 vs. 4	0.47 (0.39 – 0.58)	-7.21	27616	< 0.001 *
	2 vs. 3	2.97 (2.42 – 3.64)	10.47	27616	< 0.001 *
	2 vs. 4	1.06 (0.87 – 1.3)	0.58	27616	0.937 *
	3 vs. 4	0.36 (0.29 – 0.44)	-9.88	27616	< 0.001 *
Word	1st vs. 2nd	0.85 (0.72 – 0.99)	-2.03	27616	0.042 *
Noise location	Front vs. Back	0.08 (0.07 – 0.1)	-26.09	27616	< 0.001 *
Hearing aid × Noise location	Unaided Front vs. Unaided Back	0.27 (0.21 – 0.36)	-9.19	27616	< 0.001 *
	Omni Front vs. Omni Back	0.28 (0.21 – 0.37)	-9.05	27616	< 0.001 *
	OSN Front vs. OSN Back	0.01 (0.01 – 0.01)	-34.82	27616	< 0.001 *
Hearing aid × Volume	Unaided -10 vs. Unaided 5	0.01 (0.00 – 0.01)	-114.16	27616	< 0.001 *
	Omni -10 vs. Omni 5	0.01 (0.00 – 0.01)	-103.06	27616	< 0.001 *
	OSN -10 vs. OSN 5	0.01 (0.00 – 0.01)	-63.85	27616	< 0.001 *

Table 6.14 Post hoc testing from the prediction of SII weighted output SNR from experiment 2.

6.4 Discussion

The aims of this study were to consider how the SSiN-HA could be used to assess advanced hearing aid features and to present listeners' perspectives and experiences of completing the task. After fitting all participants with the same hearing aid type, SSiN-HA results were compared between two directionality settings: omnidirectional (OMNI) and adaptive directionality (OSN).

At the group level, OSN did not improve word identification, was detrimental to relative localisation performance, but reduced reaction times, compared to the OMNI. Hearing aid output measurements found OSN to improve output SNR across azimuth compared to the unaided and OMNI conditions. Unsurprisingly, given the front-facing focus of modern digital hearing aids, the introduction of a rear noise source and less favourable input SNRs, compared to those used in the behavioural SSiN-HA (phase 1), resulted in the largest differences between OSN and OMNI conditions. Therefore, the inclusion of a rear source and a range of input SNRs in the behavioural SSiN-HA would give a more comprehensive picture of hearing aid performance, relevant to complex environments. From the participants' perspective, the SSiN-HA demonstrates an assessment scenario that better reflects real world listening, compared to current audiological assessment methods.

Firstly, the task was adapted to better reflect the complex listening environments hearing aid users may experience. The adaptations to the task, compared to the SSiN reported in the previous chapter, included the increase in overall level of the multi-talker babble from 52 dBSPL to 70 dBSPL and a change in the duration of the babble presentation. Previously, the SSiN presented multi-talker babble with a ramped onset and offset for every trial. However, silent intervals between stimuli can affect hearing aid processing as the attack and release times within hearing devices can vary and be as large as several seconds in particular conditions (Smits et al., 2013). Therefore, it was hypothesised that continuous multi-talker babble would help avoid these unwanted effects. It is also more realistic to think of a complex listening environment where the background noise is present for a longer period, e.g., in a restaurant or pub, rather than noise ramping on and off every few seconds.

Currently, there is no UK clinical audiology guidance recognising the need for ecologically valid testing, including spatial hearing assessment, for patients with hearing aids. The present study trialled the applicability of the SSiN in the assessment of Oticon's adaptive directionality (OSN) and comparison to omnidirectionality. Such assessment methods could have potential to assist audiologists' clinical decision making regarding the patient candidacy for these hearing aid features as well as the identification of patient factors that might influence hearing aid uptake or benefit including listening effort, relative localisation, and speech in noise perception abilities.

In the present study, the SSiN-HA was used to compare word identification and relative localisation performance and associated reaction times between OSN and OMNI hearing aid settings. During the task, multi-talker babble was presented from the right or left side of space and monosyllabic word pairs were presented from locations spaced 30° apart, from -90° to +90° azimuth. The participants faced the midline (0° azimuth) throughout testing. Findings from the previous chapter found that hearing aid users could perform with SSiN dual task without floor effects, and this was also true of the SSiN-HA in the current study. Overall, there were no significant differences in word identification performance between OSN and OMNI settings. This is consistent with previous literature that also found no significant difference between these settings, when the background noise was speech and OSN did not significantly reduce word identification performance compared to OMNI, at any speaker location (Browning et al., 2019). Therefore, OSN may offer advantages over fully fixed directionality, particularly in dynamic environments where speech is coming from unpredictable locations around the listener and towards the most off-axis areas. OSN may also be advantageous for listeners who cannot consistently turn their head towards the target speaker or change a fixed microphone setting manually on the hearing aids.

Despite similar word identification performance within the OSN and OMNI settings, there was a trend for participants' performance to improve across the time course of the SSiN-HA trials in the OSN condition, which was not observed in the OMNI condition. Also, the OSN setting resulted in faster reaction times, for both word identification reaction time and relative localisation reaction time, compared to the OMNI condition. Reaction time has been found to be a useful measure of listening effort during testing scenarios where speech intelligibility is optimal (Houben et al., 2013). In the SSiN-HA used in the present study, background babble was presented at 70 dBSPL, and all participants performed the task within positive SNRs. This is reflective of many everyday communication situations that take place in positive SNRs and result in high speech intelligibility (Lunner et al., 2016). Also, the average SNR for hearing aid users in realistic environments has been found to be approximately 5 dB or higher (Smeds et al., 2015). Such SNRs would generally result in near-ceiling performance during behavioural speech perception tasks but it is important to explore hearing aid processing in these realistic SNRs. Results in the present study correspond with previous research reporting a reduction in listening effort in OSN testing conditions compared the OMNI condition (Wendt et al., 2017). The reduced listening effort in the OSN condition may have released sufficient cognitive resources for participants to exhibit a trend for better performance across SSiN-HA trials compared to the OMNI condition.

In the present study, OSN did not affect word identification performance but there was a significant negative effect on relative localisation performance compared to the OMNI condition. Previous research comparing OMNI, fully directional microphones and asymmetric microphones found no significant effect of microphone type on horizontal localisation (using the following speaker locations: -60°, -45°, +45°, +60°). Furthermore, directional microphones have been found to reduce front-back confusions in research settings (Carette et al., 2014; Keidser et al., 2009). Research has also found that asymmetric directional microphones (directional microphone activated only one side) results in localisation bias to the side with more gain available for off axis listening (e.g., OMNI) (Keidser et al., 2006). However, more recently, such differences were not exhibited by listeners with severe hearing loss (Picou & Ricketts, 2017). The relative localisation differences between OSN and OMNI align with findings from Van den Bogaert et al. (2006) who also reported a trend for localisation performance to be better in the OMNI condition compared to the adaptive directional microphone. The researchers reported adaptive directionality to have a negative impact on localisation ability in the area from 60° to 90° and not in the area from -45° to +45°. Although statistical analysis in the present study could not determine speaker locations where OSN resulted in worse relative localisation performance, compared to OMNI (the statistical model failed to converge when the Group x Speaker location interaction was included), **Figure 6.12** shows there was a trend for a stronger performance difference to occur at the most peripheral locations (+/-75°).

The double blinded nature of this study is a strength of the present study as the lack of blinding and randomisation has been noted as a methodological limitation of previous studies involving the behavioural assessment of hearing aid algorithms (Lakshmi et al., 2021). The hearing aid acclimatisation period (4–6 weeks) is another strength to this study, which other hearing aid studies of OSN have not been able to implement (Browning et al., 2019). The small sample size (*n* = 6) is a limitation. However, this study forms the ideal starting point for planning a larger trial using the SSiN-HA as an outcome measure of auditory rehabilitation tools or hearing aid features. A larger trial was planned but postponed due to the COVID-19 pandemic. Results from power analysis suggest that the present study was significant underpowered, and more participants are needed to determine whether the performance differences observed are accurate. It is possible that the small OMNI vs OSN effects observed are present but cannot be confirmed due to the study being underpowered, rather than concluding that no effects are present.

Results from phase 1 of the chapter were presented at international conferences and with the hearing aid manufacturers to further investigate the use of the SSiN-HA in the assessment of advanced hearing aid features (Parmar et al., 2019). The outcome of these discussions was the decision to carry out hearing aid technical measurements to better understand how the hearing aid output SNR differs per hearing aid condition, within the SSiN-HA test paradigm.

In phase 2 of this chapter, the SSiN-HA was reviewed by participants that completed the SSiN-HA in phase 1. This qualitative review included a questionnaire and online focus group to gain feedback about the usability, accessibility, and overall experience of carrying out the SSiN-HA. The review also included how the SSiN-HA test paradigm relates to both the challenging natural everyday listening environments, and to common audiology tests currently used in the clinic. Qualitative research has been used alongside clinical intervention development to optimise intervention content, delivery, and acceptability (Donovan et al., 2002; Moore et al., 2015) and actively involving patients and the public in research can lead to better, clearer, more relevant research (National Institute for Health Research, 2021). In healthcare research, qualitative methods such as telephone interviews, semi-structured interviews, surveys and focus groups have been used to evaluate health promotion activities (Burn et al., 2021), develop health education resources (Ferguson et al., 2018) and health intervention strategies (Vincent et al., 2006). In fact, a lack of stakeholder/patient involvement has been reported to be a key weakness in the development of health education tools (Van Velsen et al., 2013) as this could result in the creation of tools and resources that are not aligned with the target audience/end user's needs (Ferguson et al., 2018). Within hearing research, patient involvement has been found to be particularly beneficial during the design of communication tools, as end users were put at the centre of the process (Ellis & Kurniawan, 2000; Hanssen & Dahl, 2016). This process can also help identify unforeseen positive contributions or limitations of the product.

Overall, participants reported positive experiences of carrying out the SSiN-HA as it was a challenging task of localisation and speech identification in the presence of background noise. Many reported that they had not experienced speech in noise testing in their routine audiology appointments, but that speech discrimination was one of their most common complaints with their hearing loss/hearing aids. These findings align with those from Chapter 3 of this thesis which revealed that speech testing was underutilised in UK audiology practice. Participants also reflected on specific difficulties and challenges they had whilst completing the SSiN-HA. Key areas of evaluation are presented in **Table 6.15,** alongside some actionable changes that could take place in order to improve usability and accessibility during testing.

This phase of reviewing the SSiN-HA has identified key areas of improvement and these should be considered before the task is used more regularly within research or clinical practice. However, the qualitative data collection presented here is only the views and opinions of six participants. Future work could include a larger sample to get a broader understanding of the usability of the SSiN-HA. Also, the facilitator of the focus group was the same person that carried out the data collection in phase 1 and all data analysis. Future focus groups should be led by a second facilitator who did not carry out previous data collection to avoid various biases. Finally, participants commented on various aspects of current audiology assessment and rehabilitation that may be suboptimal in meeting patients' wants and needs. Future work should collect service user feedback and perspectives from a more diverse group of participants as this could identify service strengths and areas for improvement.

Area of evaluation	**Summary of feedback**	**Actionable changes**
Hardware	Touchscreen difficult to use	Touch screen to be updated
Human factors	The test is quite tiring, and breaks are needed to avoid fatigue	Regular breaks should be encouraged and emphasized before testing
Test environment	Anechoic chamber comfortable overall but needs some getting used to	Include a period of time to adjust to anechoic chamber before testing.
Stimuli	Low number of words, background noise only from the front.	Background noise from the rear should be introduced. Consider additional word groups
Test instructions	Main difficulty was understanding the relative localisation task	Clear instructions or demo video to emphasis the spatial elements of the relative localisation task

Table 6.15 Summary of qualitative feedback and SSiN design implications.

Phase 3 of this chapter analysed hearing aid processing in response to the SSiN-HA test paradigm. This method was used to further investigate the behavioural findings presented in phase 1 of this chapter and used the same hearing aids. Use of different hearing aid algorithms and processing schemes will lead to different hearing aid output SNRs depending on device characteristics including wide dynamic range compression and noise reduction. Previous studies using hearing aid output measurements have used limited speaker locations not reflecting the dynamic nature of complex environments. Therefore, to better understand the behavioural SSiN-HA findings from phase 1 of this chapter, hearing aid technical measurements were carried out to investigate adaptive directionality modified output SNR, calculated using the phase inversion method, when presented with the SSiN-HA test paradigm (experiment 2). Given that simple loudspeaker test designs may be available in the clinical environment, a two-speaker set up where speech and noise are presented spatially separated (speech front, noise back) and collocated (speech front, noise front) (experiment 1) was also utilised.

The hearing aid technical measurements completed in the present study demonstrated how the OSN and OMNI systems react to the SSiN-HA test stimuli identified key factors influencing hearing aid processing and how hearing aid features can be tested. Firstly, if speech and noise are presented co-located at the midline, there was very little difference between hearing aid conditions. The inclusion of a rear noise source was beneficial in revealing benefits of fixed and adaptive directionality compared to the unaided and OMNI conditions. This is particularly evident within the most challenging input SNR (-10 dB). The SSiN-HA presents speech tokens from 7 speaker locations from -90° -+90°. Therefore, recording hearing aid output within the SSiN-HA paradigm gives a more detailed picture of the hearing aid processing across azimuth. Overall, OSN resulted in increased output SNR compared to the OMNI condition. OSN did not result in enhanced word identification performance in phase 1 of this study but the enhanced output SNR may have contributed to the observed reduction in reaction time.

Two speech tokens were presented sequentially, as in the behavioural use of the SSiN-HA. In phase 1 of this chapter, listeners found the second word presentation significantly more difficult to identify, compared to the first. This was consistent with findings in Chapter 4. The hearing aid recordings showed a significant effect of word presentation, however the mean difference between the output SNR of the first and second word was minimal, and therefore this difference may not perceptually relevant. Given this finding, and because the performance difference between first and second word presentations is also present within normal hearing listeners, it may be due to attentional or cognitive factors as mentioned in Chapter 4 and 5 of this study.

During group conversation, a listener would be required to locate sounds around them and segregate speech from competing speech or background noise. Testing word identification and relative localisation performance across azimuth in the frontal hemisphere could be beneficial to the listener as it better reflects everyday listening situations, compared to presenting speech from the midline alone. Information gathered from the SSiN-HA could therefore be used to demonstrate the benefits and limitations of hearing devices and advanced features to patients and help introduce communication tactics to demonstrate when features are most effective, e.g., optimal positioning in a restaurant. The SSiN-HA results are reported in percentage correct across space and this could help patients understand and interpret the results compared to measures of spatial advantage available clinically (Cameron & Dillon, 2007).

In the present study, adaptive directionality was not detrimental to word identification at off axis position (+/-90°), compared to OMNI settings. Therefore, there may be scope for such features to be activated for populations who are not able to manually switch between omnidirectional and fixed directionality, e.g., paediatric populations, to optimise speech perception around them to optimise incidental learning.

Future development or clinical use of the SSiN-HA could include the inclusion of a rear source of multi-talker babble. The technical measurements presented in phase 3 of this study found that the inclusion of a rear noise source led to the largest differences in hearing aid output SNR and therefore this could lead to more significant observable differences in performance in the SSiN-HA. These additional sources of multi-talker babble would further enhance ecological validity of the task. Further improvements could include a reduction in trials to avoid listener fatigue/learning effects. Also, improvements to the test environment could improve accessibility. Testing in a clinical environment with a multi-speaker array may be challenging due to time and resource availability reported in Chapter 3 of this study.

6.4.1 The Action Research Process

In this chapter, an action research approach was used to further develop the SSiN to explore its clinical usability to test hearing aid users word identification and relative localisation performance. Within the action research cycle (**Figure 6.1**), this activity included engagement with key stakeholders to reflect on previous SSiN datasets and suggest suitable refinements. A subset of hearing aid users then completed the adapted SSiN-HA and further consultation with academics and hearing aid manufacturers was carried out to plan hearing aid output measurements. This process was successful in providing a collaborative approach to uncovering gaps in the research protocol and issues with the SSiN test before piloting solutions to close the identified gaps. This process was in agreement with the general purpose of action research as it “aims to resolves problems rather than merely investigating them” (Whitehead et al., 2003). Furthermore, the hearing aid user group were able to provide critical feedback on the SSiN user experience and provide further suggestions for improvement. The involvement of hearing aid users helped facilitate closer working partnerships between the researchers and the participants as they were required to play an active role in the research. Also, the action research approach encouraged interprofessional knowledge sharing so that a more comprehensive research protocol could be delivered (e.g. the inclusion of hearing aid technical measurements).

6.5 Conclusion

There is potential for the SSiN-HA to be used in the assessment of advanced hearing aid features, like adaptive directionality algorithms. In the present study, the SSiN-HA detected participants' reaction times were reduced in the adaptive directionality condition compared to omnidirectionality, despite word identification performance remaining constant between conditions. The SSiN-HA could help clinicians assess a listeners' candidacy for these features and assess hearing aid benefit.

The action research approach used in the present study has involved clinicians, researchers and hearing aid users to adapt and review the SSiN-HA. Participants reported positive experiences in completing the SSiN-HA overall and identified key areas of improvement that are required to enhance the user experience. Practical challenges included the long test duration and limited number of word groups.

Some hearing aid users felt the current test battery used in hearing aid services did not relate to the everyday, challenging listening difficulties they faced. Therefore, there is scope for the SSiN-HA to help patients understand the benefits and limitations of hearing aids (and advanced features) on spatial hearing, in dynamic acoustic scenes. However, the results in the current chapter were from a small group of hearing aid users and there was a lack of diversity (e.g. in educational level and age range) within the group. Also, the participants' involvement in the SSiN-HA trials may have biased their views of audiological testing reported in the focus group. Therefore, the next chapter of this thesis involved a broader range of hearing aid users, including those that had not previously taken part in any research presented in this thesis, and explored their perspectives of the current UK audiological assessment process. Collecting a broad range of hearing aid user perspectives could help identify factors that influence SSiN use and potential patient benefit.

Chapter 7: Experienced Hearing Aid Users' Perspectives of Assessment and Communication within Audiology

This work has been published in the International Journal of Audiology: Experienced hearing aid users' perspectives of assessment and communication within audiology: a qualitative study using digital methods, Parmar et al. (2021).

The qualitative review presented in phase 2 of Chapter 6 highlighted hearing aid users' views and opinions of the SSiN. Some participants mentioned that they had not experienced speech testing, in quiet or in noise, during their previous experiences of audiological assessment before performing the SSiN. Others also reported the value in performing such tests related to the specific listening difficulties they experienced in everyday situations (e.g., following speech in noisy, dynamic environments). To explore a broader range of hearing aid users' experiences of audiology assessment and include those who have not performed the SSiN, an online focus group and 14 semi-structured interviews were conducted in this study. This approach investigated experienced hearing aid users' perspectives of assessment in audiology and this chapter answers the final research question of this thesis. Exploring hearing aid user perspectives can help better understand the current speech testing landscape and the potential clinical applicability and use of the SSiN for this population.

7.1 Abstract

Objective: To explore experienced hearing aid users' perspectives of audiological assessments and the patient–audiologist communication dynamic during clinical interactions.

Design: A qualitative study was implemented incorporating both an online focus group and online semi-structured interviews. Sessions were audio-recorded and transcribed verbatim. Iterative-inductive thematic analysis was conducted to identify themes related to assessment and communication within audiology practice.

Samples: Seven experienced hearing aid users took part in an online focus group and 14 adults participated in semi-structured interviews (age range: 22–86 years; 12 females, 9 males).

Results: Themes related to assessment included the unaided and aided testing procedure and relating tests to real world hearing difficulties. Themes related to communication included the importance of communication strategies, explanation of test results and patient-centred care in audiology.

Conclusion: To ensure that hearing aid services meet the needs of the service users, we should explore user perspectives and proactively adapt service delivery. This approach should be ongoing, in response to advances in hearing aid technology. Within audiology, experienced hearing aid users' value (a) comprehensive, relatable hearing assessment; (b) clear, concise, deaf aware patient–audiologist communication; (d) accessible services and (e) a personalised approach to recommend suitable technology and address patient-specific aspects of hearing loss.

7.2 Introduction

Effective patient–clinician communication is an essential part of patient-centred care (Zill et al., 2015); however, clinicians working with people with hearing loss may face additional challenges due to the impact of hearing loss on communication (Mick et al., 2014). Within audiology, the patient–audiologist interaction has been recognised as an important factor contributing to patient satisfaction and HA adoption use (Grenness et al., 2014a; Ismail et al., 2019; Poost-Foroosh et al., 2011; Sciacca et al., 2017) and has been investigated across a variety of populations and settings (Ekberg et al., 2014a; Mehta et al., 2019; Tai et al., 2019; Watermeyer et al., 2020; Watermeyer et al., 2017). Importantly, researchers have demonstrated that audiologists tend to use clinician-centred approaches in practice without addressing patients’ concerns (Tai et al., 2019), contrasting the patient-centred approach at the core of audiologists’ clinical responsibility (American Speech-Language-Hearing Association, 2018). Furthermore, evidence suggests that psychosocial support is not routinely provided in audiology practice (Bennett et al., 2020; Ekberg et al., 2014b). Audiologists vary considerably in their interaction style with patients, and in some cases use overly detailed scientific explanations without personalised care (Watermeyer et al., 2017).

A patient’s HA usage and communication needs may differ based on factors including the degree of hearing loss (Hartley et al., 2010), lifestyle (Barker et al., 2016), perceived benefit of HAs, perceived hearing disability, shared decision-making and the role of communication partners (Hickson et al., 2014; Meyer et al., 2014; Ng & Loke, 2015). It is also important to recognise that the provision of audiology-based healthcare services diverges around the world, and in some cases, HA users may have access to different service providers. An international investigation of hearing help-seeking and rehabilitation revealed mixed results regarding the hearing assessment process and the applicability of test results to everyday listening difficulties (Laplante-Lévesque et al., 2012), highlighting the need for specific patient-centred approaches to help professionals improve communication. Furthermore, Preminger et al. (2015) noted that some HA users had preconceived notions about private versus public hearing healthcare. The authors reported that relational competence, including the clinicians’ overall communication manner, was an important component of trust within the patient–audiologist dynamic (Preminger et al., 2015).

Recently, researchers have focussed on enhancing the ecological validity of audiological assessment (Keidser et al., 2020), and the development of tools to effectively explain assessment results to patients (Klyn et al., 2019), with the view of individualising care. Considering these findings, as well as the influence of the patient–audiologist interaction and the importance of ensuring HA services meet the needs of the service users, user perspectives should be explored to proactively adapt service delivery. This study investigated experienced HA users' perspectives of audiological assessments using iterative-inductive thematic analysis based on semi-structured interviews and an online focus group. Interviews focussed on the style of communication during patient–audiologist interactions, including the type of information given to patients by audiologists.

7.3 Methods

7.3.1 Ethical approval

This study was approved by the University College London (UCL) Ethics Committee (project no. 3866/001). Data complied with the General Data Protection Regulation (EU 2016/679). Each participant provided written consent, personal identities were anonymised during transcription and audio recordings were subsequently destroyed.

7.3.2 Recruitment

Experienced HA users (i.e., adults with over four years' experience of regular HA use) with no known neurological conditions were identified through a database of individuals with hearing loss who had volunteered to take part in research studies at the UCL Ear Institute. Experienced HA users were targeted for this study (rather than first-time users) because of their increased exposure to a range of audiology services and clinicians as well as increased awareness of the hearing healthcare pathway. Email invitations were sent to potential participants who had been in contact with their audiology provider within the last 24 months.

Purposive sampling with maximum variation was employed to prioritise enrolment of eligible participants in one-to-one interviews and maximise the diversity of views and experiences (Suri, 2011). Purposive sampling allows the examination of a diverse range of characteristics relevant to hearing aid use. Therefore, in the present study participants were selected non-randomly to maximise the diversity of participants along multiple dimensions (e.g. age, hearing aid experience, health sector). Upon expressing interest, participants completed a demographic questionnaire adapted from Dawes et al. (2014). A sampling matrix was then employed to ensure the inclusion of interviewees with diverse backgrounds (see Appendices 9.9).

7.3.3 Participants

A total of 21 adults with an average of 17 years of HA use participated in this study. Participants for the focus group had previously piloted the SSiN in Chapter 6. Those that completed semi-structured interviews (*n* = 14) had not taken part in any other process within this thesis. Demographics are provided in **Table 7.1** and **7.2**.

Item	Characteristics	Frequency
Age group	18-30	1
	31-40	1
	41-50	2
	51-60	6
	61-70	6
	71-80	2
	81+	3
Sex	Female	12
	Male	9
Level of education	Secondary school	4
	Trade qualification	2
	Diploma	2
	University degree	7
	Post graduate qualification	5
	PhD	1
Work status	Working	11
	Retired	10
Audiology provider	Private	9
	Public	12

Table 7.1 Participant demographics.

Table 7.2 Demographics of all participants. *Hearing ability*: 1 = great difficulty, 100 = no difficulty. *Hearing aid satisfaction*: 1 = very dissatisfied, 100 = very satisfied. *Time since contact with audiology.

Identifier	Sex	Age	Hearing loss	HAs	Years of HA use	Time since contact*	HA provider	Occupation	Educational level	Hours of Ha use/ day	Self-rated unaided hearing ability	Self-rated aided hearing ability	HA satisfaction
AB	M	81	Moderate	Bilateral	17	1 year	Public	Retired	University degree	16	11	89	88
CD	M	59	Moderate	Bilateral	9	2 year	Public	Administrator	Secondary school	16	30	70	20
EF	F	49	Moderate	Bilateral	19	2 months	Private independent	Administrator	University degree	7	50	90	100
GH	F	68	Moderate	Bilateral	8	1 week	Public	Retired teacher	Post graduate	15	64	29	52
IJ	M	68	Mild	Bilateral	4	1 year	Public	Retired	Secondary school	14	60	60	60
KL	F	70	Mild	Bilateral	5	5 months	Public	Retired statistician	Post graduate	16	77	88	83
LM	M	74	Moderate	Bilateral	15	2 months	Public	Retired	Trades qualification	18	30	79	85
NO	F	60	Moderate	Bilateral	30	2 months	Private (Independent) & public	Careers advisor	Post graduate qualification	5-12	5	80	85
PQ	M	65	Mild	Bilateral	5	3 years	Private (National)	Census manager	Post graduate	16	76	96	85
RS	F	36	Mild to profound	Bilateral	35	2 months	Private (Independent) & public	Veterinary nurse	Trades qualification	12-14	1	70	100
TU	F	85	Moderate	Bilateral	8	2 months	Private (National)	Retired lecturer	Diploma	15	60	80	80
WX	M	57	Moderate to severe	Unilateral	37	2 years	Public	Director	University degree	14	10	81	81
YZ	M	76	Severe	Bilateral	66	2 years	Private (Independent) & public	Retired journalist	Diploma	16	1	71	85
QP	F	23	Mild to severe	Bilateral	18	1 month	Public	Audiologist	University degree	14	52	80	90
ON	F	60	Severe	Bilateral	11	3 years	Private (Independent)	Administrator	Secondary school	8	1	80	10
ML	F	43	Moderate	Unilateral	4	1 week	Public	Social worker	University degree	12	6	70	85
LK	M	54	Severe	Bilateral	34	1 month	Private (Independent)	Managing director	University degree	14	1	51	51
JI	M	86	Mild	Bilateral	4	1 month	Private (National)	Retired civil engineer	Post graduate qualification	12	76	100	100
HG	F	55	Mild to moderate	Bilateral	5	1 month	Private&Public	Retired librarian	University degree	12-16	34	24	84
FE	F	62	Severe to profound	Bilateral	16	1 month	Public	Self employed	PhD	16	1	71	92
DC	F	62	Moderate to severe	Bilateral	23	2 years	Public	Retired assistant	Secondary school	15	24	68	60

7.3.4 Procedure

7.3.4.1 Topic guide

This study implemented a semi-structured approach to better understand "participants' experiences, how they describe their experiences, and the meaning they make of those experiences" in an extended conversational format (Rubin & Rubin, 2012). The topic guide was developed based on open-ended questions (e.g., "Describe your experiences of hearing assessment") and follow-up probes (see Appendices 9.7 for the complete topic guide). Once compiled, third-party audiologists and experienced HA users reviewed the topic guide content and interpretability.

The focus group was initially conducted as an explorative process to ensure that the target discussion topics (a) were easily interpretable, (b) aligned with the main research questions and were appropriate for use within the semi-structured interview format (Cyr, 2016). All focus group participants reported good interpretability of questions, and no changes were required prior to inclusion in the semi-structured interviews. Thus, the focus group data was included in the analysis and the topic guide from the focus group was used in all interviews.

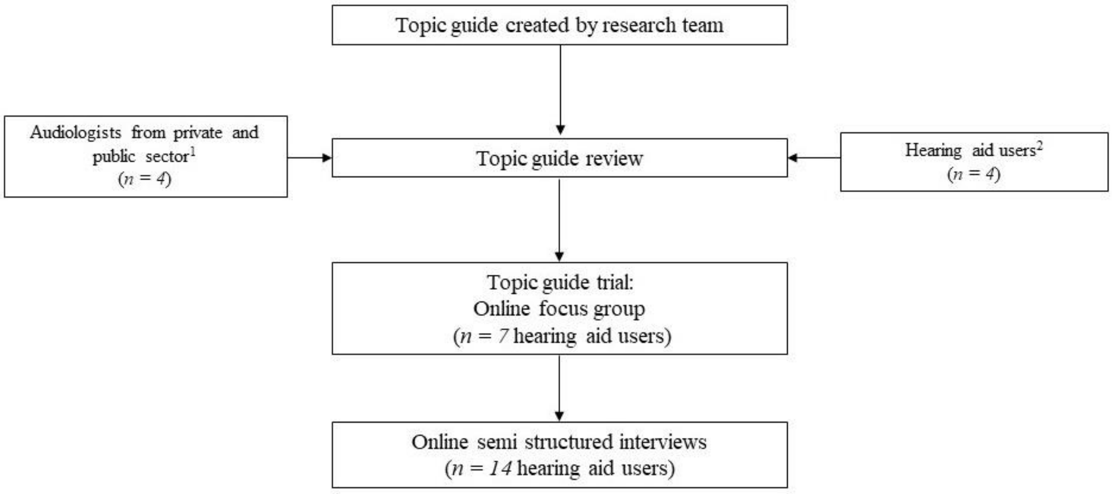


Figure 7.7.1 Topic guide development. ^{1}Audiologists suggested the inclusion of questions regarding the use of aided assessment methods, ^{2}Hearing aid users recommended questions about accessibility and communication experiences within the audiology reception area/waiting area.

7.3.4.2 Online protocol

Focus group and interview sessions were conducted between January and March 2021. The focus group was conducted via Zoom, as all participants had previous experience with this platform, did not require closed captions and were comfortable with the visual gallery layout. Semi-structured interview participants chose their preferred online platform (Zoom or Microsoft Teams) based on their personal communication needs (e.g., closed captioning). All participants were offered a 1:1 trial call prior to the main session to check audio and internet quality.

The interview facilitator (the author) hosted each video call from a professional setting within their own home. Participants took part in the online video conference from their homes and were encouraged to sit in a well-lit room with minimal background noise. Participants wore their HAs throughout the video call and chose to use headsets, Bluetooth streamers or loudspeakers based on their communication needs. The virtual waiting room was open one hour before each scheduled call to allow for audio and Bluetooth connection testing.

7.3.4.2.1 Focus group

Focus groups of six to ten participants are generally optimal for ensuring all individuals are able to contribute and provide a range of views without being led by the consensus of a larger group (Morgan, 1998). The nature of the online video conference environment also impacts group facilitation and communication considerably, particularly for people with hearing difficulties (Dawes et al., 2014). Thus, the focus group was limited to seven participants and lasted 90 minutes. Participants were encouraged to use a laptop or tablet (rather than a smartphone) and keep their cameras switched on in gallery view to optimise audibility and access the nonverbal cues.

Specific instructions were provided prior to the focus group session time to optimise communication and best replicate the interactive nature of in-person focus groups (see Appendices 9.8.1). During the session, all participants' microphones were muted. Participants were able to unmute if they wanted to join the discussion; focus group members were asked to raise their hand (either physically or by using a virtual signalling feature within the video conferencing software) to indicate they would like to contribute to the discussion.

7.3.4.2.2 Semi-structured interviews

Due to the one-to-one nature of the semi-structured interviews, participants were able to use their preferred communication device (including smartphones); all parties kept their cameras and microphones switched on for the duration of the interview. On average, each interview session took 46 minutes (range: 35–58 minutes). To avoid fatigue, the facilitator ensured interviews did not exceed the maximum allotted time of one hour (Adams, 2015).

7.3.5 Data analysis

Iterative inductive thematic analysis with a descriptive phenomenological approach was used to identify, analyse and report patterns within the data (Braun & Clarke, 2006). The thematic analysis also utilised a descriptive approach with a focus on lived experience.

Inductive (bottom-up) thematic analysis was implemented by the first two authors, with coded data organised into general themes centring around experiences during audiology appointments and patient–audiologist communication. A saturation point was reached after inductive coding of the 11th interview (participant PQ) and was confirmed by conducting three additional interviews for which no new themes emerged. The author and a second member of the research team (research audiologist) double-coded 25% of the transcripts and any discrepancies were resolved at two separate time points within the study. Coding and themes were compared to triangulate analysis.

7.4 Results

7.4.1 Experience of hearing assessment

Here, participants focussed on their recent audiology hearing assessment experiences. Two themes were identified: (a) testing procedure and (b) relating tests to real world hearing difficulties.

7.4.1.1 Testing procedure

Participants described their experiences undergoing pure tone audiometry, including aspects of the patient–audiologist interaction and certain testing instructions that helped them feel more comfortable.

> Something that really stood out in my mind, no matter how faint the noise is that it's just as important as the louder ones. Now in the past I remember I've sat there thinking can I hear that?…This time I was really determined that I was gonna press it if it was there was even a quiet sound. (LK, 54-year-old male, private sector)

Some participants mentioned completing speech testing during audiology assessments and reported the value of understanding the benefits of their HAs when switching between aided and unaided testing.

> It made me realise what I couldn't hear, because he did a test first of all without my hearing aids in and then he read the words again in a different order with my hearing aids in and it made me understand what letter sounds that I couldn't hear, what I was mixing up. That was very useful from a self-awareness point of view. (HG, 55-year-old female, private and public sector)

> And then I went private and he kind of explained to me, this is how it works in terms of picking up speech and really emphasised on speech in testing. And I was able to really kind of understand what I couldn't hear and why I couldn't hear certain sounds in relation to my hearing loss. So, it's really interesting. (RS, 36-year-old female, private sector)

7.4.1.2 Relating tests to real world hearing difficulties

Participants described the experience of aided assessment once new HAs had been fitted or existing HAs had been adjusted, with a variety of aided testing techniques (e.g., speech perception testing or presentation of distractor stimuli). However, participants reported that audiologists tended to ask about their opinions of the HA sound quality rather than performing aided assessments or using outcome measures.

> They ask: "How does that sound?" and "Are you comfortable with that?" and yeah that's usually how it's done. (WX, 57-year-old male, public sector)

The benefits and challenges of replicating externally valid situations in a controlled clinical environment were discussed in detail. For example, the limitation of conducting HA fittings in a quiet room was emphasised, as was the benefit of using speakers to play background noise to simulate noisy environments. When realistic sounds and background noise were used within the audiology assessment, participants reported feeling more confident wearing their HAs outside of the clinic and expressed a reduced need to return to the clinic for adjustments.

> And I think it gives you confidence to know that you can pick up certain speech with the hearing aids you've got, kind of the reassurance to know I can still pick up speech. (RS, 36-year-old female, private sector)

However, other respondents indicated that a simulated environment was still unrealistic compared to everyday challenging listening situations.

> They would test different noises and then I'll put one [hearing aid] in and the other one in to see how it felt and their voice as they were speaking to me, but it's not a good test of the real world to be honest because of course you know my perfect world isn't one of being quiet without background noise. That's not how we hear. (ML, 43-year-old female, public sector)

Some participants noted that it would be beneficial to record their listening difficulties in environments they regularly experience (e.g., home, work) or have a trial period wearing HAs outside the clinic with the option of providing immediate feedback.

> I can hear you in a completely silent room, but as soon I walk out the door it isn't right. So, the advantage and it's not perfect, but you can actually have the audiologist or receptionist or someone random person that happens to be in the building, come in and they can have a conversation while you've got music or street sounds on, so it gives you a much better idea because they can tweak it while you're there. (ON, 60-year-old female, private sector)

> I've had the thing that mimics restaurants. If only they could come with me or if only they could just come with me and tell me about the street, or come to work with me. (LK, 54-year-old-male, private sector)

> You've got all the other kind of speakers that generate all sorts of background noise so that you can try them in background noise and then you can wander out in the street in them for a few minutes and come back. (NO, 60-year-old female, private and public sector)

7.4.2 Patient–audiologist communication

Participants discussed their experiences within specific scenarios they had encountered or related to communication techniques they hoped audiologists would incorporate in future meetings. Three themes were identified: (a) importance of communication strategies, (b) explanation of test results and (c) patient-centred care. Participants felt that the lack of individualised care and inadequate communication strategies amongst practitioners negatively impacted their experiences.

7.4.2.1 Importance of communication strategies

First, participants emphasised the importance of professional development training regarding communication skills and deaf awareness for all audiology staff, including receptionists. Participants also recounted specific situations where audiologists had not used adequate communication skills (e.g., conducting clinical questionnaires when the patient was not wearing their HAs) and indicated that some healthcare professionals did not seem to be aware of the communication barriers people with HAs face.

> I've had it where I've had my impressions taken, they've filled my ears obviously with the putty and start talking to me and I've not looked at them. And then it's kind of… I laugh about it. Quite often I'm one of those I kind of brush things off quite a lot. (QP, 23-year-old female, public sector)

> I mean many times I've been sat there unaided, with the audiologist talking to me, turning around to put the tube in and I think don't you know…you of all people must know I can't hear a thing you're saying. It's just annoying. (WX, 57-year-old male, public sector)

> Some audiologists really have…very minimal experience of working with patients like myself, with the type of hearing loss that I have. One had a tendency to over-pronounce and I said you don't need to speak to me like I'm a 5-year-old. (RS, 36-year-old female, private sector)

> And the audiologist is clearly checking setting your hearing aids against whatever's on the computer. And if you felt like they were concentrating on something, and then you had a question…. Would you feel comfortable to ask it? (AB, 81-year-old male, public sector)

To better understand the firsthand experience of hearing loss and the perspective of their patients, experienced HA users suggested audiologists should spend time with temporary simulated hearing loss (e.g., ear plugs). They also stressed the importance of having working loop systems and visual displays in the reception areas to alert patients:

> The first thing I would do is I would arrange for them to have a week with earplugs in. Just so they would appreciate what people who can't hear are up against. It happens every time when I don't have the aids in my ears because they're adjusting them and they try and speak to me, I do that [points to ear], and they realise I can't hear them. (WX, 57-year-old male, public sector)

> Somebody with really good deaf awareness that faces you when they speak, they explain what they're going to do before they do it, they're not somebody that just comes and says right sit in that booth, I'll put these on, press the button when you hear something. (HG, 55-year-old female, private and public sector) Finally, some participants reported positive experiences involving being treated by audiologists with hearing loss. In these cases, they felt audiologists had an enhanced awareness of the impact of hearing loss and a unique ability to relate to the hearing difficulties experienced by patients.

> I think possibly if more deaf people were involved in audiology, not just one deaf audiologist, but if more people, more deaf people were involved all the way through then there might be some changes. (FE, 62-year-old female, public sector)

> My audiologist was deaf, and it was quite an experience. I knew that the person had really good understanding, really good deaf awareness because not all audiologists that I've seen have a good deaf awareness. (HG, 55-year-old female, private and public sector)

In addition, some participants reported communication barriers in the waiting area and with administrative staff.

> In the reception I feel like…do I really have to tell you that I'm deaf? I would've thought in this environment this is somewhere where I'm safe, you know where I'm with like-minded people and I don't have to explain myself. (LK, 54-year-old male, private sector)

> There's a big waiting room, the audiologist calls my number and then they walked away and didn't have a chance to see the lip reading or anything. (LM, 74-year-old male, public sector)

7.4.2.2 Explanation of test results

Participants explained their general understanding of audiometry results and they reported engaging in varying levels of explanation with audiologists when interpreting test results. Some respondents felt their audiologist's description was sufficient for their needs and trusted the audiologist's judgement without requiring additional detail. Others, however, were not shown the audiogram and felt they would have benefitted from more information. Some participants felt audiologists assumed audiograms had been explained to the patient in-depth at an earlier date because they were long-term HA users and thus were comfortable reporting when there were no significant changes to hearing thresholds, even if the patient was unfamiliar with audiogram reports.

> I mean it appears on the screen and I sort of look vaguely at the screen but not with great interest, I trust, I trust her. (TU, 85-year-old female, private sector)

> My audiologist just said something like, well there's not much change. (CD, 59-year-old male, public sector)

> Because when they do the testing, they didn't tell me the results of the testing, of how beneficial my hearing aids actually were. I just felt like I had this massive gap in my knowledge and my understanding of my hearing and it's my hearing, it's mine, no-one else's. (RS, 36-year-old female, private sector)

HA users who received a more thorough explanation reported more benefits in linking pure tone thresholds with relatable sounds in their everyday environments. Moreover, participants felt the process of linking audiogram results to everyday sounds gave them a better understanding of why they could not hear certain sounds in their daily life and helped them feel more confident in relaying results to communication partners. Many respondents felt they would have benefited from being given a copy of their audiogram results to monitor the progression of their hearing loss and consolidate their knowledge outside the clinic.

> They say there has not been much change and it's like well actually I want more information than that because my hearing's really important to me. It is about understanding how to interpret an audiogram for one. Oh yes, oh this is why I can't hear these sounds that I know.… It can give me more confidence. (RS, 36-year-old female, private sector)

> My graph, it's my hearing, I always get a copy. I've got a copy of nearly every test I've done. If I'm not offered it, I get offended. I want a copy. (NO, 60-year-old female, private and public sector)
>
> When it was explained from my graph that the low frequencies were the ones that I was missing which is why I find men more difficult to hear often because they've got lower voices or deeper tones and that sort of, it was almost like a little bit of a jigsaw puzzle going oh, that's why I can't hear speech. (HG, 55-year-old female, private and public sector)

7.4.2.3 Patient-centred care

Participants shared individualised care experiences within audiology services and recommendations for improvements in this area. A primary suggestion was to include more specific, personalised questioning within the assessment—especially regarding the impact of hearing loss on employment, education, leisure and home life—so audiologists could provide or recommend suitable intervention options.

> And so, the impression I get from audiologists is they think my lifestyle is just like an old person's lifestyle and it isn't. Every patient is different and that's really crucial to the advice they can give as an audiologist. (RS, 36-year-old female, private and public sector)
>
> Just with having one conversation she really got it, straight away, she saw how upset I was and understood about the impact it has, because that's it isn't it, it's not just oh you know you have a bit of trouble with the phone, it's like well that impacts on everything. So, I think the wider issues that hearing loss brings, not just to my identity, to how I fit in with you know my relationships, going out—everything. (ML, 43-year-old female, public sector)

Given that HA services have high technical demands, participants felt audiologists need to balance optimising HA technology (e.g., performing real ear measurements) with patient communication. This could help services become more patient-focussed (rather than technology- or clinician-focussed). Other experienced HA users wanted to know more about the technological capabilities of their HAs and additional devices that could be beneficial for managing hearing difficulties at home or at work.

> My audiologist made me feel that he was committed to my needs, my specific ones. With a lot of audiologists, it's about right "let's give you technology", but my audiologist knows my needs above the hearing aids are really important. And I know that if things weren't right, I could ring and he'd get me in tomorrow. You know that's the big difference (LK, 54-year-old male, private sector)
>
> It was more about the hearing aids than the person with the hearing loss. And it shouldn't be. (HG, 55-year-old female, private and public sector)

Experienced HA users also commented on the impact of clinician continuity in HA services. Some participants felt it was vital to see the same clinician at each appointment because they had taken time to build the rapport and trust. However, others felt that it was not as important whether there was a significant amount of time between appointments.

> You have a relationship and I think that relationship and trust is really important. I realise it's not always possible to see the same person, but I think if it can be done it's important. (LK, 54-year-old male, private sector)

> Seeing the same audiologist is hugely important, and it's taken me a while to find the right person. I've been through so many audiologists. (NO, 60-year-old female, private and public sector)

> I don't think it makes any difference, you only see somebody once every three years you know, it's not personal in any way. (FE, 60-year-old female, public sector)

Finally, HA users reported time constraints within the audiology consultation as a notable barrier to patient-centred care.

> I've only been in one time, where someone has actually taken the time to go into detail. Where they ask how the hearing aid sounds, and really listen to the answer to suggest alternative settings. Apart from that, it's always been once we've gone through the test, they ask are these settings and if any problems, give us a call. They don't get time to get to know you. (CD, 59-year-old male, public sector)

> I think with the public sector the biggest learning curve was to ask a lot more questions. I would say to anybody going to an audiologist. ask them questions, tell them what you need your hearing aids for, what's most important to you. From a private provider they actually do that because you know you've got your nice hour-long appointment to have a chat and develop a professional relationship. I think it's really important. (HG, 55-year-old female, private and public sector)

7.5 Discussion

To ensure HA services meet the needs of service users, a greater understanding of user experiences and proactive adaptation to service delivery is necessary. To address this issue, this chapter used an online focus group and semi-structured interviews to highlight elements of the audiology assessment process and communication that experienced HA users value.

Adults with hearing loss have previously reported that audiologists were not aware of their communication needs, and instead used "information dumping with a script like approach" (Watermeyer et al., 2015b). Accordingly, patients may have poor recall and a limited understanding of technical information related to the nature, degree, and severity of hearing loss. Some evidence-based recommendations are available for audiologists to improve their reporting and communication skills at the initial audiology appointment (Grenness et al., 2015; Watermeyer et al., 2015b), but there are currently no national or international standards. This study adds to the current body of knowledge by confirming that HA users are exposed to various communication styles during audiology consultations. Many experienced HA users preferred receiving clear, relatable explanations of pure tone audiometry results from their audiologists that could be easily related to real world sounds. Despite a lack of consensus regarding whether and how the audiogram should be explained to patients in detail, evidence-based tools could help audiologists discuss test results with patients, with a focus on the functional impact of hearing loss (Bundesen, 2021).

Beyond audiometry, interviewees reported having minimal experience with formal aided and unaided functional hearing assessments, including the use of speech or background noise. Instead, audiologists tend to rely on patients' self-reports to determine HA sound quality within the consultation room, thus limiting ecological validity relating to everyday environments. Some HA users felt it would be beneficial to keep track of HA sound quality across a range of real scenarios (e.g., sound quality diary). However, an extended period between audiology appointments, particularly within the public sector, would mean that such feedback may not be considered in a timely manner. The use of remote care and ecological momentary assessment (a method to track a phenomenon of interest in someone's natural environment) could provide a solution to increasing responsivity to feedback in audiology and accommodating time-sensitive adjustments (Convery et al., 2020; Jenstad et al., 2021).

Hearing loss can negatively impact communication and participation in activities (Meyer et al., 2016); thus, it is not surprising that many experienced HA users in this study preferred audiologists asking personalised questions to individualise audiology assessment and rehabilitation. The World Health Organisation's International Classification of Functioning, Disability and Health (ICF) model has been applied within the hearing healthcare context to recognise that hearing loss is not defined solely by the status of the objective bodily function, but also influenced by factors involving the individual within specific contexts (Lind et al., 2016). Implementation of self-report questionnaires and HA validation measures can help promote a patient-focussed rehabilitation process (Hickson & Scarinci, 2007). However, researchers have noted a lack of consensus regarding the optimal outcome measures to use in audiology practice (Granberg et al., 2014). The Brief ICF Core Set for Hearing Loss provides a minimum standard for the assessment of functioning in adults with hearing loss. As such, its use in clinical practice may allow for a more holistic approach to audiological assessment (Karlsson et al., 2021; van Leeuwen et al., 2020).

By definition, patients presenting at an audiology department will likely have some form of hearing difficulty. Therefore, it is imperative that audiology environments are as accessible as possible. However, a recent survey revealed that assistive communication devices were only available in 64% of audiology reception areas (Jama et al., 2020). This study presents specific communication barriers that HA users experienced, including poor communication accommodations for patients and time constraints within public audiology services limiting adequate care and communication. Interviewees felt all audiology staff should participate in ongoing professional training regarding communication strategies, deaf awareness and simulated hearing loss to better understand and empathize with the communication barriers that patients encounter. Moving forward, it could be beneficial to involve patients in audiology service development and evaluation to improve accessibility for patients with hearing loss. Beyond audiology, it is important to explore the deaf awareness in a range of health services and the access to healthcare for those with hearing loss. A large-scale survey of service users could identify key barriers. Such evidence would help distribute the necessary recourses to improve accessibility. This is particularly relevant in the NHS where accessibility, personalised care and tackling health inequalities are featured in the long term strategy plan (Alderwick & Dixon, 2019).

The financing and distribution of HAs vary globally; some countries offer universal or selective public insurance for HA services (e.g., Australia, UK), whilst others rely solely on private insurance or out-of-pocket payments (e.g. US, Japan; Yong et al., 2019). Experienced HA users who had received public-sector care reported that the lack of individualised care and limited availability of tests and assessment tools were most likely due to time and resource constraints. Additional services available in the private sector are also likely associated with the commercial nature of private-sector provision. Further evidence is needed to better understand which assessment and rehabilitation tools add value to long-term HA users' experience of audiology services, technology uptake and understanding of diagnostic testing results.

Researchers have indicated that audiologists tend to focus on technological aspects rather than considering how HAs address activity limitations and participation restrictions (Meyer et al., 2017). This study also acknowledges the presence of sophisticated technical equipment within audiology services: experienced HA users felt it would be beneficial to have a better balance between technology and patient factors during consultations. This finding can be considered in two ways. First, there is a need to offset the technical diagnostic measures or HA verification methods (e.g., real ear measurements) with personalised patient interaction. These beliefs are in line with a recent report indicating HA users were interested in learning more about the technical process during the clinic session (Ryall et al., 2021), from which the authors provided suggestions to help audiologists make such information accessible. Second, participants felt individualised questioning would help audiologists better understand patients' specific needs and expectations, with the goal of matching patients to technology suitable to their lifestyle. Notably, this study suggests that clinician continuity could help improve patient–clinician rapport and trust within HA services, although an association between clinician continuity and HA outcomes has yet to be established (Bennett et al., 2016). Collectively, this study aligns with an operationalised, patient-centred audiology rehabilitation model (Grenness et al., 2014a), highlighting the need to focus on the patient–clinician relationship, adequately informing and involving patients in results interpretation and individualising care.

Because hearing loss and the onset of HA use are most common in older adults (aged 65+; Barker et al., 2020), most research evaluating audiology service provision has focussed on the outcomes and experiences of older adults. In contrast, a strength of this study is the inclusion of younger HA users and participants with recent audiology service experiences in both the private and public sectors. This diversity permits a rich understanding of audiology experiences for a more heterogeneous and representative group of patients and acknowledges the needs of younger individuals with hearing loss. The diversity within participants' service providers also helps facilitate the comparison of results between countries. The implementation and detailed description of online techniques and accommodations for conducting semi-structured interviews and focus groups with HA users is a further strength of this study. These methods are applicable across a range of applications and such strategies will be beneficial for future studies involving special populations or in-person restrictions. A primary limitation of this study is that ethnicity and socioeconomic status characteristics were not recorded; such factors influence access to health services and could be considered within future research. Also, the participant group was skewed towards more highly educated (degree level and higher) respondents.

7.5.1 Reflexivity statement

Reflexivity is a vital part of qualitative research and is the way researchers acknowledge how research processes may shape the research outcomes (Hardy et al., 2001). Here, a reflexivity statement helps demonstrate how the author has considered any impact they, as a researcher, had on the research process (Newton et al., 2012). Reflexivity helps enhance "the credibility of the findings by accounting for researcher's values, beliefs, knowledge and biases" (Cutcliffe, 2003, p. 137).

I used an ongoing reflexivity approach during initial project planning, data collection, group analysis and kept fieldnotes to reflect on the research process, personal feelings and biases that may have influenced findings. Whilst creating participant recruitment materials (e.g. posters and social media posts), I did not specify that the lead researcher was also an audiologist. Also, statements on the advertising materials did not mention specific questions from the topic guide in order to avoid any bias within the recruitment stage. Once recruited, participants were made aware of my role as a practicing audiologist and PhD candidate, but they were not aware of my clinical practice location or specialist area.

My field notes included descriptions of what happened during the data collection process, including comments about participants' body language. Subjective researcher observations were added to these notes to capture any emotions evoked or provide comparative comments between participants.

My role as an audiologist allowed me to approach this chapter with knowledge of the subject area and prior clinical knowledge of patient experiences. However, my role also affected the way some participants interacted with me. Sometimes such interactions were positive as participants were open to discussing these matters with a clinical professional and some were pleased to see audiologists engaging in such patient-involved research. On the other hand, participants often assumed I knew the context behind their statements and sometimes shortened their sentences or used abbreviations to convey their messages. Therefore, I had to be more alert and aware of how my presence shaped the conversation. For example, when participant AB was asked about the communication practices in experienced in audiology the following fieldnotes were recorded:

> *AB smiles a lot before answering the question. Seems to shrug his shoulders first and make a facial expression before attempting to answer the question—not sure whether this is because he might feel uncomfortable speaking freely to an audiologist if his experiences were negative. I decide to repeat the question slightly differently and leaving a longer pause to help him feel more comfortable in expressing his thoughts. Leaving a longer pause seemed to give him more space and then he answered freely. His comments were in fact negative about deaf awareness in audiology, and he finished his statement with "sorry, I know you're an audiologist, but it's important to tell you the real story*".

Reflecting on these field notes helped me adapt and refine the data collection process accordingly. Field notes were also kept during the coding stage. The following excerpt is taken from my field notes completed during data analysis:

Line by line coding from the text transcript can be tricky as I remember the emotion in the participants voice but the words they used doesn't seem to be as emotive. Also, some of the terms this participant uses seem shortened because they I know I am an audiologist and perhaps they think I can fill in the gaps for them. For the next interview I should ask them to complete such statements to avoid mis interpretation. For this interview the shortened comment was a side comment and not specifically relevant to my question: "they [hearing aids] make an awful noise, but that test—you know the beep one—does not help with that."

Therefore, future work could include the coding of subjects' body language, gestures, tone of voice, abbreviations and mis-interpretations, to create a more complete picture of the experiences (Murray & Holmes, 2014). Coding nonverbal cues may be of particular importance when working with deaf participants in future as they may rely more on gesturing to relay their messages clearly. On reflection, understanding some of the practical implications of coding nonverbal behaviours during clinical interactions could inform future work in this area and customise communication interventions (Blanch-Hartigan et al., 2018).

Although the participants and I had a mutual audiology-specific knowledge base, I have not had experience of having hearing loss or using hearing aids. There was also a patient–clinician power difference and participants knew I was a practicing audiologist. Studying human phenomena where the researcher does not have experience may also shape outcomes and be a barrier to identifying subtle expressions (Berger, 2015). Consultation with others in the research group, other audiologists, and audiology service users, helped me review my own position and opinions to ensure I could best convey what the participants were saying, rather than rely on what I thought and believed. Also, future interviews in this area could be led by an interviewer who is not a professional audiologist to avoid potential bias. However, I felt it was important to follow some important steps to help alleviate the effects of bias: a) using methods of reflexivity (e.g. including use of a reflexivity diary), b) attending formal interviewing training and c) piloting the interview guide.

7.6 Conclusion

To ensure that HA services meet the needs of the service users, it is important to explore user perspectives and proactively adapt service delivery, whilst maintaining cost-effective, quality services. Within audiology, experienced HA users' value (a) comprehensive, relatable hearing assessments; (b) clear, concise, deaf aware patient–audiologist communication; (c) accessible services and (d) a personalised approach to recommend suitable technology and address patient-specific aspects of hearing loss.

Chapter 8: General Discussion

8.1 Context and Conclusions

The aims of work presented in this thesis were to advance the understanding of how speech testing is, and can be, used for hearing device users within the audiological test battery. This included an exploration of how speech testing was currently being carried out for adult patients attending audiology clinics in the UK and the development of a more complex test design, the Spatial Speech in Noise Test, to assess the relative localisation and word identification performance of listeners as well as an evaluation of its use for participants with normal hearing and bilateral hearing aids.

The three core contributions of this thesis are 1) unveiling of the distinct inconsistency in speech testing practices in the UK, 2) the introduction of a new relative localisation and word identification task that can be adapted for audiological clinical practice and 3) the consideration of hearing aid users' experience of the use of speech within audiology assessment. The inclusion of clinicians' views and practices as well as patients' experiences throughout this thesis offers a holistic approach to the development of clinical tools, like the SSiN, to ensure important aspects surrounding service provision and context are acknowledged.

Recent UK health policy and strategy documents recognise the benefit of personalised care and the need for patient-centred healthcare (National Health Service England, 2019; NHS England Department of Health and Social Care, 2021) This need is echoed by the findings of this thesis. Firstly, through an online survey, hearing healthcare professionals highlighted the use of speech testing tools to explore the needs of patients and identify appropriate intervention options (Chapter 3). Also, in Chapter 7, experienced hearing aid users completed an online focus group and semi-structured interviews and reported appreciating the use of personalised questioning and assessments that reflected their individual listening difficulties. They also recognised the value of effective patient–audiologist communication and identified the lack of deaf awareness in audiology practice. This finding is aligned with recent literature from the audiology setting (Hulme et al., 2021). The lack of deaf awareness and clinicians' use of ineffective communication strategies for patients with hearing loss has also been identified in other UK healthcare contexts over the years (Gilmore et al., 2019; Heron & Wharrad, 2000; Hines, 2000; Middleton et al., 2010; Reeves & Kokoruwe, 2009;

Roper, 1995; Ubido et al., 2002). Recommendations from these studies have included: a) creating a toolkit for health professionals, b) ongoing deaf awareness training among junior doctors, c) greater provision of on-call specialised sign language interpreters and d) adding visual displays to waiting areas. The present findings reiterate these suggestions and raise the following additional audiology-specific recommendations: 1) healthcare professionals should experience (temporary) hearing loss simulations (e.g. use of ear plugs) during training and/or professional development to better understand audiology patients' experiences, 2) audiology professionals should be mindful alternative communication strategies when patients are unaided (e.g., when taking ear impressions), 3) ensure functional loop/telecoil systems are present, and 4) involve more people with hearing loss in audiology service provision and development.

Audiological assessment tools and amplification devices are rapidly advancing, and yet the core diagnostic hearing assessment, pure tone audiometry, remains at the heart of clinical assessment. However, the identification of pure tone stimuli in quiet environments differs from the speech-in-noise focussed nature of everyday communication. Despite a plethora of speech perception assessment methods, their use in UK adult audiology was largely unknown, until now. Chapter 3 of this thesis narrows the gap in the literature through the development and implementation of an online questionnaire to investigate the use of speech testing in UK audiology practice (*n* = 295). This research is the first to highlight how speech stimuli is underutilised in the audiological test battery for adult patients in the UK, compared to other countries. This study also found that private sector hearing healthcare professionals use speech perception testing significantly more than public sector clinicians. Overall, the key barriers to speech testing uptake appear to be the lack of clinical time, equipment and training. Three key themes pertaining to the benefits of speech testing were also unveiled by hearing healthcare professionals: 1) speech testing is helpful during patient counselling, 2) speech testing is useful when adjusting hearing aid settings, 3) speech testing is valuable as a diagnostic tool. Due to the inconsistency of service provision observed, it would be beneficial to create an accessible evidence base of validated speech test materials and practical guidance for hearing healthcare trainees and professionals. The inclusion of speech testing within national clinical guidance could help shift the distribution of clinical resources to allow for such activity.

Real-world listening scenarios can be complex and cognitively demanding. In such situations, localisation and speech discrimination abilities are critical for safety and communication. The importance of localisation cues and speech discrimination, and the observed benefits of speech perception testing was reported earlier in this thesis (Chapter 2). Chapter 4 described the step-by-step development of a simultaneous test of relative localisation and word identification (the Spatial Speech in Noise Test (SSiN)), based on the work by Bizley and colleagues (2015). The test paradigm is detailed alongside the empirical evaluation of this methodology in adults with normal hearing and bilateral hearing aid users. The goal of the SSiN is to provide a useful spatial hearing assessment that reflects the challenges of real-world listening scenarios. Therefore, the SSiN method has been refined throughout the data collection process to enhance ecological validity.

Amendments to the task were also made to adjust for significant floor effects obtained during pilot experiments with hearing aid users despite the seminal study's promising findings when testing participants with normal hearing (Bizley et al 2015). The present methodology was used to compare results from a group of normal hearing adult listeners (*n* = 38) and 22 adult bilateral hearing aid users (Chapter 5). The results found that the HA users could successfully complete the task without the floor effects but they performed significantly poorer than NH listeners. In Chapter 4, normal hearing listeners completed the SSiN by either only providing the single word identification and relative localisation responses as well as doing the task with the intended dual paradigm. Findings suggested that the SSiN dual task increased cognitive load, compared to testing these domains separately. This may better reflect the cognitive effort present in challenging listening situations.

Following an action research approach, the SSiN findings from Chapter 4 and Chapter 5 were shared with hearing aid manufacturers, patients, and researchers to improve ecological validity and suitability to use the task to assess hearing aid features. Feedback from the review led to the increase in the level and duration of background noise to match that of a realistic, busy, speech filled environment—like that of a busy restaurant or classroom. It was also recommended that hearing aid type and completion of hearing aid technical measurements should be accounted for. A subset of hearing aid users (*n* = 6) were then fitted with the same hearing aids to investigate whether the SSiN could be used to assess advanced directionality features (Chapter 6). Reaction time differences between omnidirectional and adaptive directionality were observed, although the small sample size restricted reliable interpretation of the findings. The overall results from Chapter 6 revealed a 2.8% mean word identification performance difference between the two hearing aid features and a sample size calculation was completed to establish the number of participants required to determine whether the results are reliable Power analysis suggests that 66 participants in each condition would be required to reliably depict the group differences seen in word identification performance (87.1% vs 89.9%, SD = 5.7%, Power = 0.80, alpha = 0.05). If a greater performance difference between conditions (5%) was included in power analysis, 21 participants would be required in each condition.

Key themes emerging from an online focus group with these same participants revealed several benefits of the SSiN and some improvement indicators required to improve its future use. For example, hearing aid users felt the task reflected more realistic listening scenarios than those tested in the traditional clinical environment. However, some felt the current task was quite time consuming and tiring.

8.1.1 The future of the SSiN

The current implementation of the SSiN is more cognitively demanding than testing relative localisation and word identification abilities alone and has been adapted to test hearing aid features. and a multi-speaker array. However, the current test duration limits the task's clinical applicability, particularly as the present study found a lack of clinical time in audiology already restricts the uptake of additional diagnostic measures. Currently, work is underway to shift the SSiN onto a virtual platform (Picinali et al., 2019). Use of a virtual SSiN would save clinic space and resources and there is potential for testing outside of the clinic, e.g., teleaudiology. A virtual SSiN will need to be tested on a suitable number of participants to confirm whether the spatial representations can be implemented successfully and whether listeners are able to carry out such methods. Furthermore, a virtual version with sound presented via headphones may not be suitable for testing hearing aid users in the aided condition.

The inclusion of the SSiN in audiology practice, at the assessment or rehabilitation stage, has the potential to add value to patients' experience and understanding of their spatial hearing abilities with and without hearing aids. Results from the SSiN could also help clinicians offer suitable audiological intervention options e.g. unilateral vs bilateral hearing device fitting. The SSiN offers some advantages over other clinical tests of localisation or spatial release from masking. Firstly, the SSiN tests uses more target speech locations, with smaller speaker separations, compared to other assessment methods (e.g LiSN-S (Cameron & Dillon, 2007). Also, it has been developed for use with a loudspeaker array and therefore can be used for aided assessments. SSiN results are reported as percentage correct performance of word identification and relative localisation across speaker location. This reporting method may be easier for patients to understand compared to signal to noise ratio scores reported in other speech tests (Killion et al., 2004). The reaction time and spatial release from masking data also give further insights into listeners' performance in complex environments.

8.2 Integration of Findings

This thesis identified inconsistencies in audiology clinical practice and areas of value for hearing aid users. A spatial hearing assessment tool was developed, and it has the potential to enhance ecological validity of the assessment of hearing aid users. To highlight the need to integrate speech testing, enhanced deaf awareness and patient-centred care into adult audiology, a logic model has been created (**Figure 8.1**). A logic model is a visual representation of potential interventions and anticipated outcomes (Baxter et al., 2014). In health research, evidence has been grouped to create tentative logic models to showcase the mechanisms through which interventions can improve recovery and overall health (Afifi et al., 2011; Allmark et al., 2013; De-Regil et al., 2014; Winsper et al., 2020). **Figure 8.1** shows a tentative logic model produced from this thesis and aims to give a "bigger picture" to integrate findings from the presented experimental chapters. The model starts with inputs/resources needed to undertake proposed activities (e.g., funding for clinical services, involvement from professional bodies, changes to clinical guidance documents); activities consist of several clinical and research actions intended to strengthen speech testing practice and communication in audiology. If the proposed activities are implemented, they could have the stated outcomes and impact, but are dependent on patient and clinician engagement, stakeholder involvement, funding, and long-term adherence. Here, it is expected that the integration of speech testing practices and improvement to communication within routine adult audiology could lead to improved quality of life for audiology patients. To maximise its relevance, the current logic model includes relevant stakeholder input: significant differences between private and public sector speech testing practices in the UK were revealed by hearing healthcare professionals (Chapter 3) and hearing aid users (Chapter 7). Therefore, there is scope to explore whether further research could involve the growing number private sector hearing healthcare professionals to avoid public sector regulative barriers. It is hoped that this logic model can initiate important discussions around the proposed activities and potential outcomes. The tentative process detailed here serves as a malleable model that can be adapted with the advancement of further research in the field.

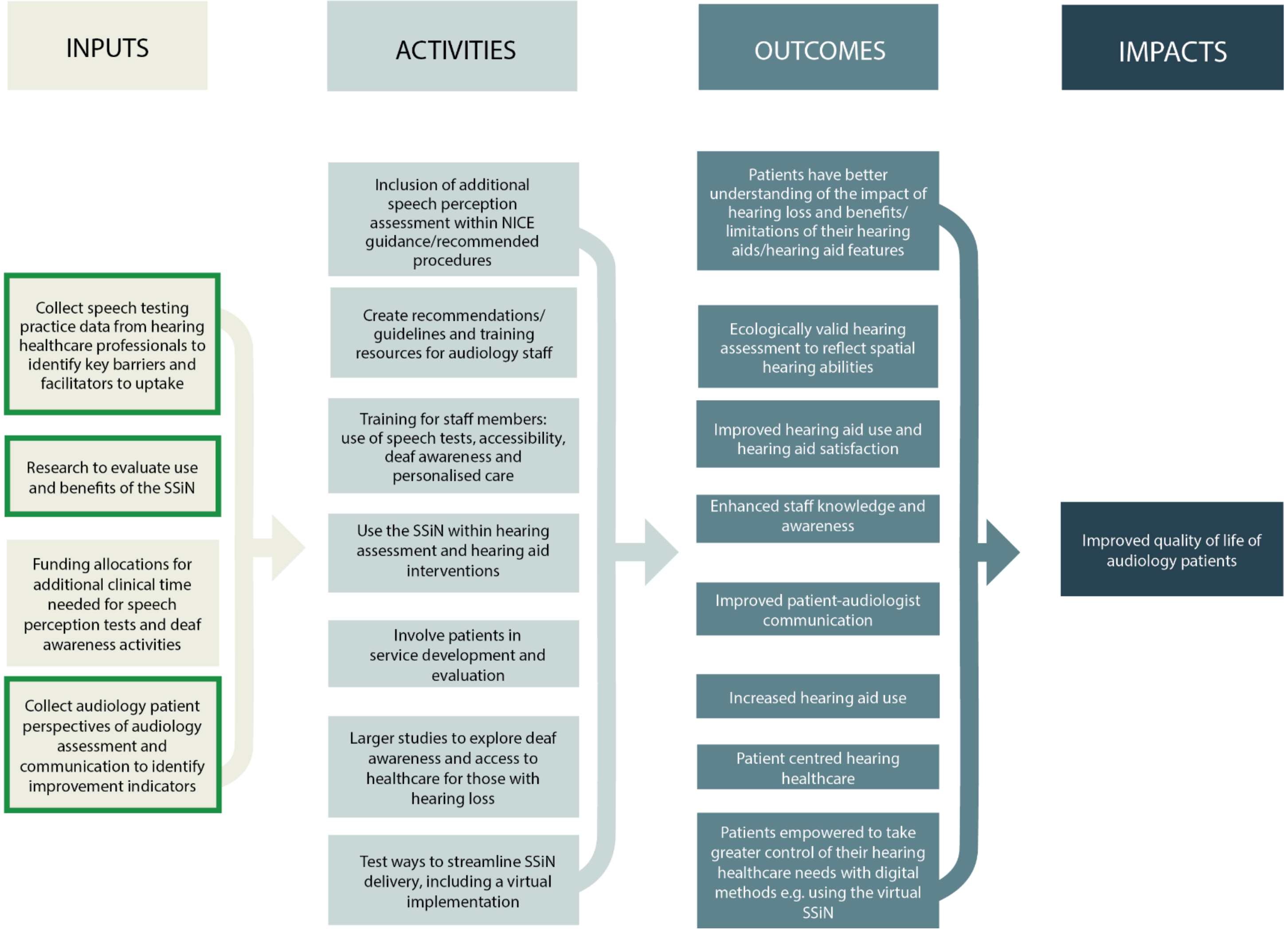


Figure 8.1 Logic model to integrate speech testing and deaf awareness into routine adult audiology services.
[The boxes highlighted with a green outline indicate areas of work already covered in this thesis]

8.3 Ongoing Work

As mentioned in Chapter 6, a larger study to explore the use of the SSiN to assess adaptive directionality was planned but disrupted due to the COVID-19 pandemic. Participants were identified and fitted with the suitable hearing aids in 2019/2020. With the national lockdown restrictions recently lifted, it is hoped that this larger study can be carried out with the appropriate sample size in the near future. To explore the SSiN predictive factors in more detail, participants in this study will complete the SSiN with and without adaptive directionality activated, in addition to cognitive assessments (e.g., working memory, processing speed), subjective ratings of listening effort and clinically available speech in noise tasks.

8.4 Work Extending from This Thesis

The qualitative study presented in Chapter 7 of this thesis has stimulated the development of a national deaf awareness patient survey. The survey has been created by a working group in the UK with representation from audiology professional bodies, patient advocates, clinicians (including the author of this thesis) and national charities. The online survey aims to explore deaf awareness, communication, and accessibility within the NHS. It is hoped that this work can lead to effective, targeted, ongoing strategies to improve healthcare for people with hearing loss.

The SSiN has been converted into a virtual reality version (SSiN-VA) through the BEARS (Both Ears) project funded by the NIHR Programme Grants for Applied Research (https://www.guysandstthomasbrc.nihr.ac.uk/microsites/bears/). The author of this thesis is part of the BEARS team and is currently validating the SSiN-VA against the SSiN version presented in this study. It is anticipated that the SSiN-VA can be adapted and used as a key outcome measure in the proposed multi-site clinical trial to assess the benefit of spatial hearing training games for children with cochlear implants.

8.5 Potential Further Investigations

Longitudinal patient studies investigating the benefits of including additional clinical tools (such as speech testing) within audiology assessments and rehabilitation are needed. This branch of research should include cost-effectiveness analyses; perspectives of clinicians and patients; and objective measures of quality of life, hearing aid use, hearing aid satisfaction, and hearing aid uptake. Clinical service surveys are another useful way to monitor trends in clinical practices if they are carried out at regular intervals. International audiology clinical practice surveys could also be distributed by audiology professional bodies to collect such data. Further investigation into the use of the SSiN for clinical populations and research exploring spatial hearing would add to the body of research presented in this thesis and advance the task’s clinical applicability. If used in clinical practice, suitable training resources would need to be developed and disseminated to clinicians.

Findings from studies of this nature has the potential to inform national and international clinical recommendations and guidance, as well as health funding streams. Questions related to speech testing practice can be adapted from those used in the present study but also incorporating more procedural details (e.g., adaptive vs. fixed levels, types of background noise, aided vs. unaided testing, types of speech stimuli). Overall, future discoveries can help produce training resources for clinicians to improve consistency of care.

8.6 Conclusion

Speech perception testing benefits the audiological assessment procedure from both the clinician’s and patient’s perspectives. However, the is a significant inconsistency of speech testing practice across the UK. Clinical practice guidance could be developed to enhance consistency of speech testing methods and recommend relevant training and resources for HHPs around the world. The inclusion of speech testing within the formal scope of practice for audiologists and within clinical practice guidance could facilitate the allocation of necessary resources for public sector HHPs in the UK and beyond.

This thesis demonstrates preliminary evidence that the Spatial Speech in Noise Test is a complex, demanding task of relative localisation and word identification that can serve as a valuable audiological testing tool for clinical populations. Nonetheless, the SSiN will require ongoing refinements to improve clinical applicability (e.g., reductions in test administration time and equipment requirements).

Importantly, audiology service users’ perspectives and experiences were included in this thesis. Within audiology, experienced hearing aid users’ value comprehensive, relatable hearing assessment, deaf aware patient–audiologist communication, accessible services, and a personalised approach to recommend suitable technology and address patient specific aspects of hearing loss. Applying the findings of this work to audiological clinical contexts can help services understand service users’ needs and ensure services are proactively adapted.

Chapter 9: Appendices

9.1 Author contributions

The author performed the experimental design, data collection, data analysis and interpretation. Data in Chapter 4 was collected in collaboration with MSc student, Dina Budeiri (supervised by the author). Experimental design for the hearing aid output measurements in Chapter 6 was assisted by Acoustics Technicians, Gordon Mills and Sebastien Santurette, using code developed by Gordon Mills. Thematic analysis coding in Chapter 3 and 7 was cross checked by audiology researchers Dr Saima Rajasingam and Dr Kinjal Mehta, respectively.

9.2 Presentations and publications arising from this thesis

Date	**Title**	**Oral/Poster/ Paper**	**Conference/journal/award**	**Location**
Jan 2018	The spatial speech test of real world listening for assessing binaural hearing	Poster	Speech in Noise workshop 2018	Glasgow, UK
Jul 2018	The Spatial Speech test: A new assessment of binaural hearing to guide the fitting of hearing devices	Poster	Improving Cochlear implant performance 2018	London, UK
Jul 2018	The Spatial Speech test: A new assessment of binaural hearing to guide the fitting of hearing devices	Oral	Work in progress talk at Eriksholm Research Centre	Denmark
Aug 2018	The Spatial Speech test: A new assessment of binaural hearing to guide the fitting of hearing devices	Poster	International Hearing Aid Research Conference 2018	Lake Tahoe, USA
Oct 2018	Testing spatial hearing to optimize the fitting of binaural hearing devices: An intro to the Spatial Speech test	Oral	World Congress of Audiology 2018	Cape Town, South Africa
Feb 2019	Testing Hearing in Space	Poster	1st Prize UCL Doctoral School Poster Competition	UCL

Mar 2019	Oticon to contribute hearing aids and technical assistance to use the SSiN to assess the Oticon features	Collaboration		Oticon (Denmark)
Jun 2019	Using the spatial speech test to assess hearing aid users	Poster	British Society of Audiology	Birmingham, UK
Jun 2019	Scholarship: International symposium on auditory and audiological research	Conference Scholarship	ISAAR	Denmark
Jun 2019	UCL Translational Research Office	Industrial Connectivity Award	£23,900 to set up hearing aid fitting clinic in UCL Ear Institute.	
Aug 2019	Using the Spatial Speech Test to compare hearing aid compensation strategies	Poster	International symposium on auditory and audiological research	Nyborg, Denmark
May 2021	Experienced hearing aid user's perspectives of assessment and communication within audiology: A qualitative review using digital methods	Poster	European Federation of Audiology Societies (EFAS)	Online
May 2021	Patterns of speech testing practice in adult audiology: A survey of hearing healthcare professionals in the United Kingdom	Poster	European Federation of Audiology Societies (EFAS)	
May 2021	The impact of COVID-19 on provision of UK audiology services & on attitudes towards delivery of telehealth services	Publication	Bhavisha Parmar, Eldre Beukes & Saima Rajasingam (2021) The impact of COVID-19 on provision of UK audiology services & on attitudes towards delivery of telehealth services,	International Journal of Audiology
Jul 2021	Adult hearing aid users' experiences of assessment and communication within audiology: A qualitative review using digital methods	Poster	Thinking Qualitatively	Online
Oct 2021	A spatial speech in noise test: Assessing the relative localisation and word identification performance of hearing aid users	Poster	British Society of Audiology conference	Sheffield
Oct 2021	Adult Hearing Aid Users' Experiences and Perspectives of Assessment and Communication within Audiology: A Qualitative Study Using Digital Methods	Poster	British Society of Audiology conference	Sheffield

Nov 2021	Audiology patients' perspectives of assessment and communication	Oral Presentation	Irish Audiology CPD Seminar	Online
Nov 2021	Experienced hearing aid users' perspectives of assessment and communication within audiology: a qualitative study using digital methods	Publication	Bhavisha J. Parmar, Kinjal Mehta, Deborah A. Vickers & Jennifer K. Bizley (2021) Experienced hearing aid users' perspectives of assessment and communication within audiology: a qualitative study using digital methods,	International Journal of Audiology
April 2022	Factors affecting use of speech testing in adult audiology	Accepted for publication on 06/04/2022		American Journal of Audiology

9.3 Survey used in Chapter 3: Speech Testing in Adult Audiology (UK)

1) Do you work in an NHS or private sector audiology department? (This survey is only suitable for clinicians working in the UK)

    a. Private sector
    b. NHS (public sector)
    c. Other (please specify)

2) What type of patients do you assess in your clinic?
    a. Adults
    b. Children
    c. Both adults and children

3) When seeing an adult patient in audiology for the first time do you perform any kind of speech perception testing as part of the assessment process?
    a. Never
    b. Rarely
    c. Sometimes
    d. Often
    e. Always

4) If applicable- What type of speech tests do you perform at the first (assessment) appointment?
    a. Speech audiometry (speech recognition threshold)
    b. QuickSIN
    c. LISN-S
    d. AB words
    e. BKB Speech in Noise Test
    f. N/A
    g. Other (please specify)

5) When fitting an adult patient with hearing aids do you perform any kind of speech testing on the day of the fitting or at the follow up appointment?
    a. Never
    b. Rarely
    c. Sometimes
    d. Often
    e. Always

6) If applicable- What type of speech testing do you carry out at the time of hearing aid fitting or follow up?
    a. Speech audiometry (speech recognition threshold)
    b. QuickSIN
    c. LISN-S
    d. AB words
    e. BKB Speech in Noise Test
    f. N/A
    g. Other (please specify)

7) If you perform speech testing, what do you use to present the speech tokens and noise?
    a. Live voice (your own voice rather than through speakers or headphones)
    b. 1 calibrated speaker
    c. 2 calibrated speakers to present speech and noise from separate locations
    d. Multi speaker array to present speech and noise from multiple locations around the patient
    e. Headphones/Inserts
    f. N/A
    g. Other (Please specify)

8) What are your main barriers/challenges to performing speech testing regularly?
    a. I do not have enough time in clinic
    b. I do not have the necessary equipment
    c. I do not see the benefit
    d. I do not have sufficient training
    e. The tests available are not sensitive enough to detect change (e.g. Changes in hearing aid features/programming)
    f. N/A
    g. Other (please specify)

9) What do you think the benefits of using speech testing in routine adult audiology are?

    Free text answer

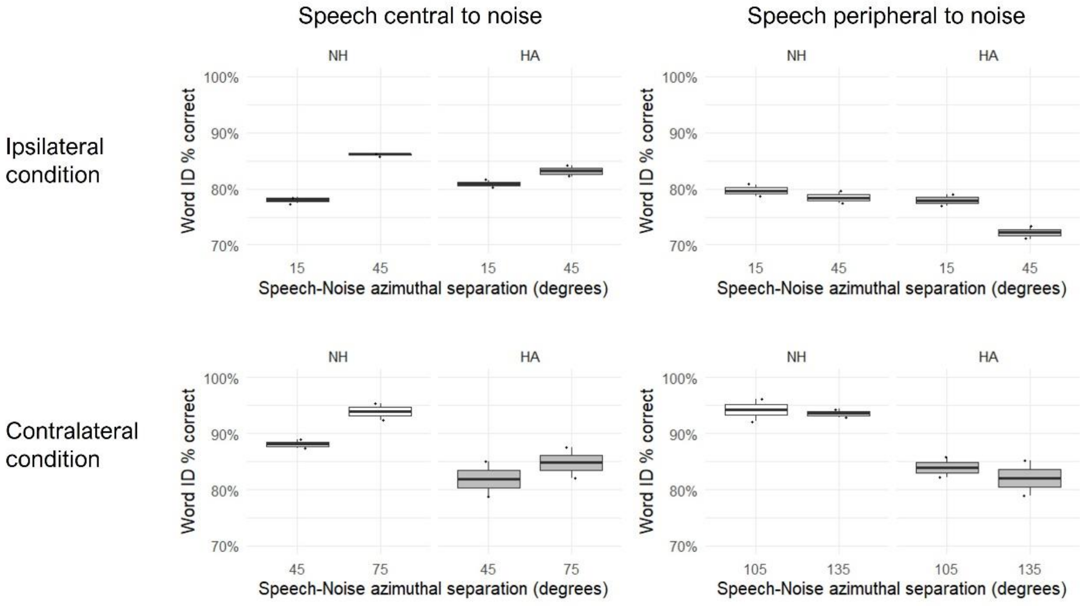
10) Do you perform any tests of localisation for adult patients in your audiology clinic? (this question was removed from analysis as publication focusses on speech testing only)
    a. Yes
    b. No
    c. If yes, please specify the types of tests you perform

11) Please select the geographical location of your workplace from the following options:

a. Scotland
b. Wales
c. Ireland
d. England- Greater London
e. England- South West
f. England- South East
g. England- Midlands
h. England- North West
i. England- North East

12) Do you use any tests to assess sound localisation? Yes / No

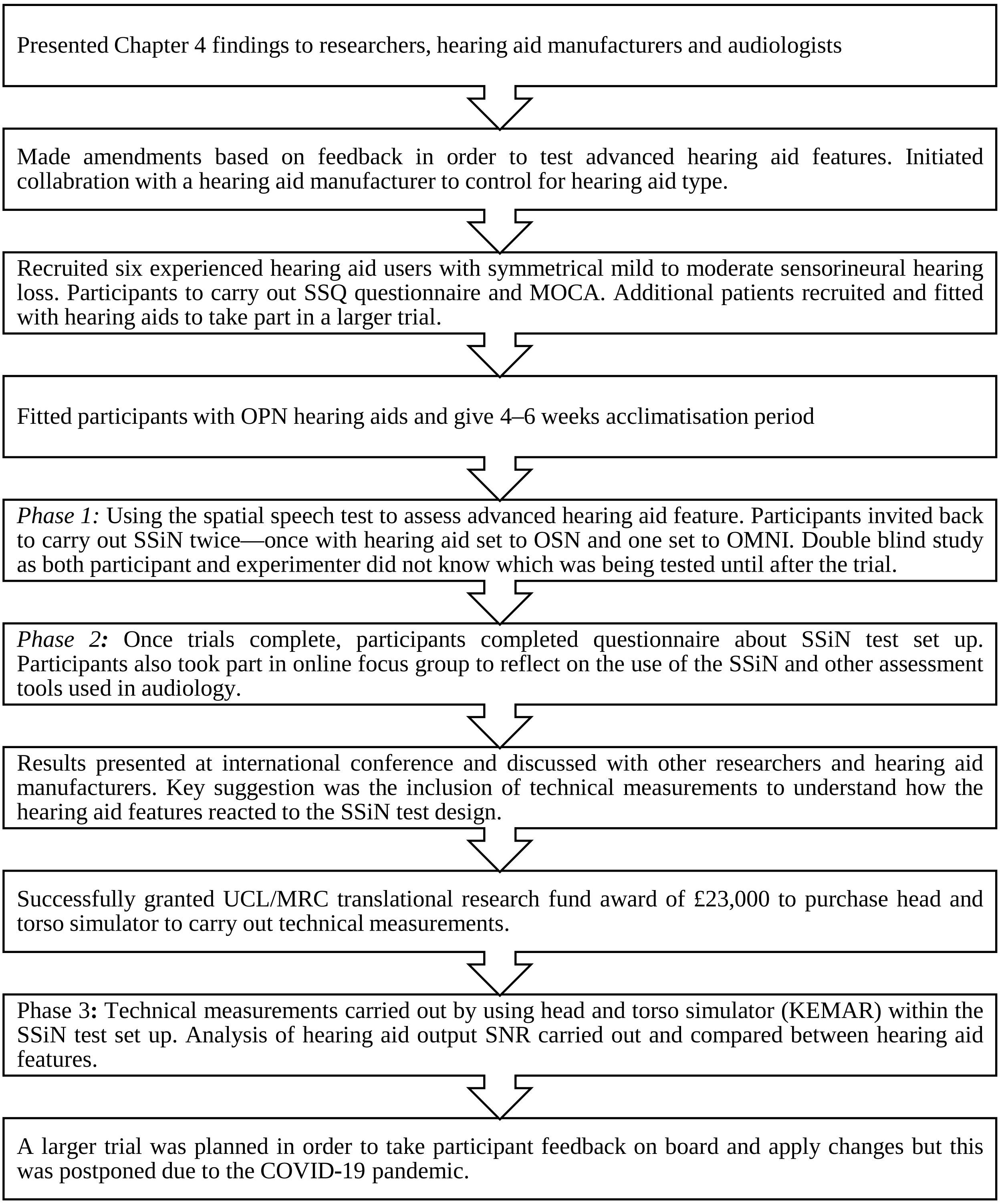
9.4 Effect of speech-noise azimuthal separation on word identification performance when speech was presented centrally or peripherally to the mean noise source location in Chapter 5.



Note: Data shown is from right sided speech presentations only

Figure A.1 Effect of speech-noise azimuthal separation on word identification performance (% correct) for normal hearing listeners and hearing aid users when speech presented centrally or peripherally to the mean noise source location (Chapter 5).

9.5 Summary of steps taken in the action research approach used in Chapter 6



Presented Chapter 4 findings to researchers, hearing aid manufacturers and audiologists

Made amendments based on feedback in order to test advanced hearing aid features. Initiated collabration with a hearing aid manufacturer to control for hearing aid type.

Recruited six experienced hearing aid users with symmetrical mild to moderate sensorineural hearing loss. Participants to carry out SSQ questionnaire and MOCA. Additional patients recruited and fitted with hearing aids to take part in a larger trial.

Fitted participants with OPN hearing aids and give 4–6 weeks acclimatisation period

Phase 1: Using the spatial speech test to assess advanced hearing aid feature. Participants invited back to carry out SSiN twice—once with hearing aid set to OSN and one set to OMNI. Double blind study as both participant and experimenter did not know which was being tested until after the trial.

*Phase 2***:** Once trials complete, participants completed questionnaire about SSiN test set up. Participants also took part in online focus group to reflect on the use of the SSiN and other assessment tools used in audiology.

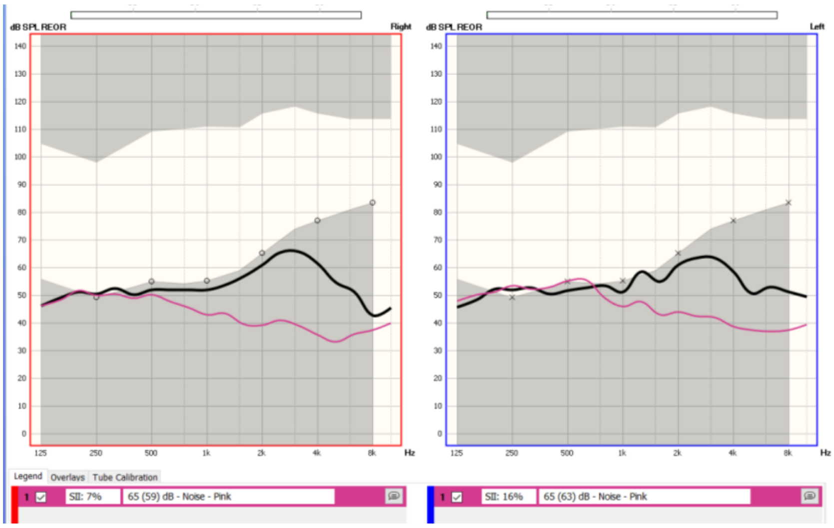
Results presented at international conference and discussed with other researchers and hearing aid manufacturers. Key suggestion was the inclusion of technical measurements to understand how the hearing aid features reacted to the SSiN test design.

Successfully granted UCL/MRC translational research fund award of £23,000 to purchase head and torso simulator to carry out technical measurements.

Phase 3**:** Technical measurements carried out by using head and torso simulator (KEMAR) within the SSiN test set up. Analysis of hearing aid output SNR carried out and compared between hearing aid features.

A larger trial was planned in order to take participant feedback on board and apply changes but this was postponed due to the COVID-19 pandemic.

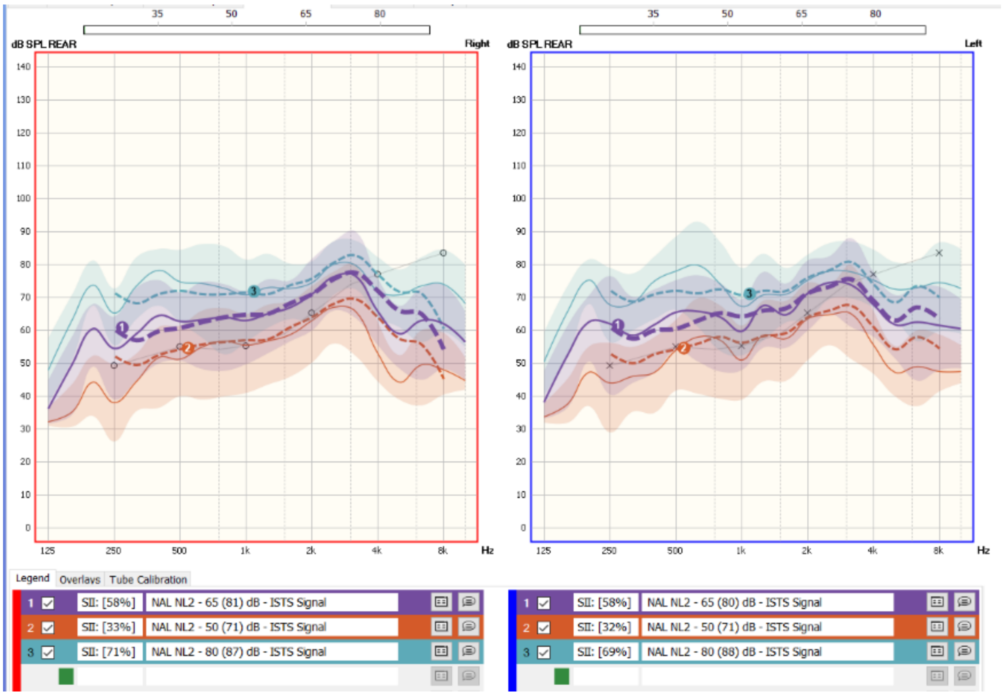
9.6 Real ear measurements from KEMAR used in Chapter 6



1 ☑ SII: 7% 65 (59) dB - Noise - Pink

1 ☑ SII: 16% 65 (63) dB - Noise - Pink

Figure A.2 Unaided and occluded real ear measurements from KEMAR.



1 ☑ SII: [58%] NAL NL2 - 65 (81) dB - ISTS Signal
2 ☑ SII: [33%] NAL NL2 - 50 (71) dB - ISTS Signal
3 ☑ SII: [71%] NAL NL2 - 80 (87) dB - ISTS Signal

1 ☑ SII: [58%] NAL NL2 - 65 (80) dB - ISTS Signal
2 ☑ SII: [32%] NAL NL2 - 50 (71) dB - ISTS Signal
3 ☑ SII: [69%] NAL NL2 - 80 (88) dB - ISTS Signal

Figure A.3 KEMAR aided real ear measurements.

9.7 RMarkdown statistical analysis from Chapter 6

Example Analysis Code: Comparing word ID & relative localisation performance and reaction times between OSN and OMNI hearing aid conditions

The following code was used for data wrangling and modelling for comparing performance between OSN vs OMNI hearing aid conditions in Chapter 6. Four models are presented: 1) Word ID performance, Word ID reaction time, relative localisation performance and relative localisation reaction time.

```
R Markdown

library('ggplot2')
library('lme4')
library('lmerTest')
library('mgcv')
library('sjPlot')
library('sjlabelled')
library('DescTools')
library('pROC')
library('usdm')
library('emmeans')
library('MuMIn')
library('DHARMa')
library('multcomp')
# Define functions

if (1) {

  glmer.sig = function(m) {


    s = summary(m)
    r = anova(m)
    for (row in 1:dim(r)[1])
      x = r[row,'F value']
      df1 = r[row, 'Df']
      if (is.null(df1)) df1 = r[row, 'npar']
      df2 = s$AICtab['df.resid']
      p = pf(x,df1,df2, lower.tail = F)
      r$DF2[row] = df2
      r$p[row] = p


    return(r)

  }
```

```
  d<-function(t.val,df,n1,n2){
    d<-t.val*(n1+n2)/(sqrt(n1*n2)*sqrt(df))
    names(d)<-"effect size d"
    return(d)
  }

}
### Load and format data ###

if (1)


  dat1 <- read.csv("OPN_formatted.csv")
  dat2 <- read.csv ("NoOPN_formatted.csv")
  dat = rbind(dat1,dat2)
  rm('dat1','dat2')

  View(dat)

  # Structure the data

  dat$subject          = as.factor(dat$subject)
  dat$sex              = as.factor(dat$sex)
  dat$group            = as.factor(dat$group)
  dat$block            = as.factor(dat$block)
  dat$word.group       = as.factor(dat$word.group)
  dat$word1            = as.factor(dat$word1)
  dat$word2            = as.factor(dat$word2)
  dat$direction        = as.factor(dat$direction)
  dat$speaker.sep      = as.factor(dat$speaker.sep)
  dat$mean.loc         = as.factor(dat$mean.loc)
  dat$noise.loc        = as.factor(dat$noise.loc)
  dat$word1.correct    = as.factor(dat$word1.correct)
  dat$word2.correct    = as.factor(dat$word2.correct)
  dat$loc.correct      = as.factor(dat$loc.correct)

  dat$age              = as.numeric(dat$age)
  dat$attenuation      = as.numeric(dat$attenuation)
  dat$trial.block      = as.numeric(dat$trial.block)
  dat$trial.total      = as.numeric(dat$trial.total)
  dat$speaker1         = as.numeric(dat$speaker1)
  dat$speaker2         = as.numeric(dat$speaker2)
  dat$word1.RT         = as.numeric(dat$word1.RT)
  dat$word2.RT         = as.numeric(dat$word2.RT)
  dat$loc.RT           = as.numeric(dat$loc.RT)
  # Create a long-form version of it to model word ID accuracy

  dat.long1 = dat
  dat.long1$word.no = 1
  dat.long1 = dat.long1[,-which(colnames(dat.long1) %in% c('word2', 'speaker2', 'speaker2.offset', 'word2.correct', 'word2.RT'))]
  colnames(dat.long1)[colnames(dat.long1)=='word1'] = 'word'
```

```
  colnames(dat.long1)[colnames(dat.long1)=='speaker1'] = 'speaker'
  colnames(dat.long1)[colnames(dat.long1)=='speaker1.offset'] = 'speaker.offset'
  colnames(dat.long1)[colnames(dat.long1)=='word1.correct'] = 'word.correct'
  colnames(dat.long1)[colnames(dat.long1)=='word1.RT'] = 'word.RT'

  dat.long2 = dat
  dat.long2$word.no = 2
  dat.long2 = dat.long2[,-which(colnames(dat.long2) %in% c('word1', 'speaker1', 's
peaker1.offset', 'word1.correct', 'word1.RT'))]
  colnames(dat.long2)[colnames(dat.long2)=='word2'] = 'word'
  colnames(dat.long2)[colnames(dat.long2)=='speaker2'] = 'speaker'
  colnames(dat.long2)[colnames(dat.long2)=='speaker2.offset'] = 'speaker.offset'
  colnames(dat.long2)[colnames(dat.long2)=='word2.correct'] = 'word.correct'
  colnames(dat.long2)[colnames(dat.long2)=='word2.RT'] = 'word.RT'

  dat.long = merge(dat.long1, dat.long2, all.x=T, all.y=T)
  dat.long$word.no = as.factor(dat.long$word.no)

  rm('dat.long1')
  rm('dat.long2')




  # Set categorical references

  dat.long$group = relevel(dat.long$group, 'NoOPN')
  dat$group = relevel(dat$group, "NoOPN")
  dat$word.group = relevel(dat$word.group, "1")
  dat$mean.loc = relevel(dat$mean.loc, "0")

  # Clean outliers in RT

  dat.long = dat.long[dat.long$word.RT>0.1 | is.na(dat.long$word.RT),]
  dat.long = dat.long[dat.long$word.RT<14 | is.na(dat.long$word.RT),]
  dat.long = dat.long[dat.long$loc.RT>1.6 | is.na(dat.long$loc.RT),]
  dat.long = dat.long[dat.long$loc.RT<14 | is.na(dat.long$loc.RT),]

  dat = dat[dat$word1.RT>0.1 | is.na(dat$word1.RT),]
  dat = dat[dat$word1.RT<14 | is.na(dat$word1.RT),]
  dat = dat[dat$word2.RT>0.1 | is.na(dat$word2.RT),]
  dat = dat[dat$word2.RT<14 | is.na(dat$word2.RT),]
  dat = dat[dat$loc.RT>1.6 | is.na(dat$loc.RT),]
  dat = dat[dat$loc.RT<14 | is.na(dat$loc.RT),]

  # Transform

  dat.long$word.RT.lg = log(dat.long$word.RT)
  dat.long$loc.RT.lg = log(dat.long$loc.RT)

  dat$word1.RT.lg = log(dat$word1.RT)
  dat$word2.RT.lg = log(dat$word2.RT)
  dat$loc.RT.lg = log(dat$loc.RT)
```

```
  # Calculate noise location and distance from stimulus

  dat.long$noise.loc.deg[dat.long$noise.loc=="L"] = -45
  dat.long$noise.loc.deg[dat.long$noise.loc=="R"] = 45
  dat.long$dist.from.noise = abs(dat.long$speaker - dat.long$noise.loc.deg)

  dat$noise.loc.deg[dat$noise.loc=="L"] = -45
  dat$noise.loc.deg[dat$noise.loc=="R"] = 45
  dat$dist.from.noise = abs(as.numeric(as.character(dat$mean.loc)) - as.numeric(as
.character(dat$noise.loc.deg)))

  # Code speaker as categorical to use all

  dat.long$speaker = as.factor(dat.long$speaker)
  dat.long$speaker = relevel(dat.long$speaker, "0")

  dat$mean.loc = relevel(dat$mean.loc, "0")

  # Scale variables for modeling

  dat.long$trial.block = scale(dat.long$trial.block, center = F)
  dat.long$age = scale(dat.long$age, center = F)
  dat.long$dist.from.noise = scale(dat.long$dist.from.noise, center = F)
  dat.long$trial.total = scale(dat.long$trial.total, center = F)

  set_label(dat.long$dist.from.noise, "Word distance from noise")
```

Model 1: Word Identification Performance

```
  form = word.correct ~ group + speaker + dist.from.noise + word.group + word.no +
         trial.total + group:trial.total + group:word.no + (1 | subject)


           m = glmer(form, dat.long, family = binomial(link = "logit"))
                                    summary (m)
  AIC(m)
  plot(simulateResiduals(m))
```

```
  View(car::Anova(m, type="III"))

  ##check model accuracy (specificity/sensitivity)
  terms = c('group', 'speaker', 'dist.from.noise', 'word.group', 'word.no', 'trial
.total', 'speaker.sep')
  dat.long.vif = dat.long[,terms]
  for (c in 1:dim(dat.long.vif)[2]) dat.long.vif[,c] = as.numeric(dat.long.vif[,c]
)
  vif(dat.long.vif)
```

```
  mt = m
  prob = predict(m, type = c("response"))
  roc.dat = data.frame(word.correct = m@frame$word.correct, prob = prob)
  g = roc(word.correct ~ prob, data = roc.dat)
## Setting levels: control = N, case = Y
## Setting direction: controls < cases
  x = as.numeric(coords(g, "best", transpose=T)['specificity'])
  y = as.numeric(coords(g, "best", transpose=T)['sensitivity'])
  plot(g, main = paste0('AUC = ', round(g$auc,3), '; sens = ', round(y,3), '; spec
= ', round(x,3)))
  points(x, y, pch=22, col='red')
```

```

   ## Post hoc testing

    r1 = as.data.frame(glht.table(summary(glht(m, mcp(group="Tukey"))))); r1$Term
= 'Group'
## Warning in mcp2matrix(model, linfct = linfct): covariate interactions found --
## default contrast might be inappropriate
    r2 = as.data.frame(glht.table(summary(glht(m, mcp(speaker="Tukey"))))); r2$Ter
m = 'Speaker'
    r3 = as.data.frame(glht.table(summary(glht(m, mcp(word.group="Tukey"))))); r3$
Term = 'Word Group'
    r4 = as.data.frame(glht.table(summary(glht(m, mcp(word.no="Tukey"))))); r4$Ter
m = 'Word group'
## Warning in mcp2matrix(model, linfct = linfct): covariate interactions found --
## default contrast might be inappropriate
    r = rbind(r1,r2,r3,r4)
    r$Contrast = rownames(r)
    rownames(r) = 1:dim(r)[1]
    colnames(r) = c('Estimate','St Error','Z','p','Term','Contrast')
    r = r[,c(5,6,1,2,3,4)]

    r$OR = exp(r$Estimate)
    r$OR.low = exp(r$Estimate - 1.96*r$`St Error`)
    r$OR.high = exp(r$Estimate + 1.96*r$`St Error`)

    r[,-c(1,2)] = round(r[,-c(1,2)],3)

    View(r)


    # Plot significant effects

  plot_model(m, type='eff', terms='speaker')
```

```
  plot_model(m, type='eff', terms='dist.from.noise')
## Package `effects` is not available, but needed for `ggeffect()`. Either install
package `effects`, or use `ggpredict()`. Calling `ggpredict()` now.FALSE
```

```
  plot_model(m, type='eff', terms='word.group')
## Package `effects` is not available, but needed for `ggeffect()`. Either install
package `effects`, or use `ggpredict()`. Calling `ggpredict()` now.FALSE
```

```
  plot_model(m, type='eff', terms='word.no')
## Package `effects` is not available, but needed for `ggeffect()`. Either install
package `effects`, or use `ggpredict()`. Calling `ggpredict()` now.FALSE
```

```
  plot_model(m, type='eff', terms='trial.total')
## Package `effects` is not available, but needed for `ggeffect()`. Either install
package `effects`, or use `ggpredict()`. Calling `ggpredict()` now.FALSE
## Data were 'prettified'. Consider using `terms="trial.total [all]"` to get smoot
h plots.
```

```
  plot_model(m, type='eff', terms=c('trial.total','group'))
## Package `effects` is not available, but needed for `ggeffect()`. Either install
package `effects`, or use `ggpredict()`. Calling `ggpredict()` now.FALSE
## Data were 'prettified'. Consider using `terms="trial.total [all]"` to get smoot
h plots.
```

```
  # Post-hoc testing

  ph1 = lsmeans(m, ~trial.total*group)
  ph1 = as.data.frame(contrast(ph1, method="pairwise"))[1:6,c(1,2,3,5,6)]
  ph1[,c(2:5)] = round(ph1[,c(2:5)],3)

  ph2 = lsmeans(m, ~group:speaker)
  ph2 = as.data.frame(contrast(ph2, method="pairwise"))[c(26,47,64,1,77,86,91),c(1
,2,3,5,6)]
  ph2[,c(2:5)] = round(ph2[,c(2:5)],3)


  emmeans(m, pairwise ~trial.total*group)
  # Condition effect size
```

Model 2: Word Identification Reaction Time

```
   m2 = lmerTest::lmer(word.RT.lg ~ group + speaker + dist.from.noise + word.group
       +word.no + trial.total + group:trial.total + (1 | subject), dat.long)

                                  summary(m2)
  View(car::Anova(m2, type="III"))

  car::Anova(m2, type="III")
##
```

```
  # Fit

  r.squaredGLMM(m2)
## Warning: 'r.squaredGLMM' now calculates a revised statistic. See the help page.
##             R2m       R2c
## [1,] 0.2090999 0.6037455
  # Residuals

  #par(mfrow=c(1,2))
  #hist(dat.long$word.RT.sq,30)
  #qqnorm(resid(m2)); qqline(resid(m2))
  #par(mfrow=c(1,1))



   r1 = as.data.frame(glht.table(summary(glht(m2, mcp(group="Tukey"))))); r1$Term
= 'Group'
  r2 = as.data.frame(glht.table(summary(glht(m2, mcp(speaker="Tukey"))))); r2$Term
= 'Location'
  r3 = as.data.frame(glht.table(summary(glht(m2, mcp(word.group="Tukey"))))); r3$T
erm = 'Word group'
  r4 = as.data.frame(glht.table(summary(glht(m2, mcp(word.no="Tukey"))))); r4$Term
= 'Word no.'
  r = rbind(r1,r2,r3,r4)
  r$Contrast = rownames(r)
  rownames(r) = 1:dim(r)[1]
  colnames(r) = c('Estimate','St Error','Z','p','Term','Contrast')
  r = r[,c(5,6,1,2,3,4)]

  r[,-c(1,2)] = round(r[,-c(1,2)],3)

  View(r)
```

Model 3: Relative Localisation Performance

```
  # Build the model


  form = loc.correct ~ group + word.group + mean.loc   + trial.total  + group:tria
l.total + (1 | subject)

  m3 = glmer(form, dat, family = binomial(link = "logit"))

  AIC(m3)
  View(car::Anova(m3, type="III"))


  # Check multicollinearity

  terms = c('group', 'word.group', 'mean.loc', 'trial.total', 'dist.from.noise')
  dat.vif = dat[,terms]
```

```
  for (c in 1:dim(dat.vif)[2]) dat.vif[,c] = as.numeric(dat.vif[,c])
  vif(dat.vif)
  # Check ROC, AUC, sensitivity and specificity

  mt = m3
  prob = predict(mt, type = c("response"))
  roc.dat = data.frame(loc.correct = mt@frame$loc.correct, prob = prob)
  g = roc(loc.correct ~ prob, data = roc.dat)
  x = as.numeric(coords(g, "best", transpose=T)['specificity'])
  y = as.numeric(coords(g, "best", transpose=T)['sensitivity'])
  plot(g, main = paste0('AUC = ', round(g$auc,3), '; sens = ', round(y,3), '; spec
= ', round(x,3)))
  points(x, y, pch=22, col='red')
```

```
  # Plot significant effects

  plot_model(m3, type='pred', terms='group')
  plot_model(m3, type='pred', terms='mean.loc')
  plot_model(m, type='pred', terms='trial.total')
  plot_model(m3, type='eff', terms=c('mean.loc','group'))
```

```
  # Post-hoc testing

  ph1 = lsmeans(m3, ~mean.loc)
  ph1 = as.data.frame(contrast(ph1, method="pairwise"))[1:6,c(1,2,3,5,6)]
  ph1[,c(2:5)] = round(ph1[,c(2:5)],3)

  ph2 = lsmeans(m3, ~group:mean.loc)
  ph2 = as.data.frame(contrast(ph2, method="pairwise"))[c(26,47,64,1,77,86,91),c(1
,2,3,5,6)]
  ph2[,c(2:5)] = round(ph2[,c(2:5)],3)

  View(ph1)
  View(ph2)


  r1 = as.data.frame(glht.table(summary(glht(m3, mcp(group="Tukey"))))); r1$Term =
'Group'
  r2 = as.data.frame(glht.table(summary(glht(m3, mcp(mean.loc="Tukey"))))); r2$Ter
m = 'Speaker'
  r3 = as.data.frame(glht.table(summary(glht(m3, mcp(word.group="Tukey"))))); r3$T
erm = 'Word Group'
  r = rbind(r1,r2,r3)
  r$Contrast = rownames(r)
  rownames(r) = 1:dim(r)[1]
  colnames(r) = c('Estimate','St Error','Z','p','Term','Contrast')
  r = r[,c(5,6,1,2,3,4)]

  r$OR = exp(r$Estimate)
  r$OR.low = exp(r$Estimate - 1.96*r$`St Error`)
  r$OR.high = exp(r$Estimate + 1.96*r$`St Error`)
```

```
  r[,-c(1,2)] = round(r[,-c(1,2)],3)

  View(r)


  # Condition effect size

  z = as.data.frame(contrast(lsmeans(m3, ~group), method="pairwise"))$z.ratio
## NOTE: Results may be misleading due to involvement in interactions
  df = glmer.sig(m3)$DF2[1]
  n1 = n2 = length(unique(dat$subject))
  cd = d(z,df,n1,n2)
```

Model 4: Relative Localisation Reaction Time

```
m4 = lmer(loc.RT.lg ~ group + word.group + mean.loc + group:trial.total + trial.to
tal  + group:mean.loc + (1 | subject), dat)


r1 = as.data.frame(glht.table(summary(glht(m4, mcp(group="Tukey"))))); r1$Term = '
Group'
  r2 = as.data.frame(glht.table(summary(glht(m4, mcp(mean.loc="Tukey"))))); r2$Ter
m = 'Location'
  r3 = as.data.frame(glht.table(summary(glht(m4, mcp(word.group="Tukey"))))); r3$T
erm = 'Word group'
  r = rbind(r1,r2,r3)
  r$Contrast = rownames(r)
  rownames(r) = 1:dim(r)[1]
  colnames(r) = c('Estimate','St Error','Z','p','Term','Contrast')
  r = r[,c(5,6,1,2,3,4)]

  r[,-c(1,2)] = round(r[,-c(1,2)],3)

  View(r)


  # Fit

  r.squaredGLMM(m4)
```

Residuals

```
 par(mfrow=c(1,2))
hist(dat$loc.RT.lg,30)
qqnorm(resid(m4)); qqline(resid(m4))
par(mfrow=c(1,1))



  # Plot effects

#  plot_model(m4, type='eff', terms='group')
#  plot_model(m4, type='eff', terms='word.group')
```

```
#  plot_model(m4, type='eff', terms='mean.loc')
#  plot_model(m4, type='eff', terms='trial.total')
#  plot_model(m4, type='eff', terms='dist.from.noise')

#  plot_model(m4, type='eff', terms=c('mean.loc', 'group'))

#  plot_model(m4, type='eff', terms=c('trial.total', 'group'))




  # Post-hoc testing

 # ph1 = lsmeans(m4, ~mean.loc)
#  ph1 = as.data.frame(contrast(ph1, method="pairwise"))[1:6,c(1,2,3,5,6)]
#  ph1[,c(2:5)] = round(ph1[,c(2:5)],3)

 # ph2 = lsmeans(m4, ~group:mean.loc)
#  ph2 = as.data.frame(contrast(ph2, method="pairwise"))[c(26,47,64,1,77,86,91),c(
1,2,3,5,6)]
 # ph2[,c(2:5)] = round(ph2[,c(2:5)],3)

#  View(ph1)
 # View(ph2)

#  ph3 = lsmeans(m4, ~word.group)
#  contrast(ph3, method="pairwise")

  # Condition effect size

  contrast = contrast(lsmeans(m4, ~group), method="pairwise")
  z = as.data.frame(contrast)$t.ratio
  df = summary(m4)$coefficients['groupOPN','df']
  n1 = n2 = length(unique(dat$subject))
  cd = d(z,df,n1,n2)
```

9.8 Topic Guide used in Chapter 7

Topic: A qualitative review of adult hearing aid users' perspectives of audiological testing techniques.

Objective: To obtain experienced hearing aid users' perspectives of the audiological assessment process with specific focus on how they relate to everyday listening situations.

Design: A focus group and/or semi-structured interview was carried out with a group of adult hearing aid users. A facilitator explored how audiology tests influenced their understanding and management of their hearing loss and hearing aids. The views were transcribed, and thematic analysis was used to understand key topics/themes in the data.

Main question	**Optional probe questions**
Opening questions: What prompted you to seek help with your hearing?	
Can you describe your experiences of completing an audiology assessment (hearing test)?	What types of tests do you remember? Tell me about the audiology assessment experience (environment/instructions/process)? Can you describe your experiences of completing audiology tests in relation to your everyday listening /communication experiences? Can you remember any hearing tests/assessments within previous audiology appointments that helped you understand your hearing loss?
If you think about the various audiology appointments you have had, how have the hearing healthcare professionals described your overall hearing ability to you?	Were there any words/terminology that you particularly remember and why? Were you shown a graph/audiogram? How did you relay the results to your friends and family? How did you feel about the communication between yourself and the audiologists?
Could you describe the experience of being fitted with hearing aids for the first time	Once the hearing aids were put in your ears for the first time were you asked to perform any listening /hearing tests whilst wearing them?

Can you describe any tests, questionnaires or monitoring tools that were used to measure the benefit of or identify issues with the hearing aid fitting?	How was benefit of hearing aids monitored or measured after the hearing aid fitting?
As a long-term hearing aid user, what is your experience of audiology follow ups?	Have you been shown/sign posted towards any other assistive listening technology or support apart from your hearing aids? How was your progress with technology monitored/issues identified?
Can you describe the communication / interactions you have experienced with audiologists?	With audiologist/reception/assisting staff? As a hearing aid user, how do you feel about the communication / interactions you have experienced? Are there specific areas of good practice or areas of improvement you have identified?

9.8.1 Instructions for participants

What is the purpose of the study?	In this study we would like to explore hearing aid user's views and opinions of clinical audiology testing and communication/interaction between you and your audiologists
Why have I been invited to take part?	You have been invited to take part in this study as you are over the age of 18, have been using a hearing aid in each ear for over 2 years and have made recent contact with your audiology provider
What will happen if I agree to take part (focus group)?	- 1x one-hour focus group session will take place online, - This will take place via free videoconferencing software (Microsoft Teams or Zoom). The choice of platform will depend on all group members comfort levels and communication needs. This will be discussed with you at the next stage. - In each session, you will be talking with Bhavisha Parmar (Audiologist) and 5-6 other focus group participants via a video call. - It would be ideal to use a tablet, laptop or PC for the call so that you can see all group members within the gallery view - We will also ask to have a brief call with you before the main focus group to check your audio and video equipment. - You may switch the video feature off during the call if you prefer and we can continue discussions with audio only however, the video call function may help with the group interaction nature of the activity. - The interview will be based within a professional setting of their own home but will be using a headset to ensure confidentiality. - During the call, all participants will be asked to mute their microphones to avoid excess background noise. If you would like to take part in a particular

	discussion point you will be asked to unmute your microphone or raise your hand so that the interviewer can see that you wish to take part. - You are encouraged to wear your hearing aids during the call, to assist with your communication needs but if you feel a headset works well then please feel free to use that. Also, if you have a Bluetooth streaming device that is compatible with your hearing aids you are more than welcome to use that. We can test connection of the additional device in the trial call. - If you have any connection issues during the call please contact Bhavisha directly via email or text. - The full information sheet is available to give you more information about confidentiality and data protection
What will happen if I agree to take part (Semi structured interview)?	- The project consists of 1x one-hour semi structured interview that will take place online, via free videoconferencing software (Microsoft Teams or Zoom). In each session, you will be talking with Bhavisha Parmar (Audiologist), via a video call. We might also ask to have a brief call with you before the main interview to check your audio and video equipment. - You may switch the video feature off during the call if you prefer and we can continue discussions with audio only however, the video call function may help with communication - You can choose whether we use Zoom or MS teams, based on your specific communication needs (e.g., use of closed captions) - You are encouraged to wear your hearing aids during the call, to assist with your communication needs but if you feel a headset works well then please feel free to use that. Also, if you have a Bluetooth streaming device that is compatible with your hearing aids you are more than welcome to use that. We can test connection of the additional device in the trial call. - Given the 1:1 nature of the interview you can use your smartphone, tablet, laptop or PC for the interview - If you have any connection issues during the call please contact Bhavisha directly via email or text. - The full information sheet is available to give you more information about confidentiality and data protection

9.9 Sampling Matrix used in Chapter 7

Aim:

- Equal representation of male and female
- Equal representation of over 60 and under 60 age groups
- Equal representation of work status (working or retired)
- Range of hearing loss severity
- Equal representation of private sector vs public sector experience

		% of participants
Sex	Male	43%
	Female	57%
Age	Under 60	47%
	Over 60	53%
Work status	Currently working	47%
	Retired	53%
Hearing loss severity	Mild	19%
	Moderate	48%
	Severe-profound	33%
Sector	Public	52%
	Private	29%
	Public & private	19%

Table A.1 Sampling matrix.

Chapter 10: References

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