Characterisation of disordered auditory processing in adults who present to audiology with hearing difficulties in presence of normal hearing thresholds: Correlation between auditory tests and symptoms

Chrysoula Spyridakou

Thesis submitted for the degree of

DOCTOR OF MEDICINE RESEARCH

University College London
Ear Institute
and
Department of Neuro-otology
Royal National Throat, Nose and Ear Hospital
London, United Kingdom

December 2013

Abstract

The diagnosis of auditory processing disorder (APD) remains controversial. Quantifying symptoms in individuals with APD by using validated questionnaires may help better understand the disorder and inform appropriate diagnostic evaluation.

Aims:

This study was aimed at characterising the symptoms in APD and correlating them with the results of auditory processing (AP) tests.

Methods:

Phase 1: Normative data of a speech-in-babble test, to be used as part of the APD test battery, were collected for 69 normal volunteers aged 20–57 years.

Phase 2: Sixty adult subjects with hearing difficulties and normal audiogram and 38 healthy age-matched controls completed three validated questionnaires (Amsterdam Inventory for Auditory Disability; Speech, Spatial and Qualities of Hearing Scale; hyperacusis questionnaire) and underwent AP tests, including dichotic digits, frequency and duration pattern, gaps-in-noise, speech-in-babble and suppression of otoacoustic emissions by contralateral noise. The subjects were categorised into the clinical APD group or clinical non- APD group depending on whether they met the criterion of two failed tests. The questionnaire scores in the three groups were compared.

Phase 3: The questionnaire scores were correlated with the APD test results in 58/60 clinical subjects and 38 of the normal subjects.

Results:

Phase 1: Normative data for the speech-in-babble test afforded an upper cut-off mean value of 4.4 dB for both ears.

Phase 2: Adults with APD presented with hearing difficulties in quiet and noise; difficulties in localising, recognising and detecting sounds and hyperacusis with significantly poorer scores compared to clinical non- APD subjects and normal controls.

Phase 3: Weak to moderate correlations were noted among the scores of the three questionnaires and the APD tests. Correlations were the strongest for the gaps-in-noise, speech-in-babble, dichotic digit tests with all three questionnaires.

Conclusions:

The three validated questionnaires may help identify adults with normal hearing who need referral for APD assessment.

Signed Statement

‘I, Chrysoula Spyridakou, confirm that this submission is the result of my own work. All help and advice, other than that received from educational supervisors, has been acknowledged, and primary and secondary sources of information have been properly attributed.

Should this statement prove to be untrue, I recognize the right and duty of the Board of Examiners to recommend what action should be taken in line with the University’s regulations.’

Acknowledgements

I would like to address special thanks to the patients and healthy volunteers who agreed to participate in this research. I fully acknowledge that without their participation, this research study would not have been possible.

I am most grateful to Dr Doris-Eva Bamiou, my research supervisor and I owe special thanks to her for her commitment in guiding me throughout my research project. Her continuous enthusiasm, encouragement and motivation have been contagious, and she has been a great teacher to me. I would also like to thank Professors Linda Luxon and Stuart Rosen for their advice and teaching. I am very grateful to Amal Al Shaikh Sulaiman and Sthella Zanchetta for their assistance with recruitment and technical support.

I would like to express my gratitude to the staff members of ENT, Neuro-otology and Audiology Departments at Royal National Throat, Nose & Ear Hospital, National Hospital for Neurology and Neurosurgery and Whittington Health for their advice and support.

Finally, I would like to thank Deborah Ridout for her expert advice on the statistical analysis of the data.

Table of Contents

List of Tables

List of Figures

List of Abbreviations

AAA: American Academy Audiology

AD: Amsterdam Disability

ADDIS Amsterdam Disability Sound Detection

ADHD: Attention Deficit Hyperactive Disorder

ADLOC: Amsterdam Disability Localisation

ADREG Amsterdam Disability Recognition of Sound

ADSQ: Amsterdam Disability Speech in Quiet

ADSN: Amsterdam Disability Speech in Noise

AFG: Auditory Figure Ground

AHYP: Attentional Hyperacusis

AND: Auditory Disability with Normal Hearing

AP: Auditory Processing

APD: Auditory Processing Disorder

ASD: Autistic Spectrum Disorder

ASHA: American Speech Hearing Association

AUD: Area Under Curve

BA: Brodmann Areas

BKB-SIN: Bamford- Kowal-Bench–Speech in Noise

BMQ: Buffalo Model Questionnaire

BSA: British Society Audiology

CANS: Central Auditory Nervous System

CHAPS: Children's Auditory Performance Scale

CHILD: Children's Home Inventory for Listening Difficulties

CHINT: Cantonese Hearing in Noise Test

CNS: Central Nervous System

CST: Connected Sentence Test

dB: Decibel

dBHL: Decibel Hearing Level

dB SPL: Decibel Sound Pressure Level

DDT: Dichotic Digit Test

DPT: Duration Pattern Test

EHYP: Emotional Hyperacusis

ENT: Ear, Nose and Throat

fMRI: Functional Magnetic resonance

FFT: Fast Fourier transform

FPT: Frequency Pattern Test

FW: Filtered Words

GIN: Gap in Noise

HINT: Hearing in Noise Test

Hyp: Hyperacusis

ICD: International Classification of Diseases

LIFE: Listening Inventory for Education

LISN-S: Listening to Spatialized Noise–Sentence

MOCB: Medial Olivocochlear Bundle

MOCS: Medial Olivocochlear System

MRI: Magnetic Resonance Imaging

NAM: Neighbourhood Activation Model

NHNN: National Hospital of Neurology and Neurosurgery

OAD: Obsure Auditory Dysfunction

OCB: Olivocochlear Bundle

PET: Positron-Emission Tomography

P SI-ICM: Paediatric Sentence Identification- Ipsilateral

RGT: Random Gaps-in-Noise

RNTNE: Royal National Throat, Nose & Ear Hospital

ROC: Receiver Operating Curve

SD: Standard Deviation

SHYP: Social Hyperacusis

SIFTER: Screening Instrument for Targeting Educational Risk

SIB: Speech in Babble

SINT: Speech-in-Noise

SINT: Speech-in-Noise Test

SL: Sensation Levels

SNR: Signal to Noise Ratio

SOAEs: Spontaneous Otoacoustic Emissions

SOC: Superior Olivary Complex

SPIN: Speech perception in noise

SSI-ICM: Synthetic Sentence Identification-Ipsilateral competing message

SSQ: Speech, Spatial and Qualities of Hearing Scale

STG: Superior Temporal Gyrus

STS: Superior Temporal Sulcus

TEOAEs: Transient Evoked Otoacoustic emissions

UCLH: University College London Hospital

WIN: Word in Noise

CHAPTER 1: INTRODUCTION

1.1 Auditory Processing Disorders - Definition and Challenges

The definition of auditory processing disorder (APD) remains challenging and debatable for professionals. Although the term auditory perceptual disorder was first used nearly 60 years ago in 1954 by Helmer Myklebust, the definition continues to evolve.

Although recent advancements in sophisticated imaging modalities (e.g. functional magnetic resonance imaging [fMRI]) have provided information about the brain constitutes involved in auditory processes and the related physiology (e.g. Millen et al., 1995; Salvi et al., 2002; Hwang et al., 2006; Patterson and Johnsrude, 2008), there are still gaps in our understanding of these processes. Although an increasing number of researches have been published over the last few decades, there are no well-standardised tests to validly diagnose APD (American Academy audiology [AAA], 2010; British Society Audiology [BSA], 2011). Clinical tests currently in use have certain limitations because they are markedly affected by linguistic and cognitive factors (Loo et al., 2013) and because APD is a complex multimodal condition that can coexist with other neurodevelopmental and sensory disorders (BSA, 2011, AAA, 2010). Unsurprisingly, there are no screening tools to help professionals identify individuals requiring an APD assessment (Moore et al., 2013).

The Steering Committee of the BSA's APD Special Interest Group in 2011 proposed that APD is caused by impaired neural function that leads to poor perception of both speech and non-speech sounds and manifests as a reduced ability to listen. Building on that definition and acknowledging that non-speech auditory processing tests only weakly correlate with reported listening behaviours and other communication indices, a white paper on APD by the same group proposed that listening ability is underpinned by high-level, cognitive and analytic processing rather than by low-level sensory processing and that, therefore, the diagnosis of APD should be established by carefully constructed listening questionnaires (Moore et al., 2013). Special

interest groups in the United States of America (American Speech Hearing Association [ASHA], 1996, 2005; AAA 2010) have published guidelines about the diagnosis and management of APD in children and adults with different approaches. Thus, the American Academy of Audiology, in their most recent clinical practice guidelines published in 2010, highlights the importance of using speech tests to diagnose APD, since difficulties in listening to speech is a primary problem in these patients and processing for speech signals is different from that of non-speech signals. Professionals working within the audiology field have recently identified a subtype of APD that can be conceptualised as a deficit in the processing of information that is specific to the auditory system (Cameron and Dillon, 2011). Thus, in view of the on-going debates about the construct of APD, professionals in the audiology field use different diagnostic criteria for APD and a recent review by Wilson and Arnott (2013) revealed 9 different diagnostic criteria with a diagnostic yield of 7.3% up to 96% for APD.

Despite the current challenges in defining and diagnosing APD, the term is now widely applied, and a specific entry in ICD 10 has also been made for this diagnosis (H93.25). The need to explicitly define the diagnostic criteria for APD (Wilson and Arnott, 2013) is, therefore, of paramount importance, when considering the results of published APD studies as well as when a clinical service is being set up. Nevertheless, the on-going debate about the definition of APD and its diagnostic criteria reflects the evolution in both the scientific understanding about auditory processing and the clinical management of individuals suspected of having APD. Prior to the APD era, researchers used various terms such as King (1954) Kopetsky (1948) syndrome, obscure auditory dysfunction (OAD) (Saunders and Haggard, 1992) and auditory disability with normal hearing (AND) (King and Stephens, 1992), in order to classify listening difficulties (predominantly) for speech in noise. These terms were used as umbrella terms and very limited audiological tests, e.g. pure tone audiometry and occasionally speech audiometry, were performed and little effort was made to characterise the deficits underpinning the clinical presentation. Those terms could thus only serve as presumptive diagnostic labels of uncertain diagnostic validity and

soon became obsolete. Thus, it was recognised that patients with these disorders may require further diagnostic assessment and appropriate management (Kennedy et al., 2006).

1.2 APD Prevalence

Because of the lack of well-standardised tests to diagnose APD, the prevalence of APD in children is not exactly known but is estimated at around 7% (Musiek et al., 1990). APD, when present from a young age, can be considered as a neurodevelopmental disorder (Moore et al., 2013). The diagnosis of APD is a clinical challenge since it may frequently co-exist with other neurodevelopmental disorders such as speech and language-related disorders, dyslexia, attention deficit hyperactive disorder (ADHD) and autistic spectrum disorders, and a multidisciplinary team of professionals is necessary to diagnose and manage children with APD (Witton, 2010)

The prevalence of APD may be higher in children with learning difficulties, and different studies propose that the prevalence varies from 30 % (King et al., 2002) to 43.3% (Iliadou et al., 2009). A study by Dawes et al. (2008) showed that 9% of children who were diagnosed with APD in a tertiary hospital in London had autism.

The prevalence of APD in adults is not known; however, it is thought to increase with age, and earlier studies have estimated that approximately 10% (Saunders and Haggard, 1992) of the adults who attend ENT/Audiology clinics and have normal hearing on pure-tone audiometry may complain of hearing loss. A more recent study by Hind et al. (2011) found a lower percentage of 0.9% (i.e. 43 adults with normal hearing in a total population of 4757 adult audiological referrals in the age range of 15 to 71 years).

Studies on the prevalence of APD in older adults indicate a prevalence of 23% (Cooper and Gates, 1991) to 50% (Jerger et al., 1989) in patients over the age of 63 years. Notably, however, the presence of age-related peripheral hearing loss in these older patients may contribute to their auditory symptoms. Very few studies have addressed APD in younger adults aged 18–60 years, with no structural brain abnormalities (e.g. Helfer and

Vargo, 2009; Neijenhuis et al., 2003). In contrast to children with APD, adults do not have speech, language or reading difficulties, although the prevalence of such problems may be underestimated. Even if there is a history of such symptoms in childhood, adult patients would have adapted to their difficulties and, therefore, their auditory symptoms are more consistent (Neijenhuis et al., 2003). Overall, there is a paucity of published studies regarding disordered auditory processing for this group of adults.

1.3 Categories of Auditory Processing Disorders

According to the BSA APD Special Interest Group (2011) Position Statement on APD, APD can be classified into three categories (Table 1.1)

Table 1.1: APD categories
Taken from BSA, 2011

Developmental APD
Cases present in childhood and there are no other known aetiological or potential risk factors. Some of these people may retain their APD into adulthood.
Acquired APD:
Cases associated with a known post-natal event (e.g. neurological trauma, infection) that could plausibly explain the APD.
Secondary APD:
Cases where APD occurs in the presence, or as a result, of peripheral hearing impairment. This includes transient hearing impairment such as otitis media with effusion.

However, this classification may not be entirely complete. For example, the presence of late-onset APD, attributed to age-related changes in auditory processing that is broadly termed as “central presbyacusis” (Welsh et al., 1985) is not included into this classification. In addition, these categories may not be mutually exclusive, for example an adult who had “developmental” APD and to some extent adapted to the presence of this disorder might also suffer from an additional acquired brain insult impacting on his/her presentation.

The following section will briefly summarise the functional anatomy of the auditory system before proceeding with a discussion on APD in adulthood.

1.4 Auditory Processing- Functional Anatomy

1.4.1 Auditory Pathway

The auditory pathway consists of peripheral (outer ear, middle ear, inner ear and auditory nerve) and central (brain stem and cortex) components. When the sound wave reaches the ear, it is converted via mechanical and electrophysiological changes to neural responses in the brain (Yost W.A., 2000) (Figure 1.1.)

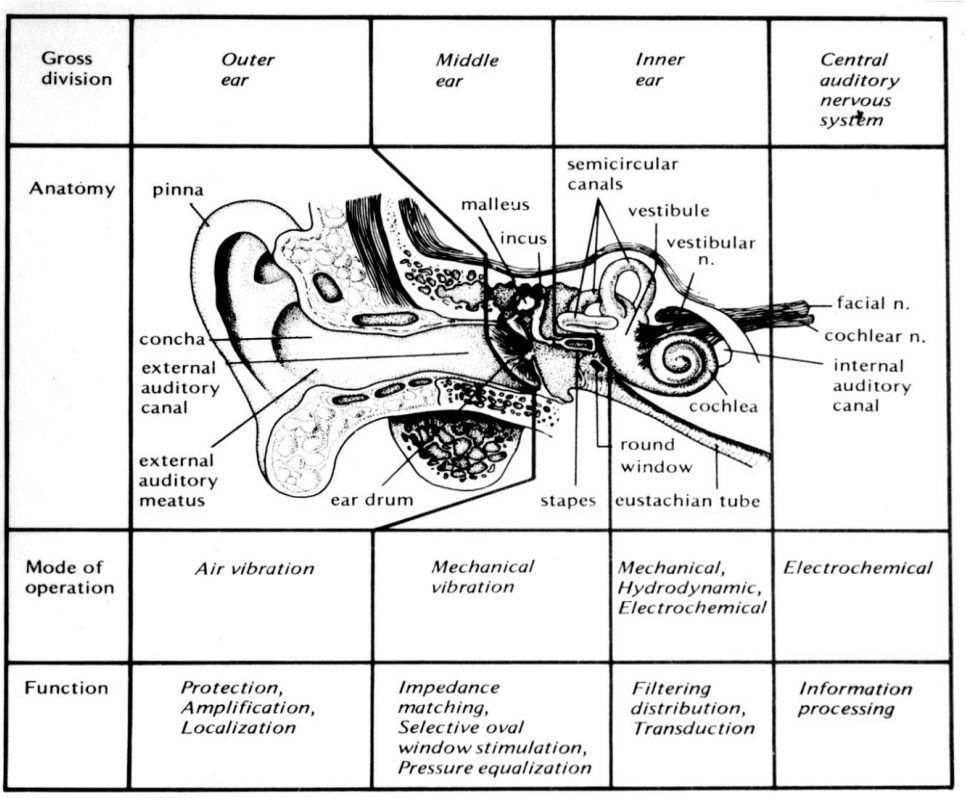


Figure 1.1: Cross section of human ear showing anatomical and functional divisions of the ear.
Yost W.A. Fundamentals of hearing: an introduction, fourth edition, 2000

The basilar membrane of the cochlea is frequency specific, and this tonotopicity continues into the central auditory system up to the cortex. The central auditory pathways extend from the brain stem (medulla) to the cerebral cortex. The auditory pathway consists of afferent and efferent neural fibres. The cell bodies of the afferent auditory neurons are present in the spiral ganglion. About 95% of the afferent auditory neurons carry information from the cochlear inner hair cell and approximately 5%, from the outer hair cells. (Santi and Manchini, 1998)

The fibres of the auditory nerve terminate at the cochlear nucleus. From the cochlear nuclei, the ascending fibres interact with each other (binaural hearing) at the level of superior olivary complex (SOC); then, via the nuclei of the lateral lemniscuses, they continue and reach the inferior colliculi and the medial geniculate body and, finally, the cortex (Musiek and Oxholm, 2003). (Figure 1.2)

Approximately 75% of the ascending central auditory nervous system (CANS) fibres leaving the cochlear nucleus cross over to the contralateral side of the brain to terminate at the SOC on the opposite side of the brainstem or project to the lateral lemniscus. The remaining 25% of the fibres follow the pathway on the ipsilateral side of the brainstem and terminate at the SOC or the lateral lemniscus (Pickles and Comis, 1973).

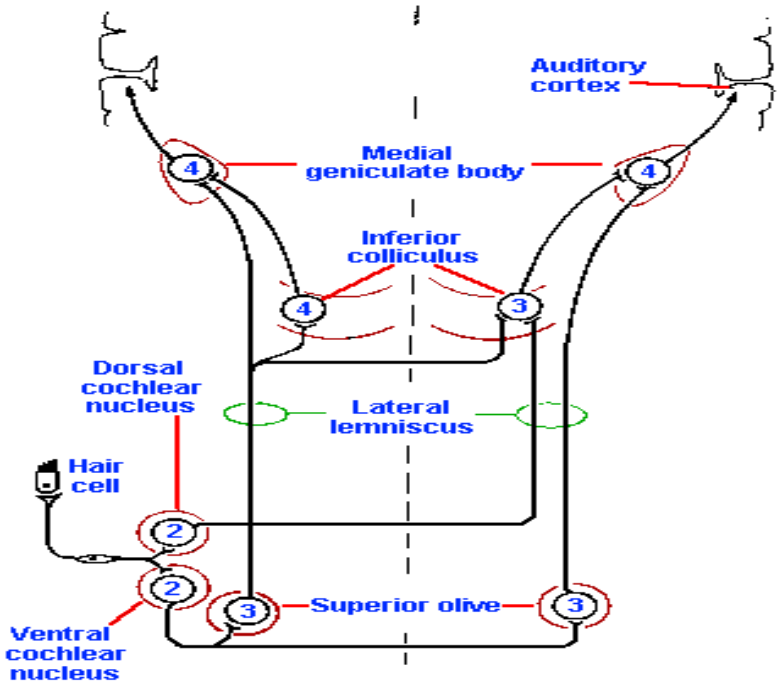


Figure 1.2: Central auditory pathway
From Michael D. Mann, The nervous system in action, Chapter 8 audition, 2005, University Nebraska www. Michaeldmann.net

1.4.2 Auditory Cortex

The auditory cortex is considered to be the Heschl's gyrus, which is located on the upper surface of the temporal lobe in the Sylvian fissure (Musiek and Oxholm, 2003). It is divided, according to the anatomical and physiological

factors, into the primary auditory cortex and associated auditory regions (Santi and Manchini, 1998). The primary auditory cortex (Brodmann areas [BA] 41 and 42) is surrounded by specific auditory and associated nonspecific areas and the Wernicke's area (BA 22 and 52). There is an asymmetry, with the left auditory area being larger than the right one. (Shapleske et al., 1999; Musiek and Oxholm, 2003). The understanding of speech is mostly dependent on the left lateralized cortical system (Scott and Johnsrude, 2003; Patterson and Johnsrude, 2008) (Figure 1.3.).

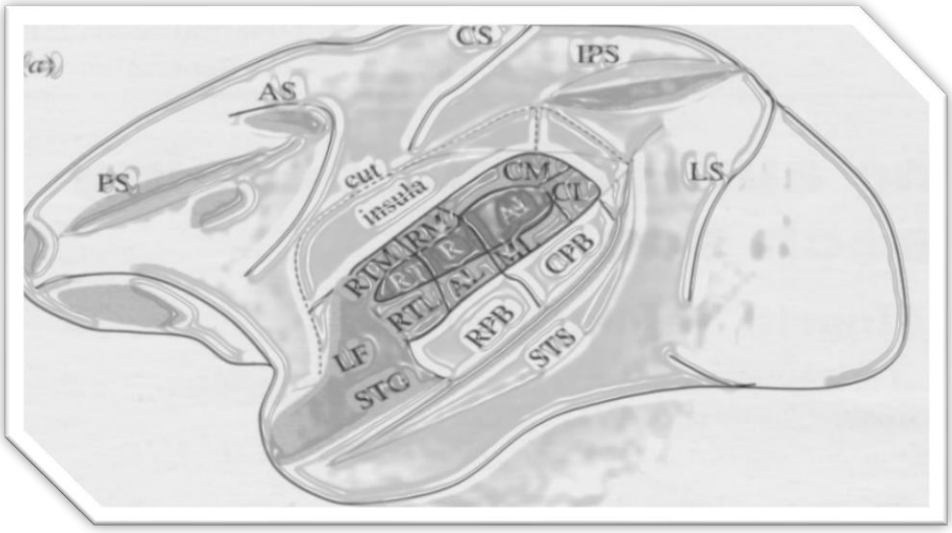


Figure 1.3:Left lateralized cortical system

List of abbreviations :AF, arcuate fasciculus; AS, arcuate sulcus; CS, central sulcus; Extm Cap, extreme capsule; IOS, inferior occipital sulcus; IPS, intraparietal sulcus; LF, lateral fissure; LS, lunate sulcus; PS, principal sulcus; SLF, superior longitudinal fasciculus; STG, superior temporal gyrus; STS, superior temporal sulcus; UnBd, uncinate bundle. Taken from Patterson and Johnsrude, 2008, Adapted from Kaas et al. (1999) and Hackett and Kaas (2004).

The tonotopic and binaural characteristics of the auditory system are retained in the primary auditory cortex. The high frequencies are represented rostrally and the low frequencies, caudally (Morel and Imig, 1987).

The associated auditory areas connect the primary cortex to the frontal, temporal and parietal regions; vision areas and somaesthetic areas (Luxon, 1981). The central auditory pathways involve all ascending and descending neuronal projections interconnecting the auditory nerve, brainstem, midbrain, thalamus and cerebral cortex (Morel and Imig, 1987).

A complex neural pathway involving the superior temporal gyrus (STG) and medial temporal cortex, where acoustic information is relayed, may play an important role in auditory (working) memory. These structures have multiple connections directly and indirectly with the medial frontal cortex, insula, medial pulvinar, thalamus and amygdala. Those anatomical connections indicate multisensory involvement in auditory memory and also the role of emotions in auditory long-term memory. (Munoz- Lopez et al., 2010).

The two cerebral hemispheres are connected by the corpus callosum. The corpus callosum consists of myelinated fibres and increases in size until the third decade. Behavioural, neuroimaging and histopathological data available from studies on humans and primates indicate that the corpus callosum may play a role in the functional specialisation of the brain (Bamiou et al., 2007). The auditory regions of the corpus callosum show the highest growth during the development of the auditory, speech and language skills, and the corpus callosum grows to more than double its birth size at the age of 2 years (Yakovlev and Lecours, 1967). Moreover, the corpus callosum is involved in the temporal transformation of neural transmission either by integrating or separating activity between neurons (Springer and Gazzaniga, 1975). Finally, it has possibly a role for spatial hearing and hemisphere dominance (Aboitiz et al., 2003). However, despite recent research, our understanding of the anatomy and physiology of the central auditory system remains incomplete.

1.4.3 Efferent Auditory Pathway

Apart from the afferent auditory pathway there is the efferent auditory pathway. The existence of efferent innervations to the mammalian cochlea was first described by Rasmussen in 1946. There are two main tracts of these efferent nerve fibers—the lateral and the medial (Warr, 1980). The lateral tract originates from cells near the lateral superior olive and is mostly composed of uncrossed, unmyelinated fibers that terminate in the inner hair cells of the cochlea. The medial tract is composed of myelinated fibres that originate in the area around the medial superior olive. Most fibres cross to the opposite cochlea (inner ear) where they connect directly to the outer hair cells (Musiek and Lamb, 1992) (Figure 1.4).

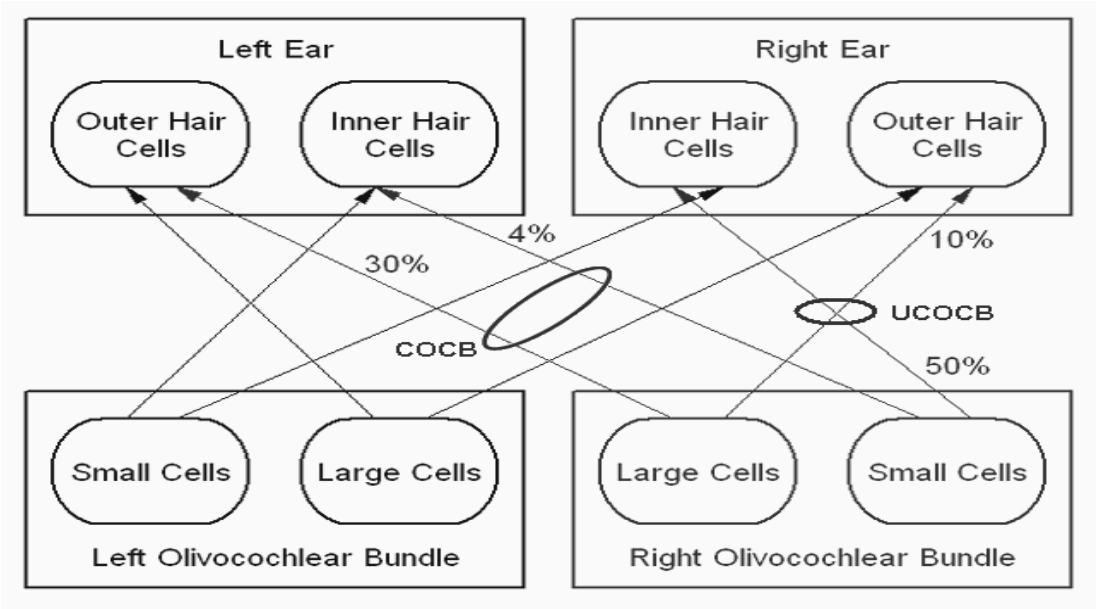


Figure 1.4: Olivocochlear bundle system
From Robert Mannell, Auditory Physiology and Psychoacoustics, Department of Linguistics, Macquarie University (www.zaenea.com)

There are several lines of evidence indicating that this pathway may be closely involved in the auditory processing of speech in noise at low levels of the auditory system, and since speech in noise difficulties are the hallmark symptoms for APD (e.g., AAA 2010), the subsequent review will summarise findings obtained in both animal and clinical human studies pertaining to these issues.

The medial olivocochlear system (MOCS) also receives projections from the central nervous system, mainly from the primary auditory cortex via the medial geniculate nucleus, the inferior colliculus and the medial superior olivary complex (Sprangler and Warr, 1991) (Figure 1. 5).

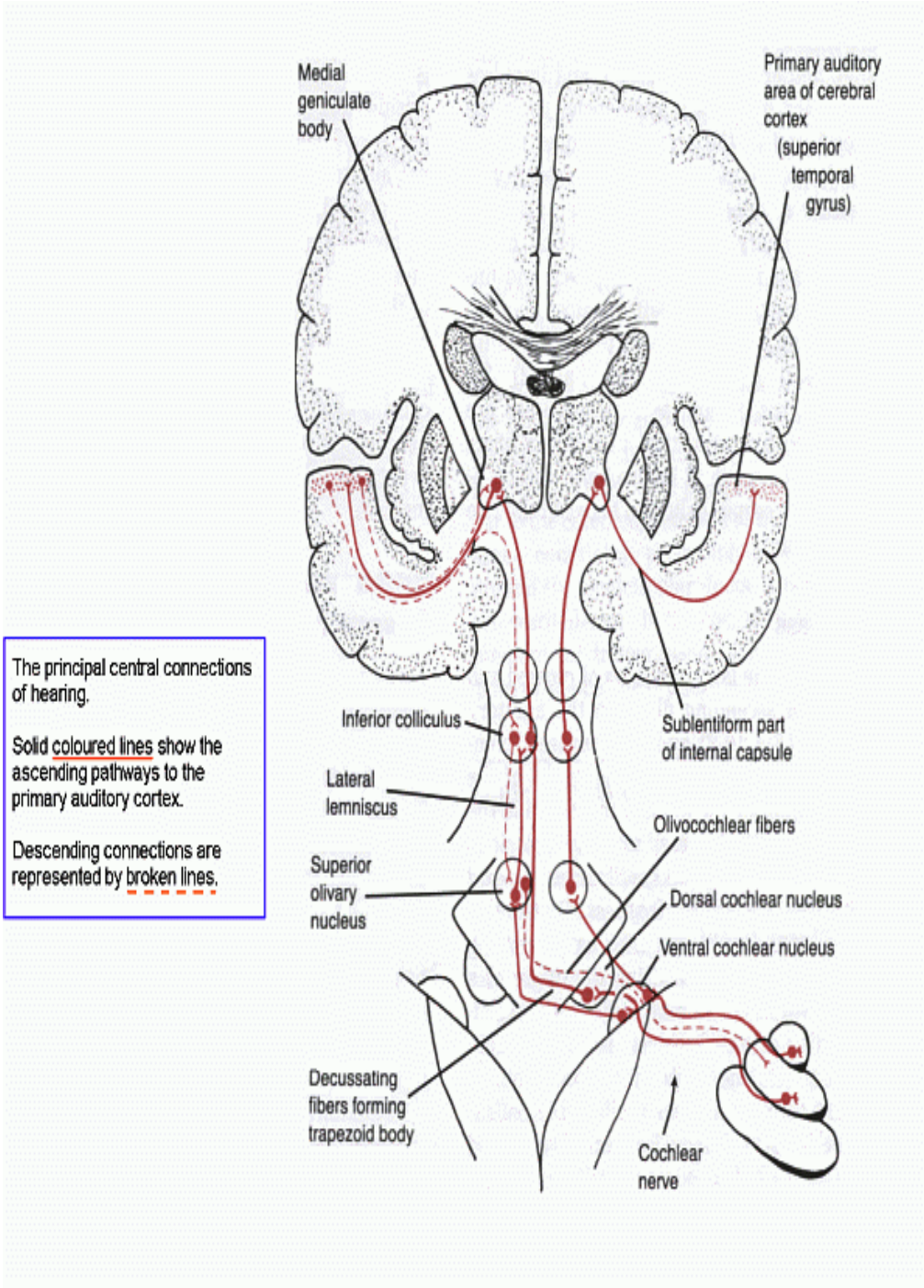


Figure 1.5: Central auditory pathway
From www. instruct.uwo.ca

Early physiological studies show that stimulation of the MOCS fibres results in reduced neural response from the cochlea and cochlear nerve (Galambos, 1956).

Animal experimental studies elucidate the functional role of the MOCS in the function of hearing in noise. Administration of atropine (a cholinergic blocker) in the region of the olivocochlear bundle (OCB) has been reported to

compromise the hearing in noise function in animals (Pickles and Comis, 1973), while other animal studies have established that the medial olivocochlear bundle (MOCB) enhances the encoding of signals in noise (Winslow and Sachs, 1988; Kawase and Liberman, 1993).

This mechanism may be related to the ability of the MOCB to trigger outer hair cell expansion/contraction, thereby enhancing or reducing basilar membrane activity. The MOCB (Guinan, 2006; Warr and Beck, 1996) decreases gain of the cochlear amplifier and its effects are different in the apical and basal turn of the cochlea.

This, in turn, may limit the cochlear nerve activity induced by unimportant (noise) stimuli, thereby resulting in a larger dynamic range for the cochlear nerve neurons response to other acoustical stimuli (Sahley et al., 1997). Experiments show that when an animal is surrounded by noise and the MOCB is triggered (by electrical stimulation or by noise on the contralateral ear), a release of the cochlear nerve from noise is accomplished, facilitating overall hearing in noise (Musiek and Oxholm, 2003).

The medial olivocochlear reflex (Winslow and Sachs, 1988) refers to the stimulation of MOCB by sounds and the resultant cochlear changes. Noise partially masks the auditory nerve responses by reducing the dynamic range of auditory nerve responses. MOCS stimulation inhibits the response to background noise; thus, restoring the dynamic range of auditory nerve response (MOCS unmasking).

Nevertheless, although these results strongly support the role of the MOCB in the discrimination of the intensity of tones in noise, this hypothesis cannot be directly tested in vivo in humans.

A non-invasive and objective method of assessing MOCB function in humans is by measuring contralateral acoustic suppression of outer hair cell responses (e.g. otoacoustic emissions). This technique is based on the finding that the amplitude of transient evoked otoacoustic emissions (TEOAEs) is reduced when a sound stimulus is presented to the opposite ear (Collett et al., 1992).

Human studies have thus proposed that the MOCB may enhance speech intelligibility in the presence of background noise (Kumar and Vanaja, 2004; Brown et al., 2010). In addition, the reduced function of the MOCB has been found in patients with symptoms of hyperacusis after head injury (Ceranic et al., 1998). There are but a few clinical studies assessing MOCB function and its relationship with speech. Kumar and Vanaja (2004) investigated the effect of contralateral acoustic stimuli on speech identification scores in the presence of ipsilateral noise and correlated psychoacoustical and physiological measures of function in 10 children with normal hearing and good academic performance. They found that contralateral acoustic stimuli enhanced the speech perception for ipsilateral signal-to-noise ratio (SNR) between +10 and +15 dB. This enhancement had significant positive correlation with the magnitude of the contralateral suppression of TEOAEs. A significant drawback of that study was that they employed English language speech test stimuli, but the children tested were not native speakers of English and their knowledge of English was not assessed prior to the study. Muchnik et al. (2004) evaluated MOCB function in 15 children (age, 8 to 13 years) who were diagnosed with APD and 15 gender- and age-matched controls. The diagnosis of APD in that study was based on the presence of behavioural symptoms and/or educational difficulties related to APD, in the absence of a learning disability, and abnormal results in one or more of three behavioural tests from an APD test battery. A significantly reduction was noted in the suppressive effect of TEOAEs in the APD group compared to the controls, indicating reduced MOCB activity in children with APD. Mukari and Mamat (2008) compared the results of speech- in-noise test and suppression of distortion product otoacoustic emissions in older and younger adults; they found that although the older group had lower contralateral suppression and poorer scores in the speech- in-noise test compared to the younger, the two tests did not show any statistically significant correlation. The differences between the results of the paediatric and adult studies may reflect the maturational aspects of the auditory pathway and differences in the linguistic and cognitive strategies employed for auditory closure in adults and children. The discrepancies in the results may also be attributed to the differences in the diagnostic criteria for APD. In order to critically assess the

role of the efferent system in listening to speech in-noise, Messing et al. (2009) and Brown et al. (2010) conducted studies on two IT auditory models in humans. Both studies showed that MOCS enhances speech intelligibility in the presence of noise. A limitation of those studies, however, was that only pink noise was used as a masker, and the impact of other types of maskers on the efferent pathway e.g. multi-talker babble was not studied. In addition, a study by Gataloumb et al. (2009) showed that there was improvement in the speech intelligibility in quiet. Since otoacoustic emissions have been reliably used in humans to measure MOCS properties (Guinan, 2010) and current evidence shows that the efferent system has an important role in listening to speech in noise, suppression of otoacoustic emissions by contralateral noise could provide a valuable and informative addition in the APD diagnostic battery.

1.5 Symptoms and Behaviours of APD

Individuals with APD can present with a variety of symptoms. Difficulties in hearing speech in demanding listening situations, such as in the presence of background noise or when more than two speakers are present, are prominent features of this clinical presentation (AAA, 2010). Additional symptoms include problems with sound localisation, poor musical skills, poor attention, poor memory and overall learning difficulties. An earlier report by ASHA (1996) proposed that patients with APD can have deficits in the skills and related behaviours (summarised in Table 1.2). While all the above mentioned symptoms and deficits are summarised in the Guidelines for the diagnosis, the treatment and management of children and adults with APD, which was published by the AAA in 2010, the level of evidence for the presence of these abnormalities in individuals with APD is currently low.

Table 1.2: Auditory skills and behaviours involved in auditory processing
From ASHA, 1996

- *Sound localization and lateralization*
- *Auditory discrimination*
- *Auditory pattern recognition*, or ability to determine similarities and differences in patterns of sounds
- *Temporal aspects*, or abilities to integrate a sequence of sounds and perceive sounds as separate when they quickly follow one another
- *Auditory performance decrements*, or ability to perceive speech or other sound when another signal is present
- *Auditory performance with degraded acoustic signals*, or ability to perceive a signal in which some of the information is missing.

1.6 Hearing Speech in Noise

The following sections will discuss the mechanisms responsible for hearing (and understanding) speech and speech in noise, since they are reported to be key areas of difficulties in APD (AAA, 2010).

1.6.1 Structure of Speech

Speech is a very complex sound, and the exact mechanism of how we hear speech, especially in noisy environments, is not yet known. Speech has phonetic properties (articulation) and acoustic properties (pitch, timbre and timing) (Yost 2000). Pitch and timing are temporal functions that are not only related to frequency resolution. Rosen (1992) reviewed the acoustic structure of speech based on its temporal properties, i.e. envelope, periodicity and fine-structure, and reported that the properties of temporal envelope include loudness, timing, rise and fall. Periodicity is due to fluctuations of periodic and aperiodic sounds and relates to speech excitation, pitch, melodic speech and intonation. Fine structure relates to timbre and quality. Binaural hearing allows us to not only detect the frequency composition of an incoming speech sound but also locate the sound sources (Kandel et al., 2000). This is a fundamental function since the energy in the sound waves is otherwise small, and the frequency composition of most sounds is complicated. It is thought that the left hemisphere is specialised for rapid temporal processing

of speech and the right hemisphere, for spectral processing (pitch) (Zatorre and Belin, 2001).

The ear has at least 3 tasks to perform when processing speech (Evans 1992): (a) to breakdown the complex speech sound into its individual frequencies (the determinant pitch frequency of the speech helps in distinguishing different speech sounds), (b) to enhance the spectral and temporal contrasts of the individual frequency components, especially in noise with poor signal-to-noise ratios and (c) to extract the behavioural meaningful cues of speech by determining tonotopicity and temporal cues of speech.

Similarly, further up the auditory pathway, fundamental aspects involved in the processing of speech sounds include its characteristic frequency, tonotopicity, non-linear suppression (when strong activity in one group of neurons suppresses the activity of adjacent neurons) and phase locking (timing) of neuronal activity (Moore et al., 2008).

1.6.2 Hearing Speech in Noise: Mechanisms

In order to hear speech in the presence of background noise, the same acoustic properties (pitch, timbre and timing) are used. Timing is fundamental; for example, stop consonants in the English language such as ‘b’ and‘d’ in the presence of noise can cause inability to differentiate speech (Anderson and Krauss, 2011).

Top-down effects of the efferent system, as described in the previous section, play an important role in hearing speech in noisy environments. The efferent fibres are more in number than the afferent ones, and the role of the former is to increase intensity, clarity and signal-to-noise ratio (Gao and Suga, 2000; Luo et al., 2008).

While listening to speech in the presence of noise, one needs to detect the component frequencies of the sound. For speech masked by, say, a single other talker, the additional problem of allocation arises, i.e. ascribing the detected components to the proper sound source. Finally, the problem is to

recognise speech when only partial information is available (Cooke et al., 2001). Speech comprises a rich and redundant source of information and prior experience and knowledge helps individuals fill the gaps when they hear speech masked in noise or distorted speech. This is based on the theory that the acoustic properties of the speech are at the bottom of the hierarchy and the linguistic and cognitive ones at the top, i.e. the top-down schema-driven mechanisms proposed by Bregman (1990). Baddeley (1992) similarly proposed a four-component model of working memory for speech comprising attention, central executive, phonological loop and visual spatial sketchpad, to which episodic buffer was recently added,. The phonological loop component is very important for the acquisition of language. The attention component appears to be important for auditory processing and listening (e.g. Moore 2012). According to James (1890), attention involves five types of cognitive behaviour: (1) perceive, (2) conceive, (3) distinguish, (4) remember and (5) shorten the reaction time of perceiving and conceiving. Attention involves multiple auditory pathways both bottom-up, with signals from the hair cells, thalamus to the auditory cortex through the thalamocortical pathways and top-down ones from the cortex back to the hair cells through the corticothalamic pathways, which reinforce the signal stream of interest and maximize expectation through feedback (Wood and Cowan, 1995).

It is well known that lip reading enhances hearing. Sumby and Pollack (1954) showed that visual cues improve comprehension of hearing speech in noise by a SNR of 15-dB. The McGurk (1976) effect illustrates that what we see influences what we hear and that this is observed even in infants of 6 months of age that have not yet developed speech skills. This audio-visual processing also requires attention (Alsius et al., 2005).

In summary, listening to speech in noise requires complex and multimodal processing, namely auditory, linguistic, cognitive and visual components, via multiple brain interconnections that are not yet fully known are essential in order to understand speech in noise.

1.6.3 Auditory Pathways that are Involved with Hearing Speech in Noise: Evidence from Imaging Studies

Recent developments in neuroimaging techniques (functional MRI [fMRI] and positron-emission tomography [PET]) that correlate structural anatomy with function have added to our knowledge about the neural brain activity during speech processing.

Studies published thus far (Millen et al., 1995; Salvi et al., 2002; Sekiyama et al., 2003; Patterson and Johnsrude, 2008; Wong et al., 2008; Okada et al., 2010) confirm the activation of superior temporal sulcus (STS) and other primary and associated areas and, therefore, the auditory element in speech processing.

Millen et al. (1995) performed fMRI on 8 adults with normal hearing (age range, 19–50 years) while the subjects listened to pure tones (1000 and 4000 Hz) and a text in English. Two of the participants were included in a third experiment in which neural activation was studied with fMRI while they listened to a text in Turkish language that was unfamiliar to them. In all those conditions, a marked bilateral activation of STG but significantly more prominently on the left side was noted in 7 of the 8 right-handed participants. The single individual who was left-handed showed more prominent activation on the right side. However, the sample size of this study was small. The linguistic information did not involve speech in noise conditions, and the authors did not mention the significance of noise interference generated by the fMRI.

Most recent neuro-imaging studies employed speech in the presence of maskers in order to investigate the brain neural systems that were activated. Salvi et al. (2002) used positron-emission tomography (PET) to examine cortical changes in 10 young adults (age range, 23–34 years) while the participants were exposed to quiet, speech, noise, and speech in noise. The noise was composed of 12-talker babbling. The results of the study, similar to those of other studies, showed the activation of the superior and middle temporal gyrus and pre-central gyrus. During the conditions of noise and

speech in noise, additional activation of the medial frontal, cerebellar areas and thalamus was noted. This indicates that listening in noisy environments is a complex auditory task that requires recruitment of cognitive and attention recourses that are not limited to what is traditionally conceived to be the central auditory pathway, as evidenced by the cerebellar involvement. This additional cognitive/attention resource recruitment is probably due to the effect of energetic masking.

Sekiyama et al. (2003) conducted a prospectively fMRI and PET study of 8 and 10 young normal subjects, respectively. They were asked to identify syllables presented auditorily (low and high speech intelligibility signal-to-noise [SNR]), visually and audiovisually. Only during the auditory presentation, bilateral activation of the STS was noted, as observed in similar studies. In the fMRI (but not PET) study, the angular gyrus (BA 39) and Broca area (BA 44 and BA 45) in the frontal cortex were also activated. Similar activations were observed for the audiovisual condition. In the noise-dominant audiovisual condition, additional findings were noted. The activation of the left temporal lobe extended posteriorly and additional activation was observed in the STG (BA 22, along with the STS) and the lateral occipito-temporal gyrus (BA 37) in both the fMRI and PET experiments. Hwang et al., in 2006, performed fMRIs in 12 healthy subjects (age range, 21–31 years) while they listened to native speech (Chinese language) and to speech in the presence of white noise (masking) binaurally. When the research participants listened to speech, the areas mostly activated were in the primary and secondary auditory cortices (BA 41 and BA 42) and in the bilateral superior and middle temporal gyri (BA 21 and BA 22). There was also some activation of the inferior frontal gyri, the anterior pole of the temporal lobe, lingual gyri and the cerebellum. When they listened to white noise, the activation was bilateral and mostly clustered at Heschl's gyrus (BAs 41 and 42), the STG (BA 22), the cuneus (BAs 18, 23 and 30), the posterior cingulate gyrus and precuneus (BA 31), but mainly on the right side. When the subjects listened to speech and white noise, the left auditory-associated cortices were activated more than those on the right side. A drawback of this study was that the noise of the fMRI scanner was not

subtracted from the analysis of the research findings and, therefore, may have influenced the activation of the abovementioned areas. The participants had the additional noise of the scanner even when they listened to speech; therefore, it was not in quiet.

Zekveld et al., in 2006, assessed activation of brain areas by fMRI in 10 adults (age range, 20–26 years) while listening to speech on noise with a varied intensity of speech but stable noise levels during the experiment. Overall, they found activation of temporal cortices, left frontal cortex and occipital cortices while the subjects listened to intelligible speech; increased activation was mainly noted in the left temporal area. Another interesting finding of this study is that while listening to unintelligible speech at very low speech-to-noise ratio, there was activation of Broca area (BA44), which is the area of internal speech representation and therefore the authors concluded that this may have triggered a top down mechanism to facilitate speech identification.

A further study by Wong P et al. in 2008, measured speech in quiet and in noise behavioural performance concurrently with fMRI in 11 young adults and the results showed involvement of the auditory cortex for both situations in the middle STG gyrus bilaterally and the left posterior STG in particular(Figure 1.6) A drawback of this study was that the research participants were presented with a list of 20 words (1 word per trial) in quiet and multi talker babbling and therefore the repetition of the words may have resulted in memorising the word list. Their findings of greater activation of left posterior STG with increase of noise differ from Hwang's et al. (2006) findings who used sentences in quiet and noise and showed activation bilaterally greater in speech in quiet but this may reflect differences in the complexity of the tasks used by the two studies

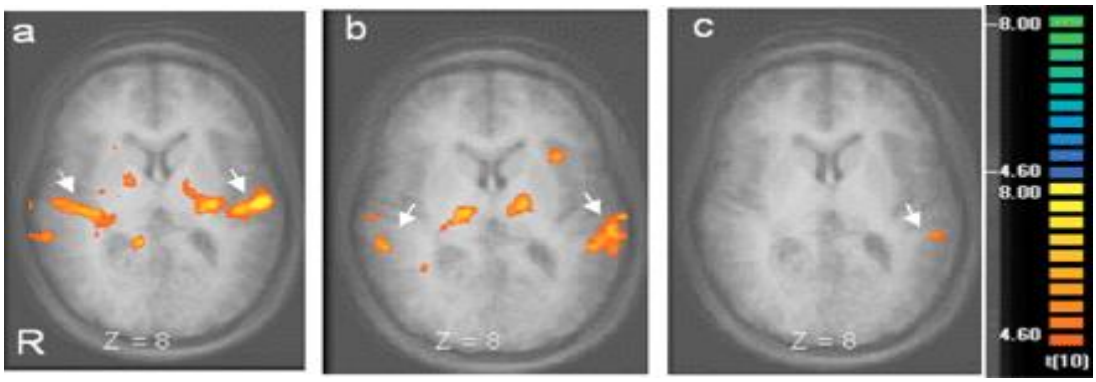


Figure 1.6: Brain activation revealed by the (a) Speech-to-noise ratio 20 vs. quiet, (b) Speech-to-noise ratio 5 vs. quiet and (c) Speech-to-noise ratio vs. quiet

Note left lateralised superior temporal gyrus (STG) activation as noise level is increased.
From Wong et al., 2008

Obleser et al. (2008) showed that on manipulation of speech in its spectral and temporal domains by using noise-band coding and simultaneously measuring the brain function with fMRI, both domains would stimulate different brain areas in a parallel way. The spectral domain would be represented in the right STS and the temporal domain, in the left STS; therefore, the right hemisphere would show more activity.

Uppenkamp et al. (2006), Wilson et al. (2004) and Salvi et al. (2002) reported that in addition to the bilateral activation of the STS, there was also minimal activation of the precentral/premotor regions in both the left and right hemispheres. This activation was observed during the perception of vowels (Uppenkamp et al., 2006) and during passive listening. Further research is needed to determine why listening to speech activates motor speech centres; nevertheless, a possible explanation may be that the acoustic-to-speech transformation relies on the temporal lobe and pre-motor regions.

In a larger study by Okada et al. (2010), 20 right-handed native English speakers between 18-47 years of age were asked to listen to 4 different auditory stimuli: (a) clear speech sentences (intelligible), (b) noise-vocoded speech (intelligible), (c) spectrally rotated speech (unintelligible) and (d) rotated noise-vocoded speech (unintelligible). During these 4 conditions, activation was largely noted in the lateral superior temporal cortex of both hemispheres. Unlike previous studies, which report a predominant activation

of the left anterior temporal area, Okada et al. noted robust bilateral activation of the anterior STS/superior temporal gyrus (STG) as well as of the posterior portions of the STS/STG. Additional smaller foci of activation were found in the inferior temporal gyrus (right), fusiform gyrus (bilateral), parahippocampal gyrus (left), inferior and middle frontal gyri (left) and cerebellum (right). The failure of the previous studies to find bilateral activation may be because those studies had smaller number of participants (N = 7–11 subjects).

Another study by Davis et al. (2011) sought to examine the top-down mechanisms in understanding sentences. fMRI was performed on 13 right-handed native English speakers volunteers aged between 18 and 45 years (mean age, 26 years) while they listened to coherent and anomalous spoken sentences presented at six SNRs between -5 and 0 dB. A bilateral activation of the temporal and frontal areas was noted. A novel contribution of this study was that antero-lateral, postero-lateral and medial regions of the temporal lobe displayed functional interactions between the sentence type and speech clarity. The areas activated during active comprehension of the degraded speech were the anterior temporal and inferior frontal regions.

A more recent study by Wild et al. (2012) tested 21 right-handed native speakers of the English language who were undergraduate students between the ages of 19 and 27 years (mean age, 21 years). To avoid the interference of the scanner noise, the sparse imaging design was used with the scanner turned off when the speech stimulus was presented. On every trial, the research participants attended to one of three simultaneously presented stimuli: a sentence (at one of four acoustic clarity levels), an auditory distracter (narrow-band noise bursts) or a visual distracter. The research participants were able to remember clear speech when they paid attention or were distracted. Data from 19 participants were analysed (data of two of the research participants were contaminated). Bilateral activation of STS was observed and the level of activation (enhancement) was correlated with intelligibility. When attention to speech was paid, the left inferior frontal gyrus activity for degraded speech was greater than that for clear speech

(i.e. a noise-elevated response), which suggested that attention enhances the processing of speech by engaging higher-order brain mechanisms. (Table 1.3)

Table 1.3: Summary of studies regarding functional imaging for hearing speech in noise

Authors	Subjects Number & Age	Speech stimulus	Brain areas activated
Millen et al., 1995	8 (21–50 y)	Familiar and unfamiliar speech	Superior temporal gyrus of both hemispheres Left>Right, in unfamiliar speech
Salvi et al., 2002	10 (23–34y)	Speech (sentences) in quiet and multi-talker babble noise	Superior and middle temporal gyri of both hemispheres Premotor temporal regions of both hemispheres Cerebellum on both hemispheres, thalamo-frontal areas, in noise
Sekiyama et al., 2003	8(22–46 y) and 10 (20–46 y)	Speech with and without visual cues	Auditory: Temporal gyri of both hemispheres and premotor temporal region. Visual: Additional occipital areas
Uppekamp at al., 2006	9 adults (20–50 y)	Speech and non-speech	Temporal gyrus of both hemispheres and premotor temporal regions
Hwang et al., 2006	12 (21–31y)	Speech (sentences) in quiet and in white noise	Superior temporal gyrus of both hemispheres Left>Right in speech in noise. Brain activation more enhanced for speech in quiet
Zekveld et al., 2006	10 (20–26 y)	Speech spectrum in noise Increase noise	Left temporal area, frontal and occipital areas Unintelligible speech: Broca area (speech centre) top-down mechanism
Wong et al., 2008	11 (20–34 y)	Speech (words) in quiet and in multi-talker babble	Temporal gyri of both hemispheres Left superior temporal gyrus increase of noise
Obleser et al., 2008	16 (20–32 y)	Spectral and temporal characteristics of speech	Spectral domain activation of right temporal gyrus; Temporal domain activation of left temporal gyrus

Okada et al., 2010	20 (18-47 y)	a) Speech sentences b) Noise-vocoded speech (intelligible) c) Rotated speech d) Rotated noise-vocoded (unintelligible) speech	Temporal gyri of both hemispheres; Activation of supratemporal regions for conditions c and d
Davis et al., 2011	13 (18-45 y)	Coherent and anomalous spoken sentences presented at six SNRs between -5 and 0 dB	Temporal and frontal areas of both sides; Antero-lateral, postero-lateral and medial regions of the temporal lobe display functional interactions between sentence type and speech clarity. Areas activated during effortful comprehension of degraded speech were the anterior temporal and inferior frontal regions.
Wild et al., 2012	21 (19-27 y)	Sentences, noise (narrow-band bursts) and visual distracters	Superior temporal sulci of both hemispheres and the level of activation (enhancement) was correlated with intelligibility.

There are several reasons for the slight discrepancies noted in the findings of the above-mentioned neuroimaging studies. The studies differ with respect to speech stimuli used: non-speech sounds (Uppekamp et al., 2006), words(Wong et al., 2008), sentences (Millen et al., 1995; Salvi et al., 2002; Sekiyama et al., 2003; Hwang et al., 2006;Okada et al., 2010, Wild et al., 2012), intelligible speech (Hwang et al., 2006; Wong et al., 2008), unintelligible speech (Zekveld et al., 2006; Okada et al., 2010; Davis et al., 2011) and unfamiliar speech (Millen et al., 1995) .

The studies also differed in the type of masking noise used: white noise (Salvi et al., 2002; Hwang et al., 2006; Wild et al., 2012), multi-talker babble (Wong et al., 2008; Okada et al., 2010) and competing sentences (Zekveld et al., 2006). The majority of the published studies have a small number of participants, and only more recent ones since 2009 have been more large scale. The noise from the fMRI scanners is an additional acoustic stimulus, and it is not clear whether or not the scanner was turned off during the presentation of the stimulus for several of these studies.

Despite the factors that may limit the interpretation of results, the above studies show consistent activation of the temporal lobes by speech in noise, but it is not clear if this is observed predominantly in one hemisphere or in both. Activation of other cortical areas such as the frontal and parietal brain areas was also noted, particularly when the task performed is more challenging; this suggests that listening to speech in noise heavily relies on the recruitment of cognitive resources; however, the areas recruited differ across these studies. Further research is needed to resolve these ambiguities and provide accurate information on the pathways involved and mechanisms relied upon for listening to speech in noise.

1.6.4 Age-Related Factors that Affect Hearing Speech in Noise

A recent study by Hind et al. (2011) found that the majority of referrals for subjects with hearing difficulties were either young children (mean age, 5.8 years; median age, 5.3 years) or older adults (mean age, 69.5 years; median age, 72.3 years). It is not surprising that such referrals pertain to the upper end of the age spectrum as well as the lower end. For the older adults in particular, age-related complex changes affect the peripheral and central auditory systems and also cause a decline of the sensory and cognitive functions. A study by the National Research Council's Committee on Hearing and Bioacoustics and Biomechanics (CHABA, 1988) showed that elderly people complain significantly more regarding difficulties in hearing speech. Older adults diagnosed with auditory processing disorders report more handicaps than those without processing disorders (Jerger et al., 1990). A study by Humes (2005) of 213 older adult hearing-aid users (age range, 60–88 years) with bilateral symmetrical hearing loss found that their performance on auditory processing tests was associated primarily with cognitive function and age. Murphy et al. (2006), however, found that older adults with normal hearing for their age (N = 36, mean age 69 years) had significantly greater difficulties than younger ones in using auditory cues and following conversations between two talkers; therefore, such difficulties were presumed to be associated with auditory processing problems and not cognitive ones. This study consisted of 4 experiments. During the first 3 experiments, the research participants listened to dialogues in a sound-

attenuated room. The dialogues were presented in quiet, moderate babble and high babble noise. In experiment 1, the dialogue and noise presentation levels were the same for all participants, but in experiments 2 and 3, the dialogue presentation and noise levels were adjusted according to the hearing thresholds of each participant. The main findings were that older research participants answered less questions correctly compared to the younger ones. Therefore, the authors conducted a fourth experiment where the spatial separation was removed by listening to speech in the presence of multi-talker babble delivered by a central loudspeaker. Twelve older and 12 younger adults participated in experiment 4, and there were no statistical differences in the responses between the two groups. Age-related neurodegenerative changes affect the brain regions such as corpus callosum (Jeeves and Moes, 1996) the right hemisphere more than the left (Brown and Jaffe 1975). Such changes may also impact on processing of speech in later life. In addition, cerebrovascular diseases that occur more frequently with increasing age may also affect auditory processing, and there are several studies on patients with stroke having disordered auditory processing (e.g. Bamiou et al., 2006; Bamiou et al. 2012).

1.7 Justification for the Research Study

Individuals with APD present with hearing difficulties in the presence of a normal audiogram. APD is classified under category H93.25 in ICD-10; however, it remains a controversial diagnosis. There is no ‘gold standard’ test, and no consensus on the diagnostic criteria for APD, while there is a wide range of diagnostic yield for the different diagnostic rules in use (Wilson and Arnott, 2013). APDs are very heterogeneous and complex. They affect both children and adults; however, the aetiology and comorbidities may well vary in the adults compared to the paediatric population. There is currently a debate among professionals regarding whether APD should be conceptualised as true auditory sensory processing disorder or whether this clinical presentation is related more closely to higher-order speech and language processing or to cognitive and attention deficits and disorders, in view of neuroimaging studies’ findings. There is a paucity of research studies

in working-age adults to compare to the published studies in paediatric and older adult populations. Comorbidities in younger adults and, therefore, confounding factors that affect diagnosis of APD may be fewer; therefore, studying this population may help better understand the clinical presentation of APD and, to some extent, the evolution of APD during the life span. There is also a pressing need for quantifying symptoms by using validated questionnaires and also correlating these with APD tests, to help inform diagnostic test choice but also conceptualisation of APD, as proposed both by consensus papers (Moore et al., 2013) and field studies (Cameron and Dillon, 2011). Such studies should be conducted on both individuals affected with APD and normal controls, since findings in clinical populations compared to normal populations may differ. For example, Ahmmed et al. (2014) found that general auditory processing was the first component that accounted for test findings in a factor analysis of a clinical paediatric population with suspected APD. On the other hand, a study in a normal paediatric population found that the cognitive element was primarily responsible for this presentation (Moore et al., 2010). In view of the wide range of the diagnostic yield for the criteria used and in the absence of widely accepted criteria (Wilson and Arnott 2013), it would be informative to include in clinical studies individuals who are referred for APD assessment but do not meet diagnostic criteria.

There is a need to assess the potential of existing questionnaires as screening tools for APD, in view of the potentially high prevalence of hearing difficulties in adults with normal audiograms (e.g. Kumar et al., 2007).Finally, there is a need to correlate symptoms with auditory test results in order to quantify the hearing difficulties and choose the appropriate management strategies.

CHAPTER 2: METHODOLOGY

2.1 Research Hypotheses

2.1.1 Primary Hypothesis

- Adults with normal hearing who are diagnosed with an APD present with self-reported auditory symptoms scores on validated questionnaires that are significantly worse than adults who do not fulfil the diagnostic criteria for APD and normal controls.

2.1.2 Secondary Hypotheses

- Validated auditory questionnaires that provide a comprehensive description of auditory symptoms will help distinguish between individuals with APD and those without APD and can be reliably used as screening tools for adults with APD who will require further assessment.
- Adult-reported symptoms will correlate with and can be quantified by auditory processing tests from the APD test battery
- A speech- in-babble (SIB) test will correlate with patient-reported auditory symptoms.

2.2 Aims of Research Study

- To collect normative data for an adaptive SIB test to use as part of a diagnostic APD battery for adults
- To assess symptom differences among adults with APD, normal controls and participants with hearing difficulties but not meeting the diagnostic criteria for APD (clinical non-APD) (AAA, 2010; BSA, 2011)
- To assess the sensitivity and specificity of three validated auditory questionnaires as screening tools for APD in adults
- To assess the correlation between self-reported auditory symptoms (on questionnaires) and auditory processing tests

2.3 Thesis Structure

This research project was divided in three separate studies (phases), presented in Chapters 3 to 5, and more detailed descriptions of participants and methods are given in each chapter. Chapter 3 (Phase 1) describes normative data collection for the SIB test used in this study. Chapter 4 (Phase 2) describes the characterisation of participants with APD, as reported by validated questionnaires and differences in questionnaire scores between the participants with hearing difficulties (clinical APD and clinical non-APD) and normal groups. Chapter 5 (Phase 3) describes the correlation between the scores of the questionnaires with the results of the auditory tests (Figure 2.1).

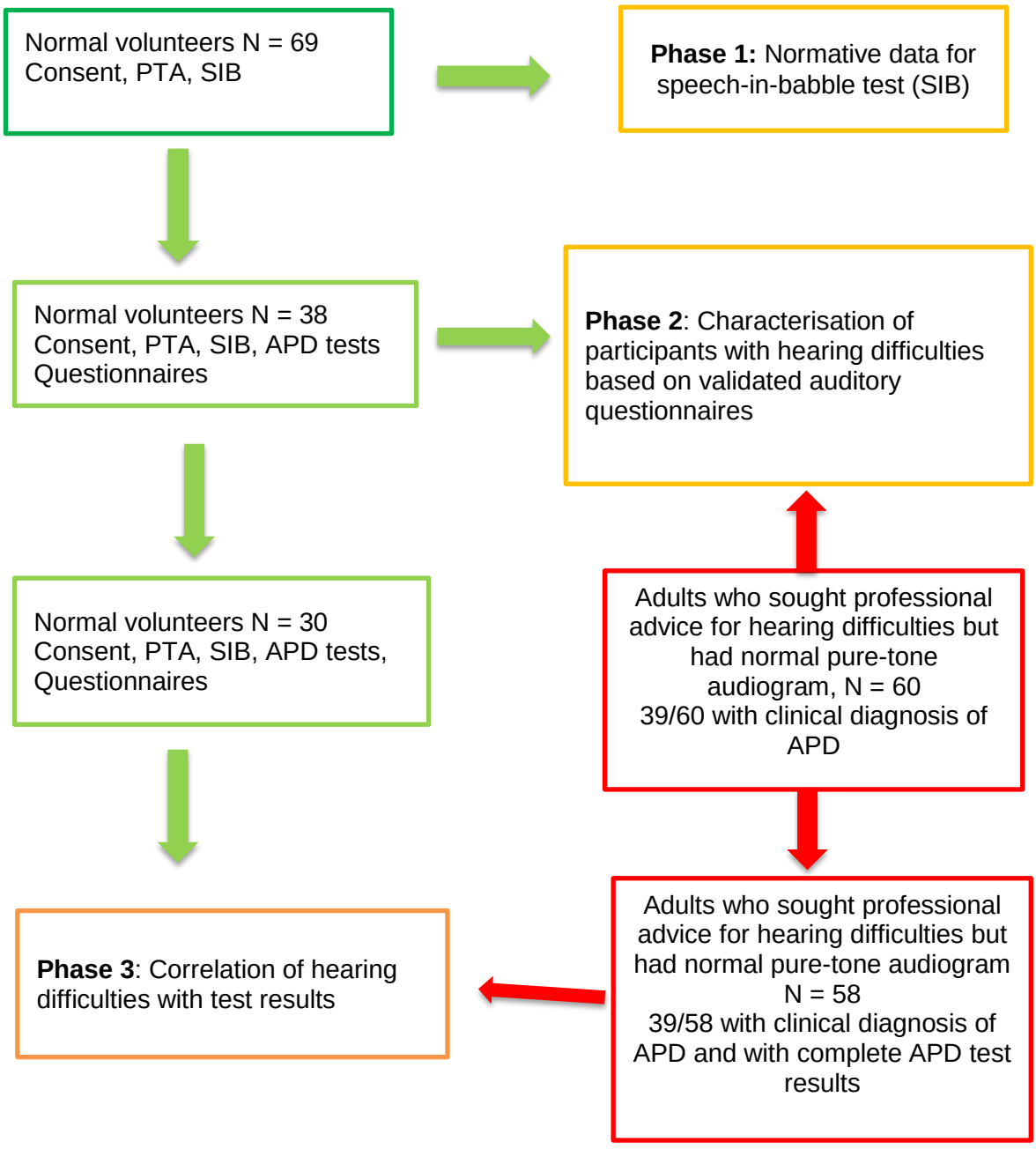


Figure 2.1: Flowchart of three studies of this research thesis

Phase 1: Collection of normative data for speech in babble test from 69 normal volunteers.
Phase 2: Characterisation of participants with hearing difficulties based on validated questionnaires. Thirty-eight of the 69 normal controls from Phase 1 of the study participated in Phase 2 along with 60 participants with reported hearing difficulties.
Phase 3: Correlation of test results with questionnaire scores. Thirty of the 38 normal controls from Phase 2 were enrolled in Phase 3, and 58 participants with hearing difficulties from Phase 2 participated in Phase 3.

2.4 Study Design

This is a prospective, normative study (Phase 1), and also a case–control study (Phases 2 and 3).

2.4.1 Setting

Patients were recruited from the direct-access audiology clinic for adults less than 60 years of age at Whittington Health, the ENT/Audiovestibular Medicine clinics at Royal National Throat, Nose and Ear Hospital (RNTNE) and the National Hospital for Neurology Neurosurgery (NHNN). Participants were tested at the RNTNE and/or the NHNN.

2.4.2 Ethics

The research study was approved by the National Research Ethics Committee of the National Hospital for Neurology and Neurosurgery (NHNN) and Institute of Neurology on 06/08/2009. (Registration number 09/H0716/ 46). The study was also approved by the Royal Free and UCLH NHS Trusts. All recruited subjects provided their written informed consent.

2.4.3 Participants

Normal controls: recruited from among hospital staff, hospital visitors, friends and relatives. The inclusion criteria were as follows:

(1) Age: 18–60 years
(2) English as first language
(3) Normal hearing ≤20dB in each audiometric frequency for 250–8000 Hz in both ears
(4) Normal function of the middle ear on both sides
(5) No history of psychiatric disease or cognitive impairment, as reported by the volunteers themselves, during the initial medical interview
(6) No hearing complaint

In all, 69 normal controls were recruited in the normative data study of SIB test (Phase 1, Chapter 3). Thirty-eight of the normal volunteers completed the study questionnaires and participated as normal controls for the analysis

of the questionnaires study (Phase 2, Chapter 4). Thirty of these 38 who had undergone the battery of auditory processing tests also participated in the study on the correlation of the questionnaire scores and results of auditory tests (Phase 3, Chapter 5). The remaining 8 of the 38 normal controls had not completed one test in the central auditory test battery and could not attend another appointment for the completion of the tests; therefore, their data were not included in the analysis of the Phase 3 study (Chapter 5).

Clinical subjects: consecutive patients with hearing/listening complaints and normal audiograms, attending the Audiology clinics between September 2009 and September 2011 were invited to participate prospectively in the study.

The inclusion criteria were as follows:

(1) Age: 18–60 years
(2) English as first language
(3) Normal hearing of ≤20 dB in each audiometric frequency for 250-8000 Hz in both ears
(4) Normal middle ear function on both sides
(5) No history of psychiatric disease or cognitive impairment, as reported by the participants themselves, during the initial medical interview
(6) No active neurological disorder and no structural abnormality on brain MRI.

Sixty adults who sought professional advice for hearing difficulties but had a normal pure-tone audiogram were recruited in the Phase 2 study. Two of those adults with reported hearing difficulties did not complete one test in the battery of APD tests and could not attend another appointment for completion of testing; therefore, their data were not included for the analysis in the Phase 3 study (Chapter 5). The subjects were classified into those with or without the clinical diagnosis of APD on the basis of the results of the auditory processing tests for APD.

2.5 APD Diagnostic Criteria Definitions

The diagnosis of APD was made on the basis of the abnormal results in at least two behavioural central auditory tests at least in one ear, one of which was a non-speech test or abnormal findings in one behavioural and one electrophysiological central auditory test (ASHA 1996; AAA 2010; BSA, 2011).

2.6 Audiological Tests

2.6.1 Pure-Tone Audiometry

The test was performed according to the guidelines published by the BSA (2011). Standard pure-tone audiometry was performed by using a GSI 61 audiometer with TDH -49 earphones in a sound-proof room. An ascending technique of 5-dB steps and descending technique of 10-dB steps were used to establish thresholds at 250, 500, 1000, 2000, 4000 and 8000 Hz. Normal hearing thresholds were considered to be ≤20 dB across the above frequency range.

2.6.2 Tympanometry

Tympanometry was performed with a 226-Hz probe signal maintained at 85-dB SPL in the sealed ear canal by using a GSI-33 Middle Ear Analyzer (BSA, 1992). Normal results were considered if the middle ear pressure was ≥150 mmH_2O and compliance was >0.3 cc.

2.6.3 Transient Evoked Otoacoustic Emissions (TEOAEs)

The test checks the cochlear outer hair-cell function (Kemp, 1978). Click stimuli are delivered through a probe in the ear canal. The inner ear responses to the click stimuli are recorded automatically. The repetition rate is 50/s, and the peak reception level is approximately 80 dB SPL. The post-stimulus recording time is 20 ms. The fast Fourier transform (FFT) spectrum analysis and average waveform calculations were performed automatically by the ILO 88/92 Otodynamic Analyser system. Normal response was

considered the finding of overall TEOAES amplitude >12 dB or amplitude of ≥6 dB in at least three adjacent frequency bands.

2.6.4 Speech –in- Babble Test

This test will be fully described in Chapter 3. Briefly, during this test, two randomly selected word lists (out of eight in total) are presented to each ear in multi-talker babble. Each word is delivered with 500 milliseconds of the babble masker at the beginning and the end of the word itself. The SNR is varied adaptively during the test, starting from +20 dB SNR and becoming more difficult after each single correct response and easier after the first incorrect response. A threshold value is thus calculated by the Matlab software as the mean SNR of 70.7% correct performance criteria (2:1 rule) from the final (six to eight) reversals (Spyridakou, et al., 2012).

2.6.5 Auditory Processing Tests

The remaining auditory processing tests were recorded on a compact disc. The compact disc was played on a Sony XE 270 CD player and passed through a GSI 61 diagnostic audiometer to TDH-50 matched earphones. The stimuli were presented at 50-dB sensation level pure-tone audiometry to each ear independently. The following central auditory processing tests were conducted.

2.6.5.1 Gaps-in-Noise Test

The gaps-in-noise (GIN) test was developed by Musiek in 2005 as a clinical tool for evaluating temporal resolution ability in a variety of clinical populations, particularly on patients with central auditory disorders.

The test is composed of a series of 6-sec segments of broadband white noise that contains 0 to 3 silent intervals (gaps in noise) of durations of 2, 3, 4,5, 6, 8, 10, 12, 15 and 20 msec (Musiek et al., 2005). The location, number and duration of the gaps vary for each segment of white noise. In all, 60 gaps are presented in each list (6 gaps per gap duration). The test has 4 lists. It is a monaural test.

The noise used in the test was a computer-generated white noise that was uniformly distributed between -32,000 and 32,000 with a root mean square value of 32,000/sqrt. The sampling rate was 44,100 Hz.

A normative data study (Samelli and Schochat, 2008) showed that the GIN test guarantees a high degree of precision in the measurement of the gap-detection thresholds. Moreover, the procedure demonstrated similar responses between different lists and for both ears (regardless of which ear was tested first). Samelli and Schochat (2008) concluded that for clinical use, the test could be done by using only two test lists instead of four, which reduces the administration time of the test by half (approximately 16 minutes). For the purposes of the present study, a different list was used for each ear, and none of the lists was used twice for the same research participant. This test provides two scores, i.e. the correct detection score (percentage of correct answers) and the gap detection threshold, which is defined as the shortest gap duration that the patient can identify in 50% of the trials. The departmental normative data at RNTNE and NHNN are correct responses of 50% or more at a minimum threshold of 6 msec.

2.6.5.2 Dichotic Digit Test

The test is a binaural central auditory test in which 2 pairs of digits are presented to the subject in each ear at 50dB SPL, and the subject has to repeat all 4 digits, not necessarily in the right order (Baran and Musiek, 2003). The digits used include the numbers 1 to 10, except 7.

Initially, the test was introduced in 1954 by Broadbent who described a technique of presenting competing sets of digits simultaneously to the two ears.

Kimura, in 1960s, performed the test in patients with temporal lobe lesions, and she suggested that during dichotic listening, the weaker ipsilateral pathways in the central auditory system tend to be suppressed. As a result of this, the neural impulses travel via the stronger pathway to reach the contralateral areas of the cerebrum.

The dichotic digit test is a sensitive test for the lesions of the auditory areas of the cortex and interhemispheric fibres. Musiek (1983) reported that the dichotic digit test can also help detect pathologies of the brain stem. Normal scores of this test are 90% or more for each ear.

2.6.5.3 The Frequency Pattern Test

This is one of the temporal pattern tests (Musiek and Pinheiro, 1987; Musiek 1994). The test items are sequences of three-tone bursts of the same duration presented monaurally. In each of the sequences, two of the tone bursts are of the same frequency, while the third one is of a different frequency. There are thus two different frequencies used in this test: a high-frequency (1.122 Hz) sound and a low-frequency (880 Hz) sound. The patient, therefore, hears patterns and is asked to either hum or label the pattern he is presented with, such as high-high-low or low-high-low. Normal scores for this test are 80% or more for each ear.

2.6.5.4 The Duration Pattern Test

This test is also a temporal pattern test (Musiek, 1994). Each pattern consists of three 1000-Hz tones of one of two durations, short (250 milliseconds) and long (500 milliseconds). That is, e.g. two short, one long or one long, two short, in disparate patterns. The test is delivered monaurally, and normative data are 70% or more in each ear.

2.6.5.5 Suppression of Transient Evoked Otoacoustic Emissions (TEOAEs) by Contralateral Noise

The same ILO 88/92 Otodynamic Analyzer System used for the TEOAEs test was used for these tests (Ceranic et al., 1998). Presence of a normal response on TEOAEs is a necessary pre-requirement for the test. During suppression of TEOAEs by contralateral noise, the TEOAE is recorded using an evoking click or tone, both with and without suppressive noise, and the difference in amplitude of the two responses is calculated ($TEOAE_{quiet}$ – $TEOAE_{noise}$).

A dual-channel otoacoustic emission analyser was used, with one channel (A) for ipsilateral and the other (B) for contralateral acoustic stimulation. A

linear click at intensity of 60 SPL was used for ipsilateral stimulation, and a broad-band noise (0.50–6 kHz) at 40 dB sensation levels (SL) was used for contralateral acoustic stimulation. The click intensity was lower than 75 dBSPL to avoid eliciting muscular contraction in the middle ear. A total of 600 sweeps were recorded, in 10 groups of 60 sweeps. The average responses were directly computed, and the difference obtained by the subtraction represented the suppression effect. When the suppression test shows TEOAE reduction (subtraction of measurements of TEOAEs with and without noise) with values of ≥1dB; then, the function of the medial olivocochlear bundle is normal (Ceranic et al., 1998).

2.7 Questionnaires

Participants were provided three validated questionnaires. The detailed descriptions of these and justification for their use are provided in Chapter 4.

i) The (Modified) Amsterdam Inventory for Auditory Disability by Meijer et al. (2003) (Appendix 1). The questionnaire is based on the Amsterdam Inventory for Auditory Disability and Handicap by Kramer et al. (1995). The first version of this questionnaire consisted of 30 questions while the modified version has 28 and assesses auditory disability in five key domains: (1) speech intelligibility in noise (question numbers: 7, 24, 18, 1 and 13), (2) speech intelligibility in quiet (question numbers: 14,19,11, 12 and 8), (3) auditory localisation (question numbers: 15, 3, 26, 20 and 9), (4) recognition of sound (4, 5, 6, 17, 22, 23, 25 and 28) and (5) detection of sound (question numbers: 27,16, 21, 2 and 10). The response are graded as follows: ‘almost never’ (0 points), ‘occasionally’ (1 point), ‘frequently’ (2 points), ‘almost always’ (3 points), where ‘almost never’ indicates hearing difficulties and ‘almost always’ indicates no hearing difficulties.

ii) The Speech, Spatial and Qualities of Hearing Scale (SSQ) by Gatehouse and Noble (2004) (Appendix 2). The questionnaire was designed to measure a range of auditory symptoms which may lead to difficulties in hearing with background noise. The questionnaire consists of 3 sections pertaining to speech hearing (questions 1–14), spatial hearing (questions 1–17) and

sound hearing (questions 1–19). The scoring system uses the ruler representation from 0 to 10, with 0 indicating complete inability and 10 indicating great ability.

iii) The Hyperacusis Questionnaire by Khalfa et al. (2001) (Appendix 3). The questionnaire is divided into 2 parts. The first part along with the individual's details includes 3 questions with regard to noise exposure and hearing problems. The second part consists of 14 questions. The hyperacusis questionnaire covers 3 domains: attention (questions 1–4), social (questions 5–10) and emotional dimension (questions 11–14).

The response categories were as follows: 'no' (0 points), 'yes a little' (1 point), 'yes quite a lot' (2 points), and 'yes a lot' (3 points).

2.8 Overview of Methods

All the study participants were administered a battery of auditory tests and questionnaires, which were filled in after the audiogram but before any further testing. Further details on the methodology of each study are provided in the ensuing chapters.

2.9 Statistical Analysis

SPSS version 17 for used for the statistical analyses.

CHAPTER 3: PHASE 1—SPEECH-IN-BABBLE TEST—NORMATIVE DATA

3.1 Overview of Speech-in-Noise Tests

3.1.1 Why do we Need Speech-in-Noise Tests?

Understanding speech in noise is a major concern relevant to not only patients with hearing loss but also those with normal hearing. The world is noisy and people face demanding listening situations in their everyday life. Speech intelligibility can be measured by speech-in-quiet audiometry; however, this test does not correspond with problems experienced in the presence of background noise.

The importance of speech- in- noise tests was highlighted in 1970 by Carhart and Tillman who recommended that speech- in-noise tests should be part of the standard audiological test battery. Over the years, several speech- in-noise tests have been developed; however, they are not part of the routine audiology test battery. According to Wilson et al. (2007), this is due to several reasons: there were no commercially available speech- in-noise tests involving the presentation of words instead of sentences until 2003; audiologists have difficulties in scoring the speech-in-noise tests and applying the scores to clinical practice and counselling; these tests are time consuming; there is a lack of available information about speech- in-noise tests.

Speech-in-noise tests should be included in the audiological assessment of patients with hearing loss and also patients with normal hearing who complain of listening difficulties in noisy environments (Wilson and McArdle, 2005). These tests may to some extent, but not entirely measure, the reported complaints of speech difficulties in noisy environments (Spyridakou et al., 2012). Since reported difficulties in hearing speech- in-noise are the most common referral reason for an APD assessment (Hind et al., 2011) and a common symptom in patients with APD (AAA, 2010), speech- in-noise tests should be part of the APD behavioural test battery (ASHA, 2005; AAA,

2010; BSA, 2011). Additionally, these tests can facilitate the assessment of the overall integrity of the central auditory system, provide information to guide the counselling of patients and can be used as an outcome measure following auditory training and/or management of hearing loss.

3.1.2 Review of Speech-in-Noise Tests

There are a variety of speech-in-noise tests in English that are in use: adaptive vs. fixed speech- in-noise; words vs. sentences; noise vs. multi-talker babbling. Although the oldest speech- in-noise test, the Synthetic Sentence Identification-Ipsilateral Competing Message (SSI-ICM), developed by Speaks and Jerger, dates back to 1965, there was a paucity of further development of speech tests until 2003. Thereafter, several speech- in-noise tests have become available for clinical use. Up to recently, commercially available speech- in- noise tests used sentence-level materials instead of words as the target stimuli. An overview of speech- in- noise tests in English with a short test description is provided in Tables 3.1 and 3.2.

Table 3.1: List of speech-in-noise tests where sentences are used with noise or multi-talker babble is used

Synthetic Sentence Identification-Ipsilateral Competing Message (SSI-ICM) Speaks and Jerger, 1965; Jerger and Jerger,1975
Sentences (i.e.10 nonsense-like) are presented to the target ear with an ipsilateral, competing, continuous discourse. The listener is required to mark the sentence heard from a printed list of 10 sentences. This type of response minimises the potential influence of language and memory, but requires that the participant be capable of reading.
Paediatric Sentence Identification-Ipsilateral Competing Message (PSI-ICM) Jerger and Jerger ,1984
Adaptation of SSI-ICM for children 3-6 years, child points to a picture presenting the stimulus word. The test can also be performed with competing discourse to the contralateral ear (PSI-CCM)
Connected Sentence Test (CST) Cox et al., 1987
Monaural speech in multi-talker babbling test, presented at a selected SNR rate. Percentage of correctly identified sentences. The test was developed initially for hearing aid users.

Speech-in-Noise Test (SINT) Fikret-Pasa, 1993
Lists of 5 sentences are presented at 4 SNRs and 2 levels. Total percentage score and an SNR for 50% performance are measured at each level of presentation. Many practitioners reported that the test is time consuming and scoring is very difficult; additionally, not all lists are equivocal, and therefore, only a few can be used.
Hearing-in-noise test (HINT) Nilsson et al.,1994
Measures speech threshold for sentences in quiet and in 3 different conditions of speech-spectrum background noise (noise from the front, left and right). The threshold corresponds to an SNR at 50% performance. The test has been used for a few APD cases but mainly for users of hearing aids.
Bamford-Kowal-Bench- Speech in Noise test (BKB-SIN) Niquette et al., 2003; Etymotic Research, 2005
Measures speech threshold for sentences in multi-talker babble at 3 selected SNRs. The threshold responds to an SNR at 50% performance.
Listening in Spatialized Noise–Sentence (LISN-S) Cameron and Dillon, 2007
Test is used for children >5 years of age. Speech reception thresholds for sentences are measured for sentences presented in 4 conditions where the multi-talking babble is manipulated with respect to location in auditory space and vocal quality of the speakers (same as or different from the target sentences).

Table 3.2: List of speech-in-noise tests that use monosyllabic words

Speech perception in noise (SPIN) Kalikow et al., 1977; Bilger et al., 1984
Scores are based on percentage of correctly identified key monosyllabic words of low and high predictable sentences. Multi-talker babble is variable. The recognition score of less predictable sentences reflects auditory processing and the recognition score of highly predictable ones reflects language processing.
Quick- Speech-in-noise test (Quick-SIN) Killion et al., 2004
Test principle based on SIN. It contains target words in lists of sentences in noise (4-talker babble) that can be used to determine signal-to-noise ratio (SNR) loss. Each list takes about one minute to administer. To obtain the value of SNR loss, the average correct score obtained at each SNR is subtracted from the score obtained at the reference 25.5 dB.
Word in Noise (WIN) Wilson, 2003; Wilson et al., 2007
The threshold is based on SNR of 50% correct performance. Test uses monosyllabic words in seven SNRs of multi-talker babble to evaluate the ability of individuals to understand speech in background noise.

3.2 Parameters of Speech-in-Noise Tests

3.2.1 Words vs. Sentences in Speech-in-Noise Tests

The majority of speech-in-noise tests use sentences, and it can be argued that these reflect better communication demands in the real listening world compared to the speech- in- noise tests that use words.

However, sentence recognition requires more complex skills than word recognition. According to current speech perception theories (Sanders, 1977), listening to speech is a function of both passive (acoustic properties of speech) and active (additional linguistic/cognitive properties) listening and both types may underlie perception, depending on the listening conditions. Although both types of listening rely on a combination of auditory processing and linguistic/cognitive skills, the recognition of sentences relies more on linguistic and cognitive skills than single words. Therefore, when performance of listeners is assessed in these tests, they do not only measure the auditory processing (McArdle and Wilson, 2008). This postulation is based on the theory that speech recognition is organised hierarchically, with the acoustic properties of speech at the bottom (bottom-up processing) and the linguistic and higher-level cognitive ones at the top of the hierarchy (top-down processing) (Luce and Pisoni, 1998; McArdle and Wilson, 2008).

According to the Neighbourhood Activation Model (NAM), words are organised on the basis of similarity in long-term memory. In order to recognise words while listening to speech, auditory sensory processing (bottom up) needs to activate the relevant neighbourhood and the word that was heard needs to be matched with one from the long-term memory (top-down) (Luce and Pisoni, 1998).

A study by Luce et al. (1990) showed that the difficulty young adults with normal hearing had in recognising the target word from the neighbourhood depended on the following factors: (a) word frequency (number of times word is used in language), (b) neighbourhood density (number of similar words) and (c) neighbourhood frequency (how frequent are all similar words in a

lexical neighbourhood). Those lexical properties determine whether a word is ‘difficult’ or ‘easy’. In addition to recognising the target word, the listener must be able to reproduce speech. Good production of speech depends upon normal perception, as per the motor theory of speech perception (Liberman, 1970), and there are overlapping neural pathways.

A study by Wilson et al. (2008) compared the performance of 14 young adults with normal hearing on 4 monosyllabic word lists: (a) PAL PB-50 (Egan, 1948), (b) W-22 (Hirsh et al., 1952), (c) North Western University Auditory Test No. 6 (NU–6; Tillman and Carhart, 1966) and (d) 1 list of monosyllabic digits (1–10, excluding the disyllabic 7). The findings of the study showed that subjects performed slightly better on digit recognition (e.g. a closed set of words) than in recognition of monosyllabic words, with a mean recognition performance that was 1–2 dB better for the digits. The phonetic/phonemic balance of word lists does not appear to affect the mean performance on word-recognition tests. McArdle and Wilson (2008) analysed data of the same study further in order to determine whether acoustic variables (root mean square and duration of words), phonetic variables (consonants, vowels, place and voicing) and lexical variances influence performance in SIN tests. The results showed that 50% of the variance in the mean performance of the tests was predominantly accounted for by acoustic and phonetic variables (45%), whereas only 3% of the variance was accounted for by lexical variables. These findings would suggest that monosyllabic word-recognition in noise is more dependent on auditory than on linguistic factors.

3.2.2 Noise vs. Multi-Talker Babbling in Speech-in-Noise Tests

Another variable in the speech- in-noise tests is the background type of noise. When the listener hears speech that is degraded due to an acoustic background of speech and non-speech signals, the effect is called masking (American Standard Association, 1960). The relationship of the level of the speech signal to that of the masking sound is described as the SNR and is expressed in decibels. At 0 dB, the speech and masking signal are of equal strength. Speech recognition performance depends on the spectral and

temporal properties of the background noise and, therefore, on the degree of direct interaction of the target and masker at the cochlear level, which may render speech inaudible (Dreschler et al., 2001). This is termed as energetic or peripheral masking and differs from the informational (central) masking in which listeners hear both the target and masker speech, but they have difficulty in dissociating the speech from the masker (Brungart et al., 2001).

Speech- in-noise tests can employ different types of noise. A study by Danhauer and Leppler (1979) compared speech understanding in adults with normal hearing in 4 types of noise: four-talker competitors, nine-talker competitors, cocktail party noise and white noise. The findings were that speech understanding was better at cocktail party noise and white noise than in multi-talker babbling. Multi-talker babbling is a more ecological type of masker since it is more similar to noises encountered in real life (Plomp, 1978).

Wilson (2003) highlighted the benefits of using multi-talker babbling as a masker; multi-talker babbling involves several speakers talking at the same time, with none of the conversations being intelligible. Multi-talker babbling is the most common environmental background noise where listeners report problems. The problems experienced by listeners in the presence of multi-talker babble are attributed to the fact that the background noise is speech-spectrum shaped (thus leading to energetic masking), while there is minimal amplitude modulation of the envelope (reducing opportunities for glimpsing), and the masker is aperiodic. The number of talkers in the babble masker affects performance on listening speech of up to 4 talkers babble, but not significantly thereafter (Rosen et al., 2013)

Another type of background noise that can be used as a masker in speech-in- noise tests is the speech-spectrum noise that uses noise with a spectrum equal to the long-term average spectrum of the recorded speech material (Nilsson et al., 1994).

Wong et al. conducted a study in 2012 to compare different types of noise in speech recognition performance: (a) speech recognition performance with

steady-state speech-spectrum-shaped noise and (b) speech recognition performance with 6 types of environmental noises, including lower deck of bus, upper deck of bus, café, Chinese restaurant, street and subway train. Thirty adults with normal hearing were tested with the Cantonese Hearing in Noise Test (CHINT). The results showed that the performance was the same for 4 out of 6 environmental sounds (café, Chinese restaurant, subway train and upper deck of bus) as in the steady-state speech spectrum- shaped noise; this similarity was not observed for noise of the lower deck of the bus and street noise. The authors concluded that for listeners with normal hearing, the speech recognition with steady-state speech-spectrum noise could predict listening situations in the majority of the real environmental sounds. Informational masking seemed to have an impact on test performance.

Wilson et al. (2007) compared the multi-talker babble with speech-spectrum noise in words-in-noise test (WIN) and found that 88% of the normally hearing participants performed better with the multi-talker babble.

A research study conducted as part of a Masters dissertation thesis by Kunaratnam et al. (2003) showed that the sensitivity of a speech- in- babble (SIB) test in identifying adults with cerebrovascular disease of the central auditory nervous system was 75% while the sensitivity of the speech-in-noise test was 50%; therefore, it was concluded that SIB was a better discriminator test for evaluating difficulty in hearing speech- in-noise due to neurological auditory processing deficits. However, cognitive function and linguistic performance of these subjects was not assessed, and the observed findings may well be due to a combination of low-level sensory processing and high-level factors affecting performance in the SIB test.

3.2.3 Effects of Fixed vs. Adaptive Speech in Noise on Speech-in-Noise Tests

Another masking parameter is the application of fixed vs. adjusted signal to noise ratio in an adaptive procedure. For some tests, the noise level is fixed with the speech level adjusted on the basis of the subject's responses

(Nilsson et al., 1994; Brand and Kollmeier, 2002), while in other SIN tests, the speech level is fixed and the noise level is adjusted (Dubno et al., 1984; Gustafsson and Arlinger, 1994). A study by Wagener and Brandt (2005) compared effects of different speech test parameters on speech intelligibility in adult listeners with normal hearing vs. listeners with hearing loss. The Oldenburg Sentence Test was employed (German Language) and 10 normal hearing subjects (median age, 26.5 years) and 10 older ones (median age, 70 years) with sensorineural hearing loss were assessed at a speech presentation level of 65 dB SPL for normal hearing subjects and up to 80 dB SPL for the hearing-impaired listeners. No differences were found between an adaptive procedure with fixed noise level and a similar adaptive procedure with fixed speech level. The fluctuating, speech-shaped noise was recommended in order to differentiate between hearing impaired and normal hearing, although the results were not statistically different. There were only mild intergroup differences between the results for continuous and gated masking noise. A recent study by Wilson and McArdle (2012) examined how speech recognition was influenced when the speech level was fixed and the noise level varied from speech recognition for a fixed noise level but variable speech level. The study involved two groups of research participants including 16 young adults (mean age: 23.5 years) with normal hearing and 48 older adults (mean age: 68.1 years) with hearing loss. Although both groups performed slightly better when the speech signal was varied and the multi-talker babble was fixed, the results were not statistically different; thus, the authors concluded that equivalent results were obtained irrespective of whether the level of the speech was fixed and the level of the noise varied or the level of the noise varied and the level of speech fixed.

3.2.4 Language and Speech-in-Noise Tests

All the above-mentioned Anglophone speech- in-noise tests were developed in the USA (American English) apart from LISN-S (Cameron and Dillon, 2007), which was developed in Australian (Australian English). Some of these tests have been adjusted and developed in other languages, e.g. HINT has been developed in Japanese, Latin American Spanish and Canadian French (Soli et al., 2002) and in Cantonese language (Wong and Soli, 2005).

For speech- in- noise tests, the listeners should be assessed in their native language even if they are proficient in a second or third language. Tabri et al. (2011) showed that bilingual and trilingual adults with normal hearing performed equally well in the speech in quiet tests, but performed significantly more poorly for their second language and even more poorly for their third language in speech- in-noise tests compared to performers assessed in their first language. Dawes and Bishop (2007) evaluated the SCAN-C in UK children. The authors compared the results of 99 Oxfordshire school children aged 6–10 years with normative data obtained for children from the USA. Across all ages, the UK children scored significantly worse on two of the subtests; the filtered words (FW) and auditory figure-ground (AFG) sections as well as on the composite score. The authors suggested that each anglophone country should record their own speech material. In the UK, there is thus a need for the development of speech- in- noise tests in British English.

3.2.5 Speech-in-Babble Test for APD Assessment

In order to assess adults for APD, a speech- in- noise test should be part of the APD test battery (AAA, 2010; BSA, 2011). In the UK, there is a paucity of speech- in-noise tests in British English. The above review of speech- in-noise tests shows the advantage of speech tests that use words vs. sentences (Wilson and McArdle, 2008) as they appear to rely more on auditory sensory processing factors than cognitive factors. Speech in multi-talker babble corresponds well with real-life listening situations (Wilson et al., 2007; Rosen et al., 2013). In view of the literature reviewed in previous paragraphs, the newly developed SIB test by Rosen (2003) could be considered sensitive (for auditory sensory processing deficits) and ecologically valid for clinical use as in order to assess adults with suspected APD.

3.3 Aim of Study (Phase 1)

The aim of the study was to establish normative data for the SIB test in adults with normal hearing, in order to use the test as part of the APD test battery of the study.

3.4 Methodology

3.4.1 Speech-in-Babble Test-Protocol

The test was presented on a calibrated computer using Matlab software with Senheiser headphones. The test was presented monaurally. The testing session was carried out in a sound-proof room. Two random lists were selected (8 in total) for each ear. The word lists have been created by Stuart Rosen. Each list contains 25 words comprising of monosyllabic phonetically (phonemically) balanced meaningful words as the speech stimulus presented with multi-talker babbling as the masker. The words are of equal lexical difficulty. The word lists were recorded by a female Southern-English speaker in an anechoic chamber. Each word was delivered with 500 milliseconds of babble masker at the beginning and the end of the word itself. The babble noise was 20-talker babble obtained from University College Hospital/Middlesex Hospital Video Laser Disc, 1993, at approximately equal sound levels. The SNR was varied adaptively during the test, starting from +20 dB SNR and increasing in difficulty after each single correct response and easier after the first incorrect response. Each ear was tested twice, which gives information of test reliability in the same subject. The listeners were required to repeat the words that they heard. A threshold value was then calculated by the Matlab software as the mean SNR of 70.7% correct performance criteria (2:1 rule) from the final (six to eight) reversals. There were two runs of the test for each ear, which gives information of test reliability in the same subject (Spyridakou et al., 2012).

3.4.2 Participants

Normal volunteers were recruited from among hospital staff, hospital visitors, friends and relatives. The inclusion criteria were as follows:

- English as first language
- Normal hearing ≤20dB in each frequency for 250–8000 Hz in both ears
- Normal middle ear function on both sides
- No history of psychiatric disease or cognitive impairment, as reported by the volunteers, during the initial medical interview

  Normal volunteers who agreed to participate in the study were given an information leaflet and signed a written consent form. All the normal volunteers underwent pure-tone audiometry tests and tympanometry prior to conducting the SIB test in order to establish normal hearing and verify the normalcy of middle ear function on both sides.

3.5 Results

3.5.1 Basic Descriptors of Participants

Seventy-four normal volunteers were recruited for the study; however, after the pure-tone audiometry tests, 5 normal volunteers were excluded since they had high-frequency, bilateral sensorineural hearing loss (excluded subjects included two women aged 62 and 73 years and 3 men aged 67, 74 and 82 years). Sixty-nine normal volunteers aged 20–57 years (mean age, 33.2 years; SD, 9.856) met the inclusion criteria and participated in the study. The participants included 40 women and 29 men (x^2 statistical test; $p = 0.248$). All participants had hearing thresholds of <20 dBHL across the frequency range (250–8000 Hz) and Jerger type A on tympanometry. They did not have any history of ear infections nor any auditory symptoms (e.g. hearing difficulties, tinnitus or hyperacusis). The mean pure-tone average for the right ear was 6.46 dBHL (SD, 3.35) and for the left ear was 6.57 dBHL (SD, 3.744). The distribution was normal for both ears, and the mean values did not differ (paired *t*-test; $p = 0.712$). After completion of the pure-tone audiometry and tympanometry, the participants underwent the SIB test. None of them were familiar with the test.

3.5.2 Mean Values of Speech-in-Babble Trials: Comparison between Ears

Table 3.3 summarises the values of the mean, median and confidence interval for the SIB test of the right and left ears for the 4 trials (two trials on each ear; Figures 3.1 and 3.2). There were no statistical significant differences between the two ears.

Table 3.3: Values of mean, median, standard deviation and confidence intervals obtained for the right and left ears in the speech-in-babble test

Right ear (n = 69)		Left ear (n = 69)		Significance difference in means–t test-p value
First trial mean and SD	1.4296 ±1.544	First trial mean and SD	1.2622 ±2.06	P = 0.542
First trial median value	1.4300	First trial median value	1.3	
95% confidence interval for mean	1.0587–1.8005	95% confidence interval for mean	0.7674–1.7570	
Second trial mean and SD	1.4309 ±1.894	Second trial mean and SD	1.0443 ±1.92689	P = 0.124
Second trial median	1.5700	Second trial median	1.1500	
95% confidence interval for mean	0.9758–1.8860	95% confidence interval for mean	0.5815–1.5072	
Significance of difference in means of two trials right ear–t test	P = 0.996	Significance of difference in means of two trials left ear–t test	P = 0.406	

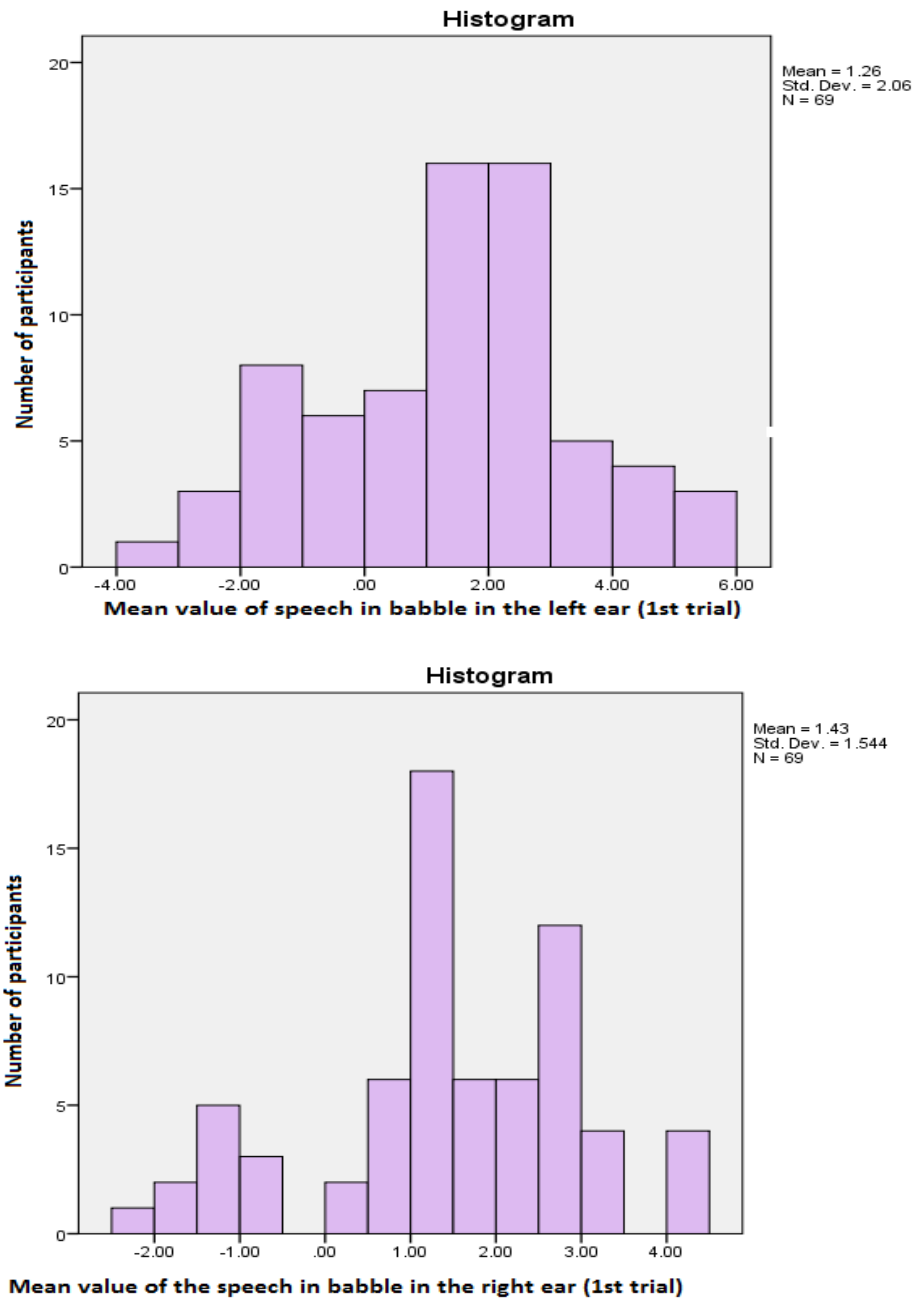


Figure 3.1: Mean values of the first trials in the speech-in-babble test in both ears

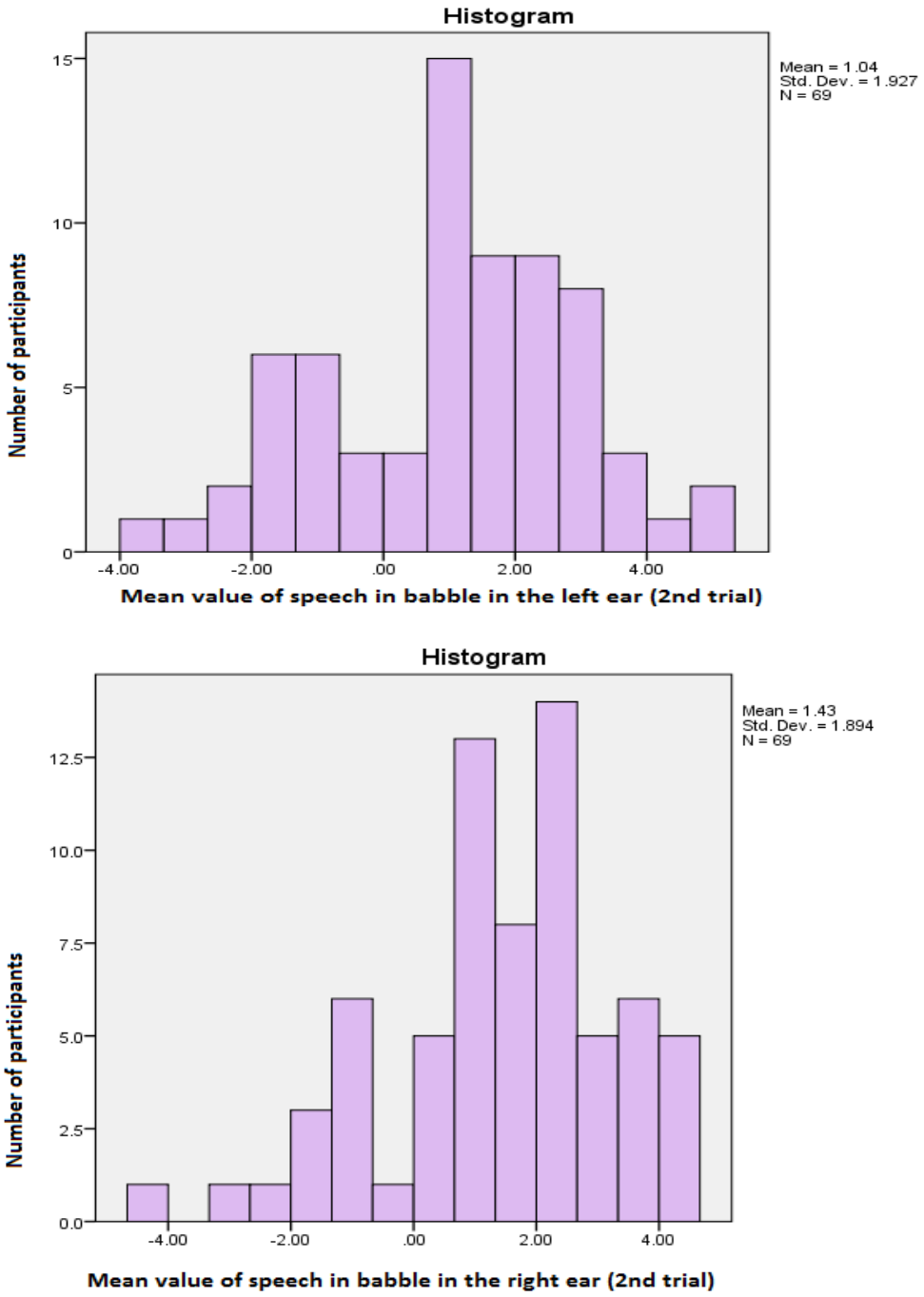


Figure 3.2: Mean values of second trials of speech-in-babble test in both ears

3.5.3 Repeatability of the Speech-in-Babble Test

A paired *t* test was used to assess repeatability, with no statistically significant differences being noted in the mean values of the two trials on each ear (Table 3.3). Figure 3.3 shows the mean value of the difference of the means between the two trials in each ear.

In order to assess repeatability among the 4 trials in both ears, a one-factor analysis of variance was used. There were no statistical differences between the mean values of the 4 trials. The significance for Mauchly's test was .419 and for epsilon .416, and therefore, sphericity was assumed. The F (3,204) value was .946, p=.419.

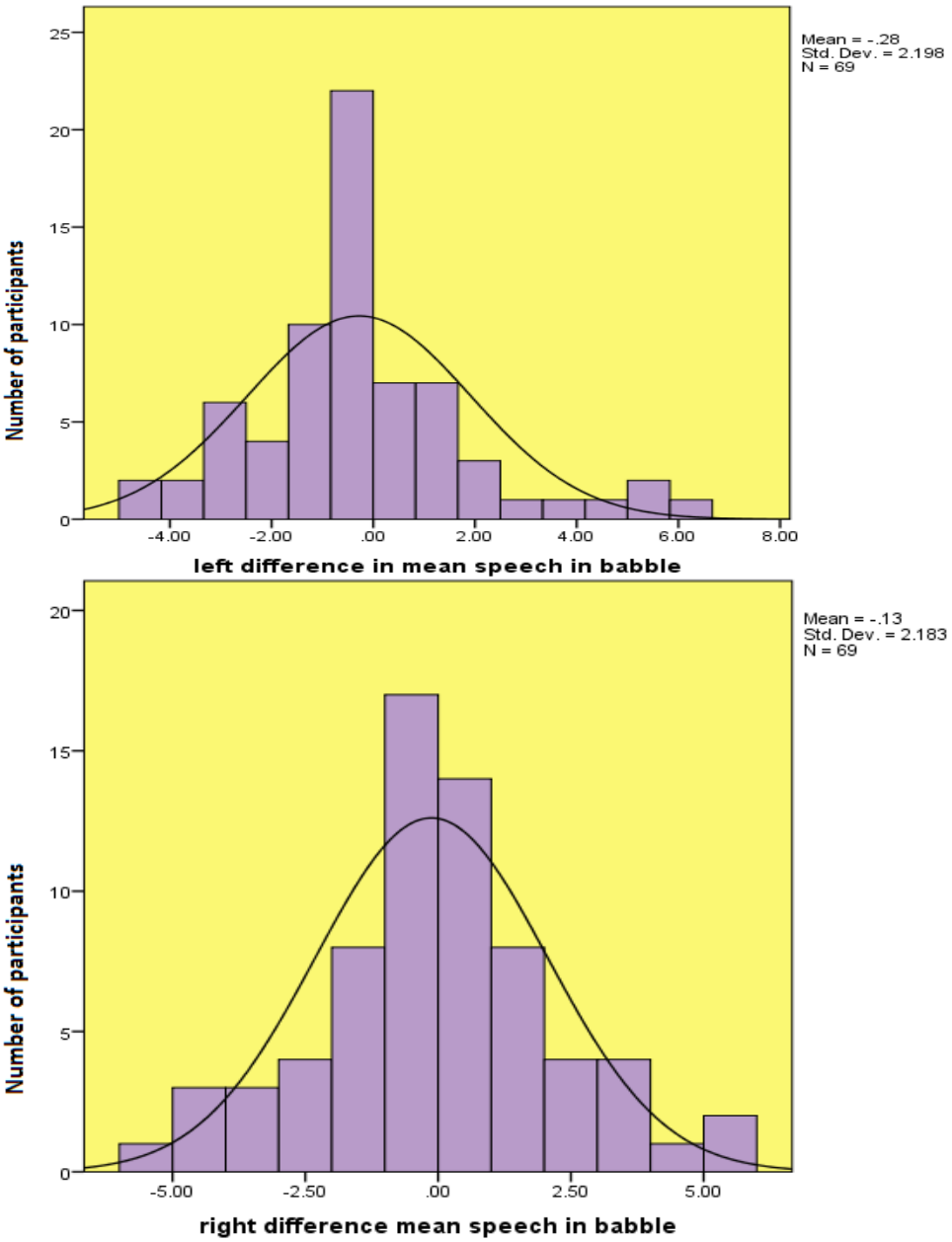


Figure 3.3: Mean value of the difference in the means of two speech-in-babble trials in both ears

3.5.4 Normal Range of Speech-in-Babble Scores

Since there was no statistical significant difference between the values obtained in the two trials and between the two ears for the normative data, the data of the second trial were used, and an overall statistical analysis for the two ears was carried out instead. The total mean value of the SIB test in both ears was 1.035 and SD was 1.75. Approximately 95% of the data values lay within 1.96 SD of the mean. Therefore, these two limits were expressed as follows:

Mean ± 1.96 × SD

Normal range: 1.03±1.96 × 1.75 = -2.4 up to +4.4 dB

Therefore, 4.4.dB was taken as the upper normal range cut-off score for the SIB test in both ears. Participants with scores >4.4 dB on the first trial were considered to have abnormal SIB test results.

3.5.5 Regression Modelling–for Age and Sex

By superficial inspection of the data, it does not appear that age and sex are confounding factors for the study. Prior to deciding on the above value of 4.4 dB as the upper normal range for the SIB test and after inspection of scatterplots (Figure 3.4), a regression analysis was conducted to assess the effects of age and sex on the results of the SIB test with the SIB mean (across trials and across ears) as the dependent variable and age and sex as independent variables (Table 3.4).

Table 3.4: Simple linear regression for speech-in-babble

	Estimated R^2	Adjusted R^2	ANOVA F value	ANOVA p value	Standardised beta	T stats	T test p value
Sex	0.82	-0.007	0.463	0.631	-0.058	-0.628	0.531
Age	0.82	-0.007	0.463	0.631	-0.083	-0.902	0.369

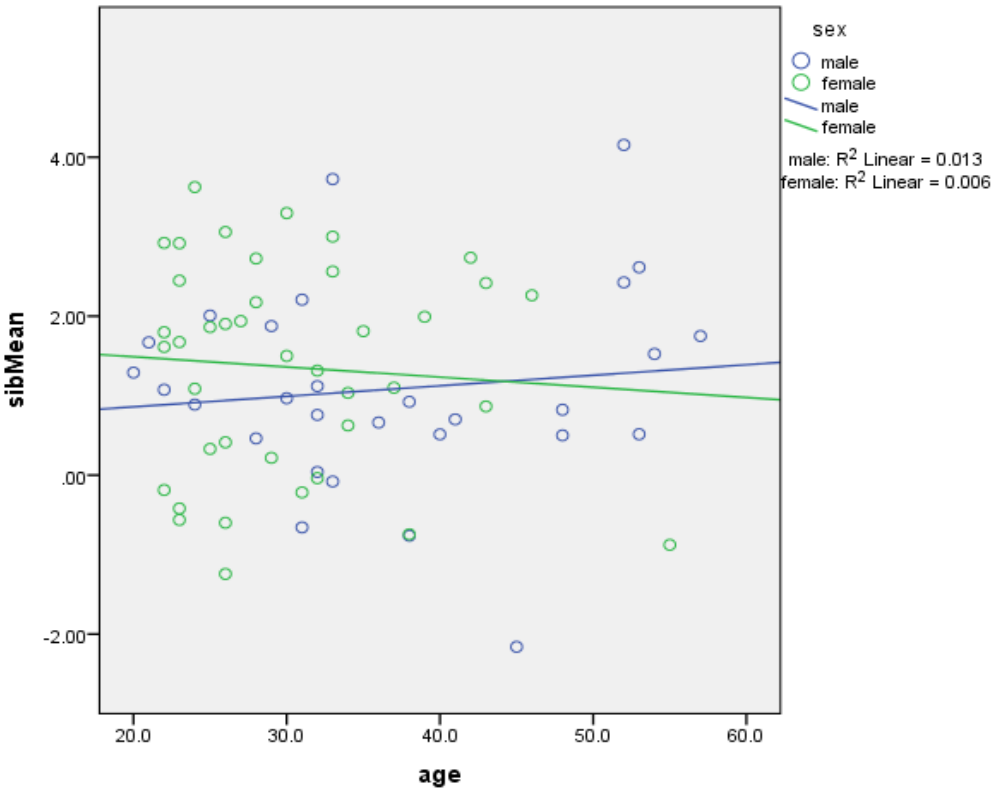


Figure 3.4: Simple linear regression for the speech-in-babble test

With SIB as the dependent variable, the following regression equation was obtained:

Y = a+b1x1+b2x2+…..+bkxk

Speech-in-babble = -0.058 (sex)-0.083(age)

Standardised beta coefficient value was similar for both sex (-0.058) and age (-0.083). R^2 was 0.82 with adjusted R^2 0.007.

This regression analysis is, therefore, a poor fit describing only 8% of the variance in the SIB test, and the overall relationship was not statistically significant (F = 0.463, p = 0539 for sex and p = 0.369 for age).

3.6 Discussion

In Phase one of the research study, normative data were established for the SIB test. The lists used were developed by Stuart Rosen and have been previously used in a pilot research study for a Masters degree in science (Kunaratnam et al., 2003).

The upper cut-off value for the normal range of the test result was obtained as 4.4 dB in each ear, and a score of >4.4 dB was classified as abnormal. Normative data were collected with the view to using the test as part of the APD diagnostic test battery as a monaural, low-redundancy speech tests, as per categories proposed by ASHA 2005 for auditory processing tests. Kunaratnam et al. (2003) conducted an unpublished study that showed that the SIB test had higher sensitivity of 70% compared to the 50% of a similar speech in a white-noise test in diagnosing adults with APD secondary to acquired brain structural abnormalities.

The test offers some advantages. Firstly, words are recorded in British English, while the great majority of anglophone speech- in- noise tests have been recorded in American English and the recently developed LISN by Cameron and Dillon (2007) is in Australian English and American English. It has been proposed that speech tests should be recorded in the patients' first language for optimal test performance (Dawes et al., 2007; Tabri et al., 2011).

A second advantage is that the test uses words rather than sentences. Although words do not represent real-life situations and lacks properties of real speech, such as word stress and dynamic range, words recognition tap predominantly into auditory skills rather than linguistic and cognitive ones, as is the case with sentences (Luce and Pisoni, 1998; McArdle and Wilson, 2008). The test, therefore, may be more suitable in assessing true auditory sensory processing problems in patients with suspected APD. Wilson et al. (2007) showed that subjects with peripheral hearing loss had significantly worse scores in the word-in-noise test (WIN tests) compared to subjects with normal hearing; they suggested that the WIN test was more sensitive in diagnosing patients with peripheral hearing loss compared to the BKB-SIN and HINT tests that employ sentences. Similar studies have not been reported for subjects with APD.

A third advantage is that SIB uses multi-talker (20 talkers) babble as a masking noise. Multi-talker babbling represents real-life listening situations (Plomp, 1978). According to Howard-Jones and Rosen (1993), when the

level of masker fluctuates, the listeners can ‘glimpse’ acoustic information. When more talkers are added and the presentation of the masker coincides with the beginning or ending of the speech, then it impacts on speech target audibility. When up to 4 talkers have been added as maskers, energetic masking will be affected, but informational masking will not, as it depends upon more central processes and adding more than 4 talkers each time will only result in small changes to speech perception (Rosen et al., 2013). The SIB test, therefore, may be used to assess the overall integrity of the auditory pathway in subjects with APD. This hypothesis will, to some extent, be addressed in Chapter 5 that pertains to the correlation of test results with participant reported symptoms.

Finally, the test is easy and quick to perform and takes approximately 5 minutes for the completion of the four trials (two in each ear), while a first trial would be sufficient since there is no difference between the first and second trial. This indicates that the test is repeatable and helps reduce the testing time even further.

The words were recorded by a female Southern English speaker, and there is some evidence that listeners may find a female voice more interesting. A recent study by Plyler et al. (2011) assessed whether the type of speech used as target signal affects the acceptance of noise levels in listeners with normal hearing. In their study, 26 males and 17 females of mean age 22 years were enrolled. The test involved listening to speech recorded by a female and a male speaker in the presence of multi-talker babbling. The research participants had to indicate acceptable loudness levels for both the speakers, for speech in quiet and SIB. Acceptable noise levels were not significantly different for either the content of the speech or the speaker’s sex. However, based on self-reported questionnaires participants were more interested in the speech made by the female speaker.

The present study did not find any statistically differences for the right and left ears or sex. This is in keeping with other studies that collected normative data for speech- in-noise tests (Fikret-Pasa, 1993; Nilsson et al., 1994; Wilson et al., 2007) that did not show any differences in the two ears. This

may be due to the fact that in all these studies, including the present, participants had normal peripheral hearing and no auditory complaints that would indicate auditory processing problems.

Age did not affect performance in the SIB test results. However, the upper age limit of our research participants was 57 years. According to CHABA (1988), older adults have significantly more difficulty in hearing speech- in-noise than younger adults. A recent study (Ben-David et al., 2012) showed that older adults (mean age, 72.3 years) had significantly higher SNR for word recognition in steady-state speech-spectrum noise compared to young adults (mean age, 20 years), and this age-related difference was higher for a babble-type masker; in addition, the ability to benefit by the earlier onset of the masker vs. the target speech was reduced in the older adults compared to the young adults, but only for the babble masker. The authors proposed that the age-related differences were due to a combination of peripheral sensory factors but also cognitive factors, in view of the more pronounced effects of informational masking in the older adults. Older adults have higher prevalence of peripheral hearing loss (Davis 1989) and those recruited by Ben-David et al. (2012) had slightly poorer average thresholds of up to 3 kHz than the younger subjects (higher frequency thresholds were not provided by the authors). In addition, older adults experience temporal resolution problems that can affect the ability of hearing degraded or distorted speech (Pichora-Fuller et al., 2007), while problems related to age can also interfere with test performance (Humes, 2005).

A limitation of the current study is that normative data for the SIB test of individuals older than 60 years were not collected. The younger age range and the presence of normal thresholds in all participants may explain why an age effect was not observed. However, in order to use the SIB test as part of the APD battery in adults for the diagnosis of APD, a comprehensive collection of normative data is required, which would include older adults.

3.7 Conclusions

Normative data were collected for a monaural SIB test performed on adults aged <60 years and having normal hearing. The test was quick to perform and recorded in British English. No statistically significant differences were noted between different ear sides, sexes or ages and between the first and second trials of the test. In the UK, there is a paucity of validated speech- in-noise tests that can be used as part of the APD diagnostic battery, and this quick, simple and reliable test can help supplement the APD test battery.

CHAPTER 4: PHASE 2. SELF-REPORTED AUDITORY SYMPTOMS IN CLINICAL PARTICIPANTS WITH HEARING DIFFICULTIES vs. NORMAL PARTICIPANTS

4.1 Introduction

Patients with APD present with a variety of symptoms. According to the ASHA (1996) statement, there are six broad categories of abnormal auditory behaviours in patients with auditory processing disorders: difficulties in sound localisation, lateralisation, auditory discrimination, auditory pattern recognition, temporal processing as well as auditory performance for competing and degrading signals. Patients with APD can have a very complex clinical picture and/or vary in their auditory presentation and therefore the quantification of their symptoms may help not only with the diagnosis but also with defining the treatment on the basis of the auditory complaints. There is paucity in published studies regarding the presenting auditory symptoms of patients with APD. This may well be because the diagnosis and definition of APD still remains controversial (Moore et al., 2013), while there is a lack of reliable screening tools to identify children and adults who need further referral for APD assessment and a lack of standardised diagnostic tests. The majority of published studies on the clinical presentation are paediatric ones (Liasis et al., 2003; Moore et al., 2010; Cameron et al., 2006; Dawes et al., 2008; Wilson et al., 2011; Iliadou and Bamiou, 2012.) and it would seem that currently, the diagnosis of APD may be determined by the referral route rather than the presenting symptoms. Professionals who are aware of APD will refer patients for such assessments (Moore et al., 2012); however, both children as well as adults who present with APD may have other co-existing disorders within speech production in domains of language, cognitive processing, social communication and attention (Moore et al., 2013). Therefore, it is very difficult to attribute the hearing difficulties only to problems within the central auditory pathways.

4.2 Outcome Measures for Defining Auditory Symptoms in Adults with APD

During recent years, self-reported measurements have become valuable tools in the field of audiology and are being widely applied from screening to intervention. Self-reported inventories are standardised questionnaires that are used to characterise an often complex clinical picture.

A good standardised questionnaire should have the following characteristics (Newman et al., 1997):

- Good reliability and validity.
- Short administration time
- Ease of scoring
- Detection of specific functional emotional and physical problems.

In addition, the standardised questionnaires should be easily understood by lay people. The questionnaires should include a variety of items, not only pertaining to the hearing difficulties but also to the identification and quantification of the difficulties encountered by each individual in their life environment and the impact of such difficulties on their quality of life.

An additional consideration is the readability of the questionnaires. Antcherson et al. (2013) assessed the readability of questionnaires that are been used to assess hearing difficulties in children and decide the need for referral to an APD clinic. These included some of the most commonly used questionnaires such as the Buffalo Model Questionnaire (BMQ) (Katz 2004), Children's Auditory Performance Scale (CHAPS) (Smoski et al., 1992), Children's Home Inventory for Listening Difficulties (CHILD) (Anderson and Smaldino, 2000), Fisher's Auditory Problem Checklist (Fisher, 1976) and Listening Inventory for Education (LIFE) (Anderson and Smaldino 1999). The authors proposed that these questionnaires were written at reading levels of 8^{th} to 10^{th} grade (13–15 years of age). They also proposed that clinicians should also take into account the functional literacy skills of the adult proxy when they use those questionnaires because it can affect how they complete

the questionnaires regarding the child's listening abilities. Although the above study refers to paediatric questionnaires, it stresses the importance of the readability of questionnaires when questionnaires are administered to adults.

The following sections will review studies of paediatric and adult populations with suspected APDs and difficulties in hearing speech- in- noise in whom hearing/listening symptoms were quantified by means of a questionnaire.

4.3 Auditory Complaints in Patients with APD

4.3.1 Paediatric Population

Seven paediatric studies were identified regarding the use of questionnaires as screening tools for APD in paediatric populations. Table 4.1 summarises the paediatric studies. Children with suspected APD have more severe hearing difficulties in the classroom, as reported by teachers (Purdy et al., 2002); speech-in-noise difficulties, as reported by parents (Liasis et al., 2003; Meister et al., 2004), general behavioural issues; speech/language abilities; speech discrimination and loudness perception(Meister et al., 2004).

Currently available validated questionnaires are not reliable diagnostic tools for evaluation of APD in children. Cameron et al. (2006) found that there was no correlation between the CHAPS questionnaire and APD test performance in a paediatric study of 10 children (mean age 8 years, 6 months). Similarly, Dawes et al. (2008) published a retrospective case review of 32 paediatric patients with APD and 57 normal controls (mean age, 10 years) and reported that the CHAPS and FISHER questionnaires were not sensitive in identifying children had APD. Wilson et al. (2011), in a retrospective case review study of 104 children (age range: 6–14 years), found a low and rather weak correlation between CHAPS, SIFTER and auditory processing tests and that the tests did not predict the presence or absence of APD. The authors concluded that these questionnaires cannot be used as screening tools in a paediatric population.

Iliadou and Bamiou (2012), however, assessed older children (age range, 11.4–12.7 years) and found that children with APD scored significantly worse

on the Quiet, Ideal, Memory and Attention subscales of CHAPS than the clinical non-APD group and on all 6 CHAPS subscales than the normal controls.

Table 4.1: Summary of paediatric studies

LD, Learning Difficulties; susp, suspected; SIFTER, Screening Instrument for Targeting Educational Risk

Study	No of children	APD definition	Questionnaires	Results
Purdy et al., 2002	10 LD 10 normal Age range: 7–11 years	ASHA 1996	Sanger et al. (1987) Smoski et al. (1992)	Children with suspected APD and LD have significantly more severe hearing difficulties in the classroom
Liasis et al., 2003	9 APD 9 normal Age range: 8–12 years	ASHA, 1996	Parental 10 item	Speech-in-noise problems worse ($p < 0.001$) in individuals with suspected APD
Meister et al., 2004	215 susp APD; 85 Normal; Age range: 6–10 years	ASHA 1996	Parental 51 items	Children with susp APD had significantly worse problems in hearing speech-in-noise, behavioural issues, speech/language abilities, loudness perception, musical cues
Cameron et al., 2006	10 susp APD; Age range: 7–9 years	ASHA	CHAPS	CHAPS not a good tool for predicting children with APD
Dawes et al., 2008	32 APD; 27 normal; Age range: 7–12 years	ASHA	CHAPS FISHER	CHAPS and FISHER not good tools for identifying children with APD
Wilson et al.,2011	104 case notes 6–14 years	ASHA 2005	CHAP SIFTER	CHAP and SIFTER not good tools in predicting APD
Iliadou and Bamiou, 2012	25 APD; 13 clinical non-APD; 24 normal; 11–12 years	BSA 2011	CHAPS	APD group significantly lower scores in CHAPS. Significant correlations between CHAPS and APD tests

4.3.2 Adult Population

Limited evidence is currently available about the audiological profile of adults with hearing difficulties who have been additionally assessed with self-

report measures such as validated questionnaires. In the early 90s, two large research studies (King and Stephens, 1992; Saunders and Haggard, 1992) were conducted in Wales and Manchester on patients with reported difficulties in hearing speech-in-noise. At that time, difficulties in hearing speech-in-noise in the UK were likely to be diagnosed as King (1954)–Kopetzky (1948) syndrome, Obscure Auditory Dysfunction(OAD) (Saunders and Haggard, 1992) or Auditory Disability with Normal Hearing (AND) (King and Stephens, 1992). King and Stephens (1992) investigated the auditory and psychological factors in 20 patients of employment age who reported difficulties in hearing speech-in-noise (classified as King–Kopetzky syndrome) vs. 20 controls (matched for age, sex and socioeconomic group). All the subjects underwent auditory tests including pure-tone audiometry, high-frequency audiometry and frequency resolution and completed questionnaires. The main findings, based on the questionnaire, was that the patients tended to be more anxious, depressed and lonely compared to the normal controls because their hearing difficulties in the presence of background noise prevented them from communicating with others. The authors felt that poor coping strategies were associated with increased anxiety and emphasized the importance of formally educating such patients about hearing tactics. In another study, Zhao and Stevens (1996) compared the speech-in-noise related difficulties in a group of patients diagnosed with King–Kopetzky syndrome and an audiological rehabilitation group of patients with hearing impairment; the patients were asked to complete an open-ended questionnaire regarding their hearing difficulties. Patients with King–Kopetzky syndrome reported more hearing difficulties in ‘live’ speech than in ‘electronic’ (television, telephone) speech as compared to the other group. Additionally, the former group reported psychological problems, such as anxiety, irritability and moodiness, more frequently than the latter one.

Saunders and Haggard (1992) conducted a study to characterise patients with difficulties in hearing speech-in-noise and determine the aetiology of their symptoms. The study protocol included hearing tests (pure-tone audiometry, frequency resolution, speech-in-noise test, sentence-completion task and lip-reading tests) and psychological assessments (a personality

questionnaire and hearing difficulties questionnaire). A subsequent study by the same authors showed that patients with obscure auditory dysfunction (OAD) differed significantly from the controls in three domains: (1) psychological domain (greater anxiety on personality test), (2) psychoacoustic domain (impaired frequency resolution, speech-in-noise threshold) and (3) cognitive/linguistic domain (lower scores on focused attention condition of a dichotic listening test). They also reported that while patients with OAD syndrome and normal hearing usually were discharged from Audiology departments, the finding of a normal audiogram did not satisfy these patients who subsequently sought a second opinion and further assessments. Their research led to the development of a package of performance tests, questionnaires and protocols for counselling. Higson et al. (1994) in a further study of 59 new OAD patients replicated the findings of the previous study by Saunders and Haggard (1992). Therefore, it was proposed that such patients had a consistent profile of poorer speech reception threshold in SINT and considered themselves handicapped by their symptoms.

Neijenhuis et al. (2003) published a study on 24 adults with suspected APD (based on reported hearing difficulties) who underwent a validated Dutch APD test battery. Adults with suspected APD obtained significantly lower scores in understanding SIN and in the auditory localisation aspects of Amsterdam Inventory for Auditory Disability compared to the normal controls. Although they also scored worse for the remaining 3 aspects of the questionnaire (speech in quiet, recognition and detection of sound) compared to the normal controls, the difference in the scores was not statistically significant. Bamiou et al. (2012) administered the Amsterdam Inventory for Auditory Disability questionnaire to 21 adult patients with stroke of the auditory brain regions and 23 normal age- and hearing-matched controls. The scores in sound recognition and localisation aspects of the questionnaire were significantly worse in stroke patients than in normal controls, and the questionnaire scores correlated significantly with the results of the tests of auditory processing but not with hearing thresholds. It was

proposed that the questionnaire could help in identifying patients who need further audiological assessment for APD.

Review of the previous literature indicates that there are but a few studies on clinical populations with APD (diagnosed by appropriate tests) that attempt to characterise the clinical presentation of these patients by means of a validated questionnaire, with even fewer such studies in the adult population. Current evidence from paediatric studies indicates that validated questionnaires cannot be used as screening tools. However, this may relate to the age of the children, as in the six of the seven studies reported, the mean age of the children was <10 years. Iliadou and Bamiou 2012, conversely, showed that in older children, the CHAPS results were significantly different in the clinical and the control groups. Age can affect not only the parental views on children's symptoms but also performance on the tests. Another possibility is that the symptoms characterisation in paediatric studies is not necessarily exhaustive, e.g. studies using the CHAPS questionnaire do not assess localisation skills or loudness discomfort. Adults, who present with auditory difficulties, on the other hand, do not have the above-mentioned confounding factors, and therefore, appropriate selected questionnaires could probably be used as screening tools.

The current study aims to assess symptom characteristics by means of validated questionnaires in a clinical population of adults who present with hearing complaints in the presence of normal audiogram and comparison with normal controls. A second aim was to assess the sensitivity and specificity of different questionnaires in screening for APD (as diagnosed on the basis of deficits in auditory processing tests and with explicit diagnostic criteria for APD).

4.4 Methods

4.4.1 Participants and Settings

English speaking patients aged 18–60 years who visited the audiology or ENT/Audiovestibular Medicine clinic for evaluation of hearing difficulties but had normal results on pure-tone audiometry were invited to participate in the

study. Those who agreed to participate were contacted via the telephone and tested at the Royal National Throat Nose Ear (RNTNE) and/or the National Hospital for Neurology & Neurosurgery (NHNN). The study protocol was explained to the patients, and an informed consent was signed. The participants underwent a structured medical interview and audiological assessment and were asked to complete the 3 inventories. The questionnaires were completed in the waiting area before testing and the investigator receiving the questionnaires checked them and also discussed any questions the participants had. Subsequently, the participants underwent the complete battery of audiological tests in a sound-proof room. The audiological tests included pure-tone audiometry, tympanometry, transient evoked otoacoustic emissions (TEOAEs) and the auditory processing tests: suppression of TEOAEs by contralateral noise, speech-in-babble (SIB) test, gap in noise (GIN) test, dichotic digit test, frequency and duration pattern tests. These tests have been described in details in Chapter 2 of the thesis. The clinical group was further categorised as clinical APD (on the basis of at least two auditory processing test abnormalities in at least one ear with at least 1 test being non-speech) or clinical non-APD (criteria not met). The clinical non-APD had normal auditory processing tests or 1 abnormal test, and therefore, they did not have APD based on our criteria.

For comparison, a normal control group was recruited from all grades of hospital staff, hospital visitors and students.

4.4.2 Questionnaires

Three validated questionnaires were used for this research study.

4.4.2.1 The (Modified) Amsterdam Inventory for Auditory Disability (AD)

This questionnaire was devised by Meijer et al. (2003) and is presented in Appendix 1. The questionnaire is based on the Amsterdam Inventory for Auditory Disability and Handicap by Kramer et al. (1995). The inventory was designed to identify factors related to hearing disability that affected the individual in daily life and to assess the impact it has on the quality of life. Normative data have been collected from a Dutch population of 272 adults

(age range, 16–66 years) with a wide range of hearing loss. The precision of its scale has been compared to some of the auditory performance tests, including (pure-tone audiogram, speech audiogram, speech reception threshold in quiet and noise and localisation of the sound) with multiple correlation coefficients ranging from R = 0.60 to R = 0.74 (Kramer et al., 1995).

The first version of this questionnaire consisted of 30 questions, while the modified version has 28 and assesses auditory disability in five key domains: (1) speech intelligibility in noise (questions 7, 24, 18, 1 and 13), (2) speech intelligibility in quiet (questions 14, 19, 11, 12 and 8), (3) auditory localisation (questions 15, 3, 26, 20 and 9), (4) recognition of sound (4, 5, 6, 17, 22, 23, 25 and 28) and (5) detection of sound (questions 27, 16, 21, 2 and 10).

This questionnaire was chosen for the research study since it has already been used for patients with suspected APD by Neijenhuis et al. (2003) and in their study, patients with suspected APD scored worse in the domains pertaining to speech intelligibly in noise and auditory localisation.

The responses were scored as ‘almost never’, ‘occasionally’, ‘frequently’ and ‘almost always’ at scores of 0, 1, 2 and 3, respectively, with 0 indicating the most severe hearing difficulty.

4.4.2.2 The Speech, Spatial and Qualities of Hearing Scale (SSQ)

This questionnaire was designed by Gatehouse and Noble (2004) and is presented in Appendix 2. The questionnaire was designed to measure a range of auditory symptoms which may lead to difficulties in hearing with background noise. It was found that along with difficulties in hearing speech-in-noise, there were additional contributing factors such as spatial (localisation) hearing difficulties, attention problems and problems with identifying the quality of sound. Data were collected from 153 individuals (average age, 71 years), and it was found that there were good correlations between hearing impairment and disability (SSQ scores) in the study by Gatehouse and Noble (2004). Briefly, the domains in the questionnaire are speech hearing (questions 1–14), spatial hearing (questions 1–17) and

sound hearing (questions 1–19), and scores are marked from 0 to 10, with 0 indicating complete inability.

This questionnaire has not been used previously in adults with APD, and it was chosen for this research study for several reasons. Firstly, similar to the Amsterdam Inventory for Auditory Disability questionnaire, this questionnaire was designed to measure a comprehensive range of auditory symptoms and, therefore, assessment of the correlation between the two questionnaires would allow for the evaluation of the consistency and reliability of the responses.

Secondly, the scoring systems in the two questionnaires are different, and therefore, it could provide information about the preference of scoring systems by research participants.

Thirdly, the ruler scoring system of the SSQ questionnaire, if the inventory was found to be a useful tool in patients with APD, could be used as an outcome measure after APD management.

4.4.2.3 The Hyperacusis Questionnaire

This questionnaire was designed by Khalfa et al. (2001) and is presented in Appendix 3. Hyperacusis is a subjective symptom of intolerance/auditory hypersensitivity to environmental sounds. The hearing of patients with this condition is normal most of the times, and they report discomfort or pain when they are exposed to particular sounds. Normative data were collected from 201 subjects (age range, 17–72 years). The questionnaire was found to be statistically reliable and consistent.

The questionnaire is divided into 2 parts. The first part along with the patient's details includes 3 questions with regard to noise exposure and hearing problems. The second part consists of 14 questions. The hyperacusis questionnaire has 3 dimensions: attention (question 1–4), social (question 5–10) and emotional (question 11–14).

The responses are graded as 0, 1, 2 and 3 for responses of 'no', 'yes a little', 'yes quite a lot' and 'yes a lot', respectively. A total score of 28 and above

represents strong symptoms of hyperacusis. According to ASHA (1996), patients with APD may have difficulties with competing and degrading signals. This questionnaire was chosen to allow for a comprehensive assessment of symptoms that may be present in different forms of APD. A study by Ceranic (1998) showed that following head injury, patients who developed hyperacusis, tinnitus and difficulty in hearing SIN showed abnormal suppression of TEOAE, indicating abnormal function at the low level of the central auditory pathway. This clinical hyperacusis may be an additional reason for the auditory difficulties experienced by individuals in noisy environment. The hyperacusis questionnaire also provides additional information about the emotional responses and social behaviours adopted by individuals because of the auditory difficulties.

4.5 Research Hypothesis

Individuals with Auditory Processing Disorders score significantly worse compared to asymptomatic participants in all three questionnaires.

4.6 Results

4.6.1 Participant Characteristics

Table 4.2 records the number of research participants, age and gender data.

Table 4.2: Participant age and sex data

	Clinical APD	Clinical non-APD	Normal controls	Significance
Number recruited	39	21	38	
Female:Male ratio	27:12 (69.2% F)	14:7 (66.6%F)	24:14 (63.1% F)	P=0.400 Kruskal-Wallis
Age (years) mean±SD	38.487±13.2285	34.135±12.3995	32.947±8.7269	P=0.057 Kruskal Wallis

In all, 103 research subjects participated in the study; however, 5 clinical research participants were excluded: one had severe depression and could not complete the questionnaires or participate in the testing; 2, although fluent in English, did not have English as their first language; and 2, did not

complete the questionnaires. Thus, 98 research participants were included in the study.

4.6.2 **Amsterdam Disability (AD) Questionnaire Scores**

Frequency distribution for the AD inventory for participants with clinical APD, clinical non-APD, and normal controls are shown in Figures 4.1 – 4.3, respectively, and the distribution of total scores is 'skewed'.

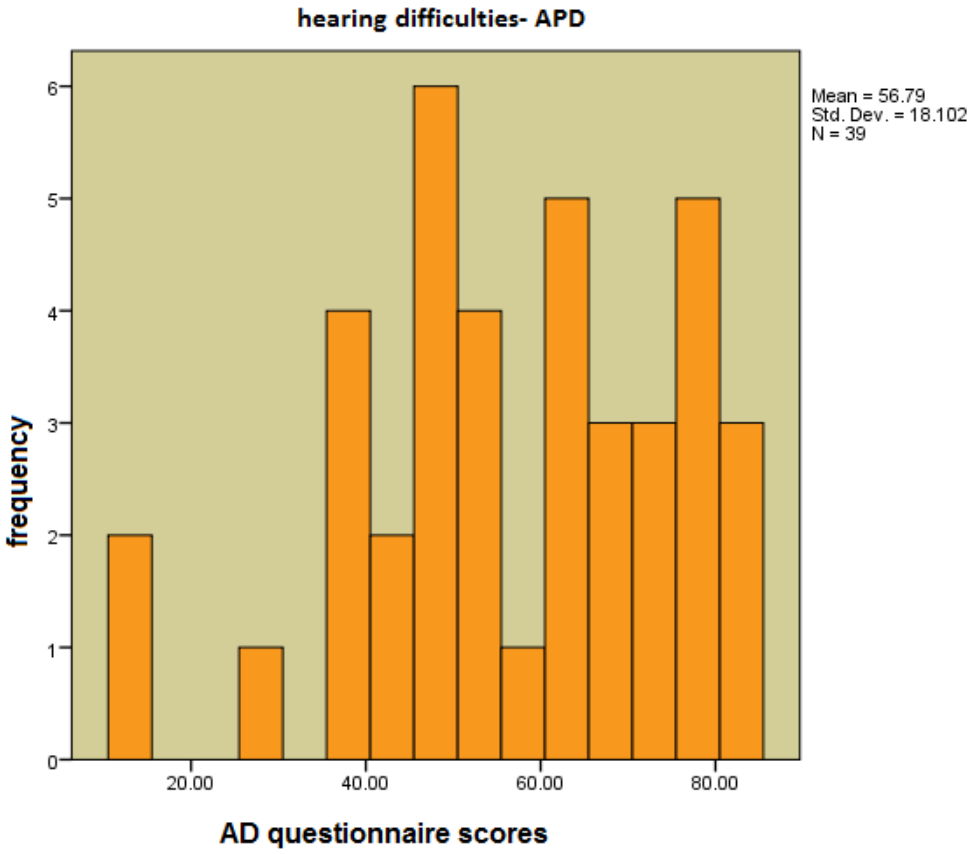


Figure 4.1: Amsterdam Disability (AD) questionnaire scores for participants with a clinical diagnosis of APD

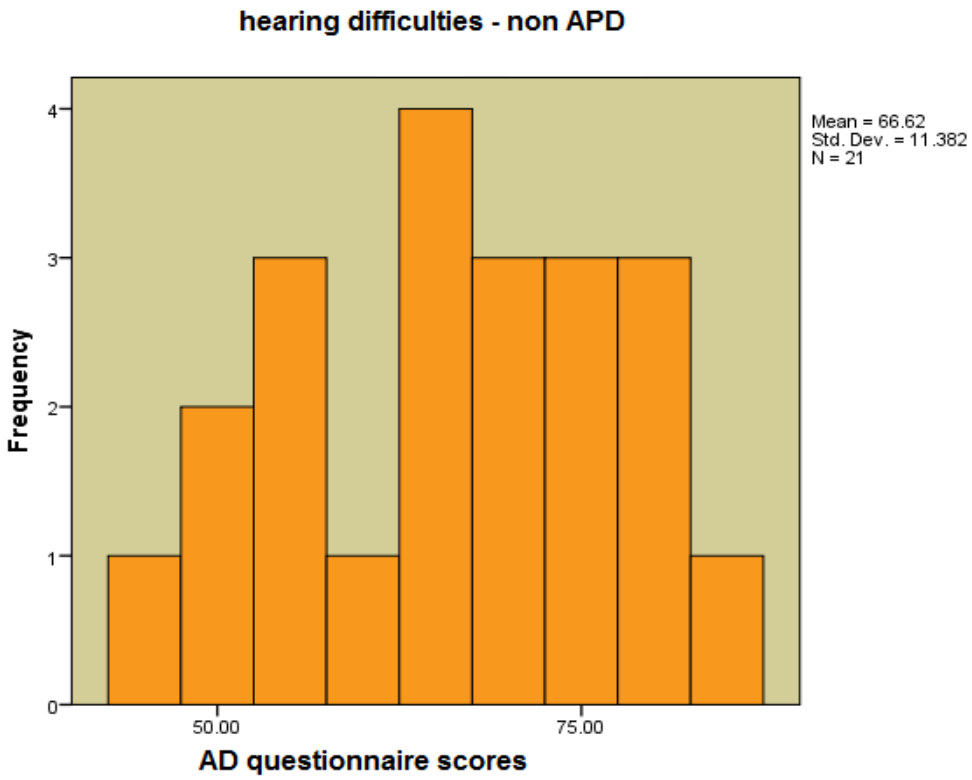


Figure 4.2: Amsterdam Disability questionnaire scores in participants with hearing difficulties but clinical non-APD

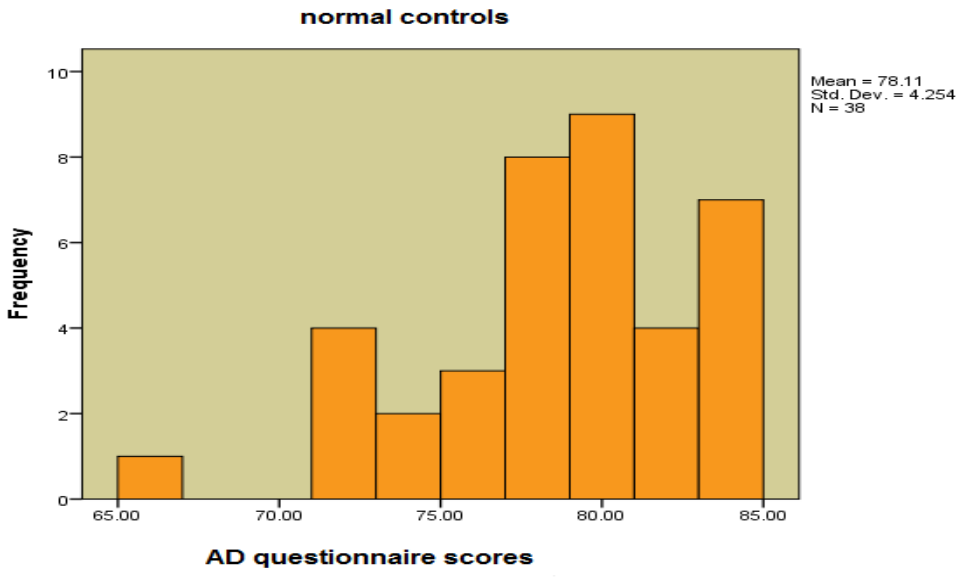


Figure 4.3: Amsterdam Disability questionnaire scores in normal controls

Table 4.3 shows the values of the mean, median and standard deviation of scores of the AD questionnaires for the three groups: clinical APD, clinical non-APD and normal controls.

Table 4.3: AD scores for the participants with clinical APD, clinical non-APD and normal controls

	Clinical APD (n = 39)	Clinical non-APD (n = 21)	Normal controls (n = 38)
Mean	56.7949	66.6190	78.1053
Median	58.0000	66.000	79.0000
SD	18.10231	11.38190	4.25402
Significance	P = 0.000	Kruskal–Wallis Test	

Table 4.4 shows the values of mean, median and SD for subjects with clinical APD, clinical non-APD and normal controls for each aspect of the questionnaire: (a) Intelligibility in noise (ADSN), (b) Intelligibility in quiet (ADSQ), (c) Auditory localisation (ADLOC), (d) recognition of sounds (ADREG) and (e) detection of sounds (ADDIS). Kruskal–Wallis testing confirms a highly significant difference among the three groups for all aspects of the questionnaire (Table 4.5).

Table 4.4: Mean, median and SD for each dimension of the Amsterdam Disability inventory for the three groups.

List of abbreviations: ADSN: (a) Amsterdam Disability speech in noise (b) ADSQ: Amsterdam Disability speech in quiet, (c) ADLOC: Amsterdam Disability localisation, (d) ADREG: Amsterdam Disability-recognition of sound and (e) ADDIS: Amsterdam Disability sound detection

		ADSN	ADSQ	ADLOC	ADREG	ADDIS
Clinical APD N = 39	Mean	7.6923	10.0000	9.4625	18.4615	11.1795
	Median	7.0000	10.0000	10.0000	20.0000	12.0000
	SD	3.36510	3.19539	4.33982	6.01685	3.63370
Clinical non-APD N = 21	Mean	9.3333	11.8095	11.6667	22.0476	11 .7619
	Median	9.0000	12.0000	12.0000	22.0000	12.0000
	SD	3.29140	2.67617	3.41077	2.13251	2.73687
Normal N = 38	Mean	13.3116	13.8947	13.8421	23.0526	14.1842
	Median	14.0000	14.0000	14.0000	23.5000	15.0000
	SD	1.86245	1.42922	1.10347	1.35462	1.08691

Table 4.5: Kruskal–Wallis non-parametric statistical analysis for three groups for all aspects of the AD questionnaire

Amsterdam Inventory	p-value
AD	0.000
ADSN	0.000
ADSQ	0.000
ADLOC	0.000
ADREG	0.000
ADDIS	0.000

Subsequently, a Mann–Whitney non-parametric test was performed to check for any statistical significant differences between the participants with clinical APD and participants with clinical non-APD. Table 4.6 records the results of Mann–Whitney non-parametric test for the AD questionnaire (overall and aspects of it) between APD and clinical non-APD and between participants with clinical non-APD and normal controls. There were significant statistical differences between all the groups in the scores, apart from the ADSN and ADDIS scores for the clinical APD and clinical non-APD groups. Since the Kruskal–Wallis test showed significant differences among the three groups, further analysis, e.g. between APD and normal control groups, was not required.

Table 4.6: Mann–Whitney non-parametric test between clinical APD and clinical non-APD groups and between clinical non-APD and normal controls groups

Significance levels ≤0.05

Amsterdam Inventory	Difference between APD group and clinical non-APD group (p-value)	Difference between normal controls and clinical non- APD group (p-value)
AD	0.041	0.01
ADSN	0.079	0.00
ADSQ	0.033	0.03
ADLOC	0.049	0.026
ADREG	0.023	0.031
ADDIS	0.693	0.04

Figures 4.4 – 4.6 show the mean values for each question of the AD questionnaire among the three groups. Figures 4.4- 4.6 show that the normal

controls scored the highest, followed by the research participants with hearing difficulties and clinical non-APD; the APD group had the worst scores in all the items of the questionnaire.

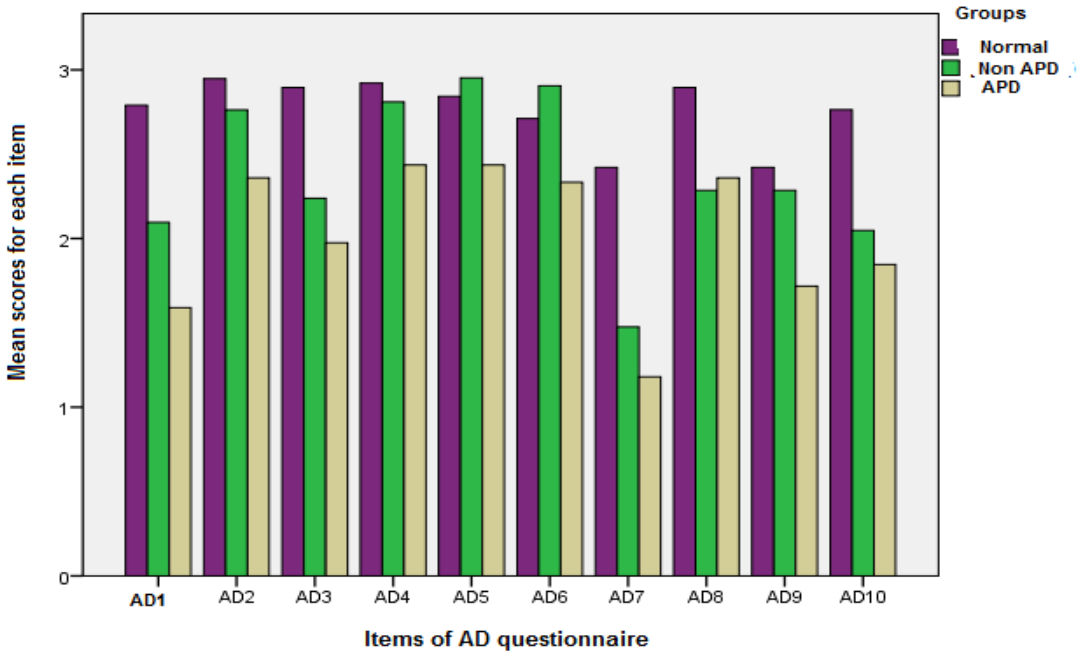


Figure 4.4: Mean scores per item (1-10) of AD questionnaire for the 3 groups

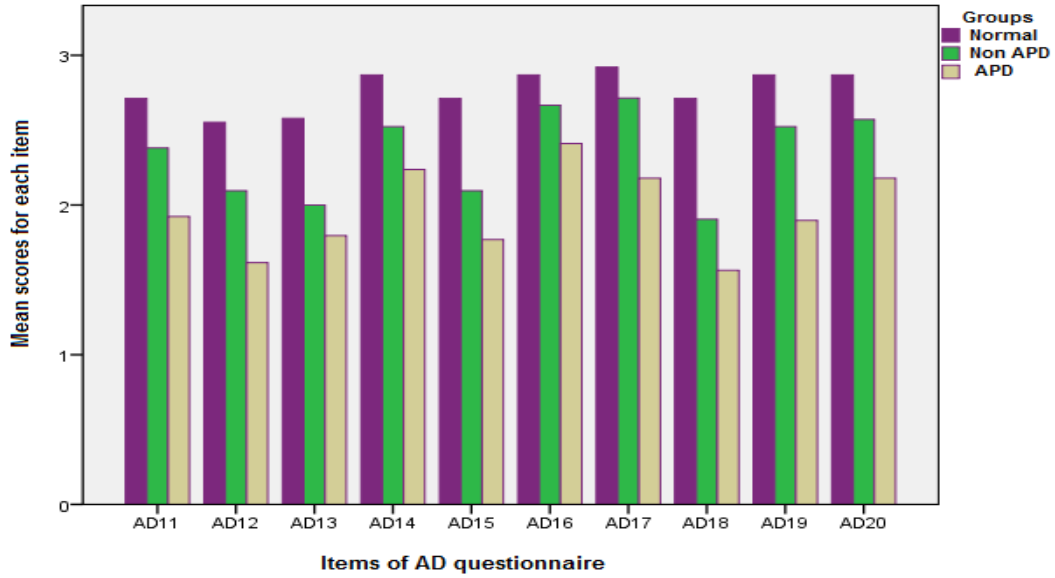


Figure 4.5: Mean scores per item (11–20) of AD questionnaire for the 3 groups

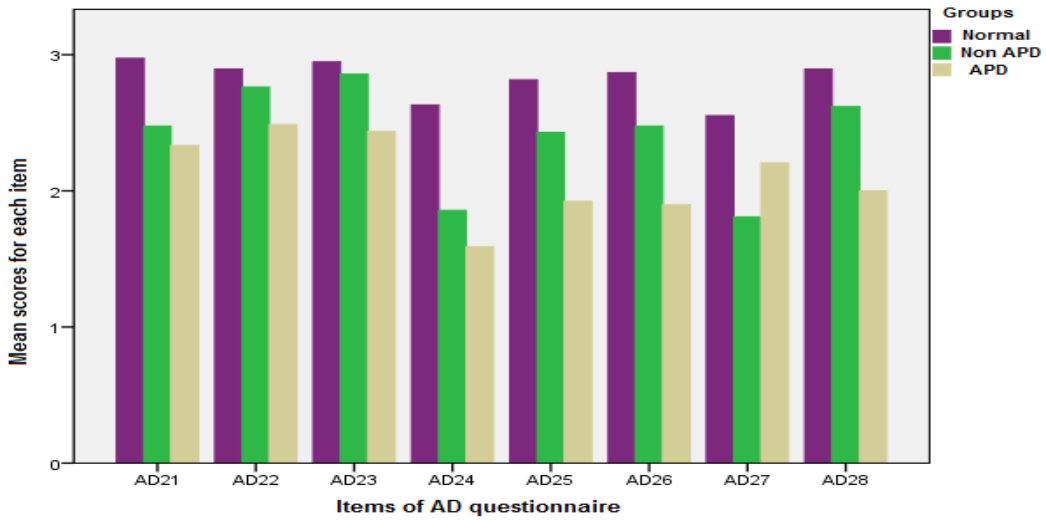


Figure 4.6: Mean scores per item (21-28) of the AD questionnaire for the three groups

4.6.3 Speech, Spatial, Quality Sound (SSQ) Questionnaire Scores

Frequency distribution for the SSQ questionnaire for participants with APD, participants with reported hearing difficulties but clinical non-APD and normal controls are shown in Figures 4.7 - 4.9 , (speech item), Figures 4.10 – 4.12 (spatial item) and Figures 4.13 – 4.15 (sound quality item) and the distribution of total scores is ‘skewed’.

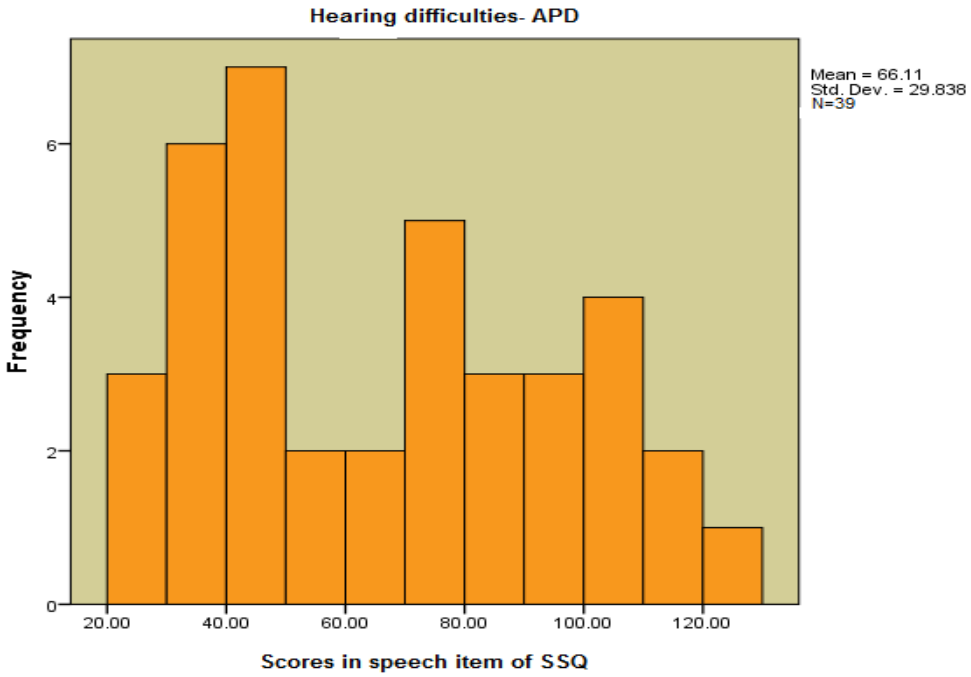


Figure 4.7: Scores in the speech item of the SSQ questionnaire in participants with APD

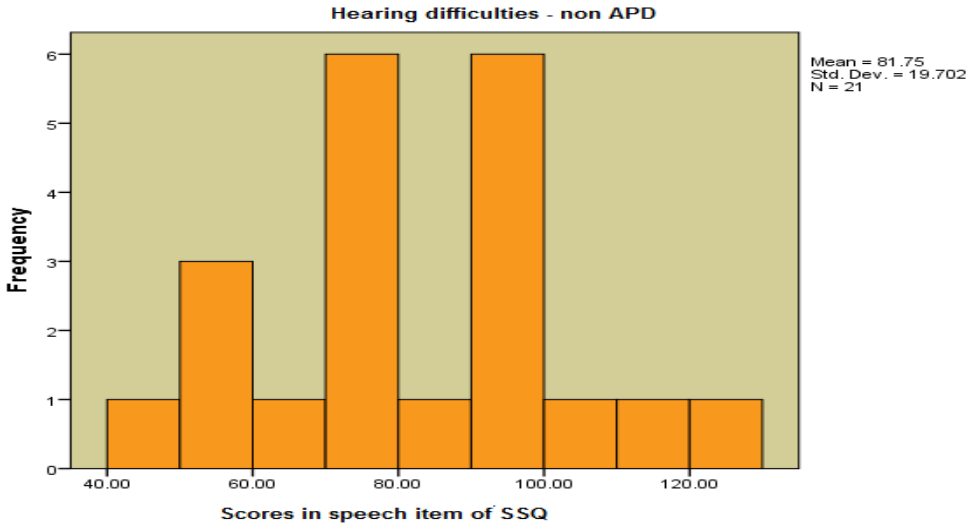


Figure 4.8: Scores in the speech item of the SSQ questionnaire in participants with hearing difficulties but clinical non-APD

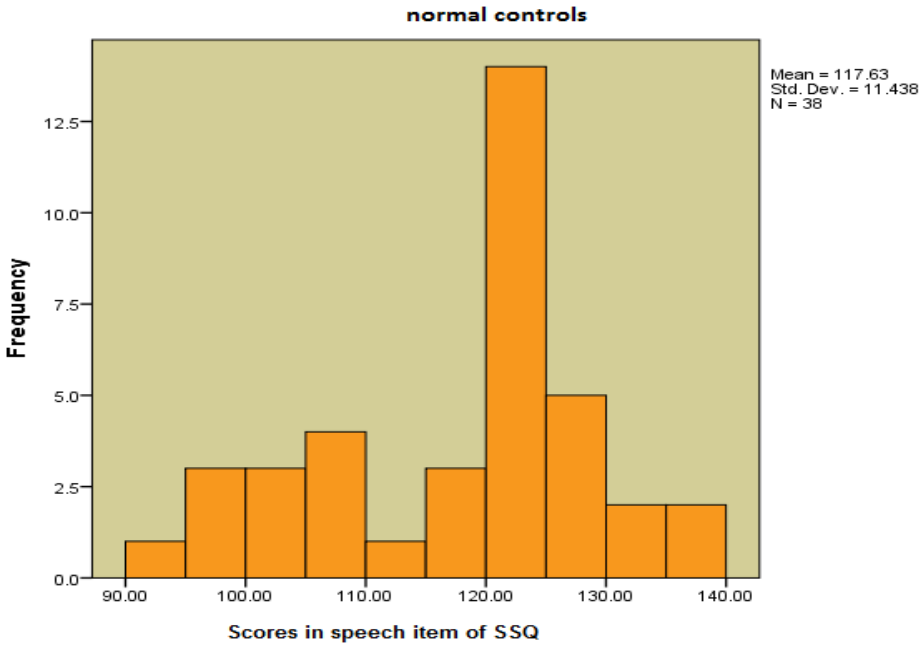


Figure 4.9: Scores in the speech item of the SSQ questionnaire in normal controls

Figures 4.6 – 4.9 show that the participants with APD had the lowest scores, followed by the participants with hearing difficulties but non- APD; the normal controls had the highest scores in the speech section of SSQ questionnaire. High scores indicate less hearing difficulties.

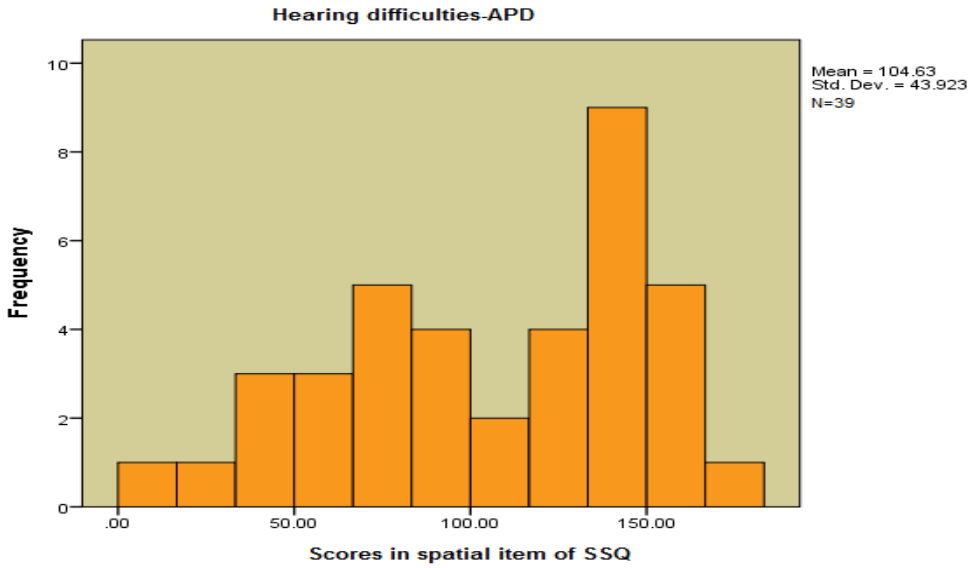


Figure 4.10: Scores in the spatial item of the SSQ questionnaire in participants with APD

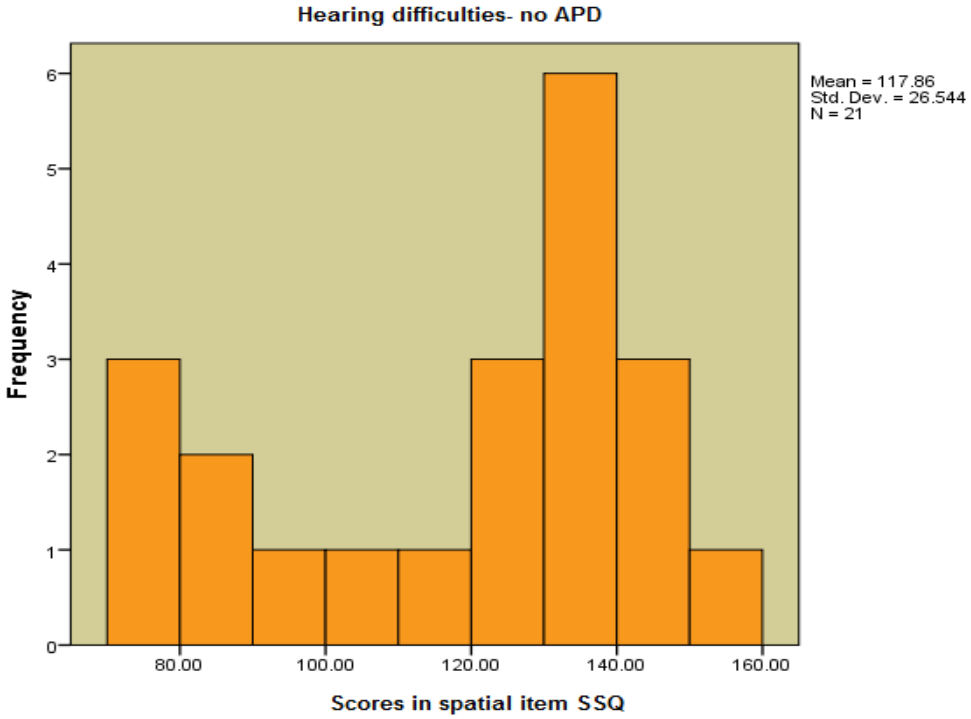


Figure 4.11: Scores in the spatial item of the SSQ questionnaire in participants with hearing difficulties but clinical non-APD

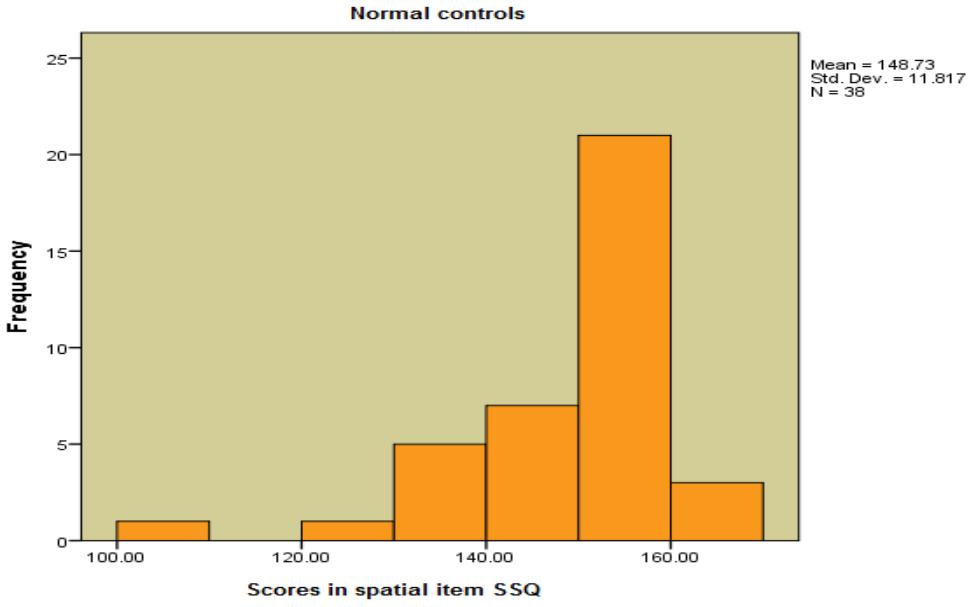


Figure 4.12: Scores in the spatial item of the SSQ questionnaire in normal controls

Figures 4.10 – 4.12 show that the participants with APD had the lowest scores, followed by the participants with hearing difficulties but non-APD,

whereas the normal controls had the highest scores in the spatial section of SSQ questionnaire. High scores indicate less difficulty in spatial awareness.

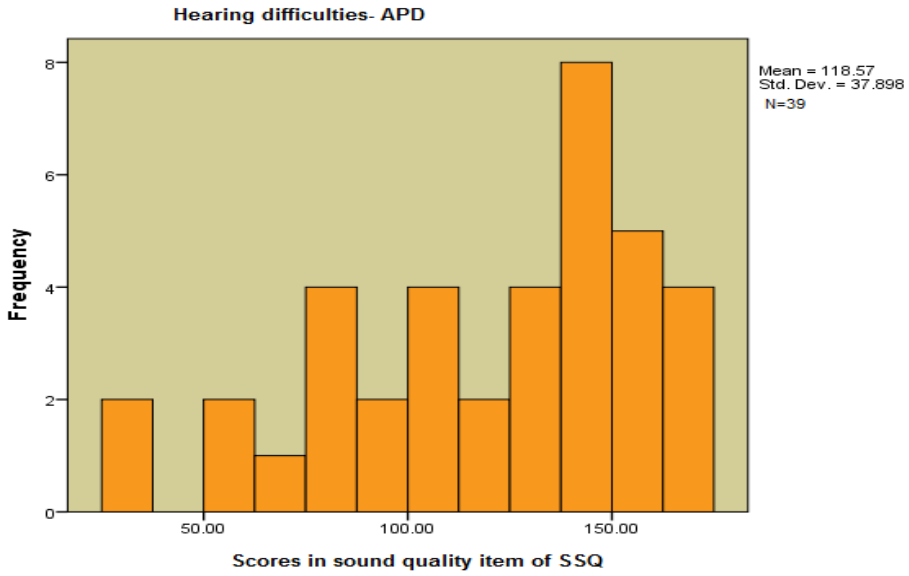


Figure 4.13: Scores in the sound quality item of the SSQ questionnaire for participants with APD

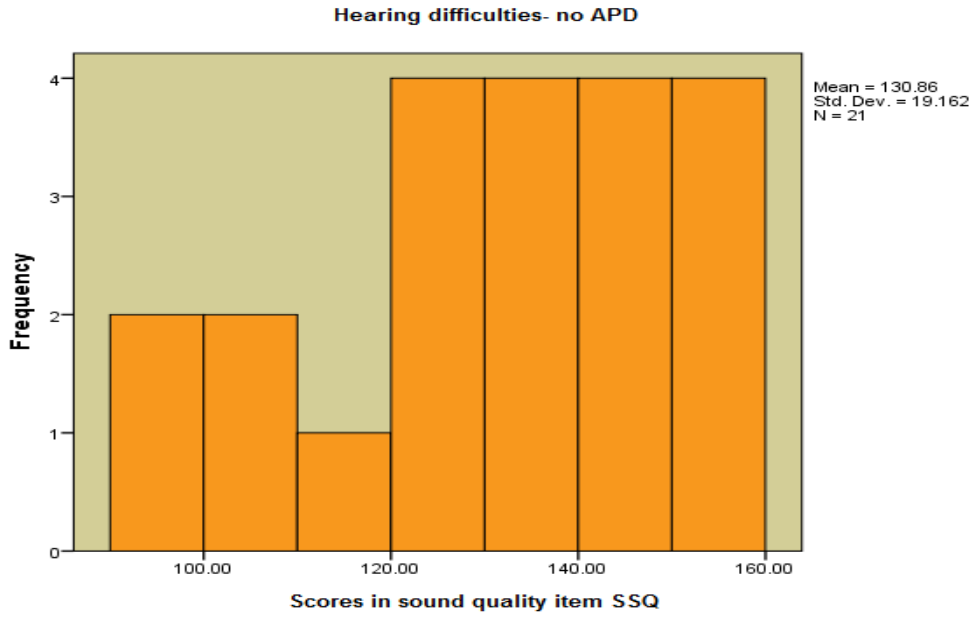


Figure 4.14: Scores in the sound quality item of the SSQ questionnaire for participants with hearing difficulties but clinical non-APD

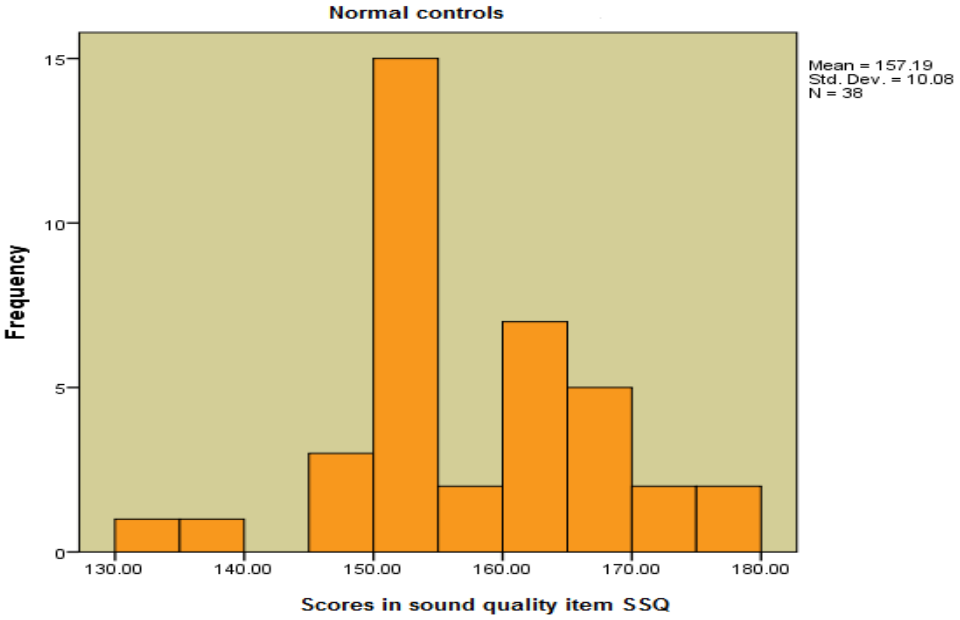


Figure 4.15: Scores in the sound quality item of the SSQ questionnaire in normal controls

Figures 4.13 – 4.15 show that the participants with APD had the lowest scores, followed by the participants with hearing difficulties but clinical non-APD; the normal controls had the highest scores in the sound-quality section of the SSQ questionnaire. High scores indicate less difficulty with sound quality.

Table 4.**7** shows the values of mean, median and SD for participants with APD, clinical non-APD, and normal controls for 3 sections of the SSQ questionnaire: (a) speech, (b) spatial and (c) quality of sound.

Table 4.7: Values of mean, median and SD of three sections of the SSQ questionnaire

Groups		SPEECH	SPATIAL	SOUND
APD (n = 39)	Mean	66.1053	104.6342	118.5658
	Median	67.0000	114.5000	131.5000
	SD	29.83835	43.92318	37.89842
Clinical non-APD (n = 21)	Mean	81.7524	117.8571	130.8571
	Median	78.0000	126.0000	136.0000
	SD	19.70248	26.54354	19.16175
Normal (n = 38)	Mean	117.6316	148.7263	157.1997
	Median	121.0000	152.0000	153.7500
	SD	11.43766	11.81652	10.07990

Kruskal–Wallis non-parametric testing confirms a statistically significant difference among the three groups for all sections of the questionnaire (Table 4.8).

Table 4.8: Kruskal–Wallis for three sections of the SSQ questionnaire in three research groups

SSQ	p-value
SPEECH	0.000
SPATIAL	0.000
QUALITY SOUND	0.000

We also conducted a Mann–Whitney non-parametric test for the clinical APD and clinical non-APD group, and there were statistically significant differences for the speech section of SSQ ($p < 0.05$), but not for the spatial and sound ones. Mann–Whitney test showed significant differences in scoring in all aspects of SSQ between participants with clinical non-APD and normal controls (See Table 4.9). As the Kruskal–Wallis test showed statistical significant differences among the three groups, no further analysis was required, e.g. Mann–Whitney non-parametric tests between APD and normal controls.

Table 4.9: Mann–Whitney non-parametric test between clinical APD and clinical non-APD groups and between clinical non-APD and normal controls.

Significance levels ≤ 0.05

SSQ	APD -Clinical non-APD p-value	Clinical non-APD - Normal p-value
SPEECH	0.047	0.000
SPATIAL	0.586	0.000
QUALITY SOUND	0.660	0.000

Figures 4.16 – 4.17 show the mean scores for each item for the speech section of SSQ questionnaire for the three research groups

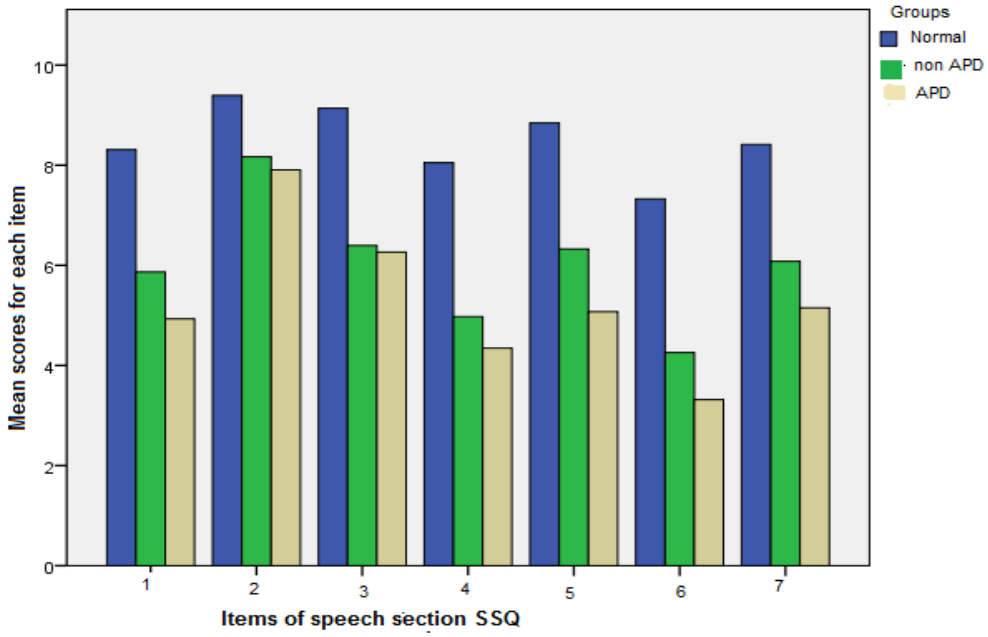


Figure 4.16: Mean scores per item (1–7) of the speech section of SSQ questionnaire in the three groups

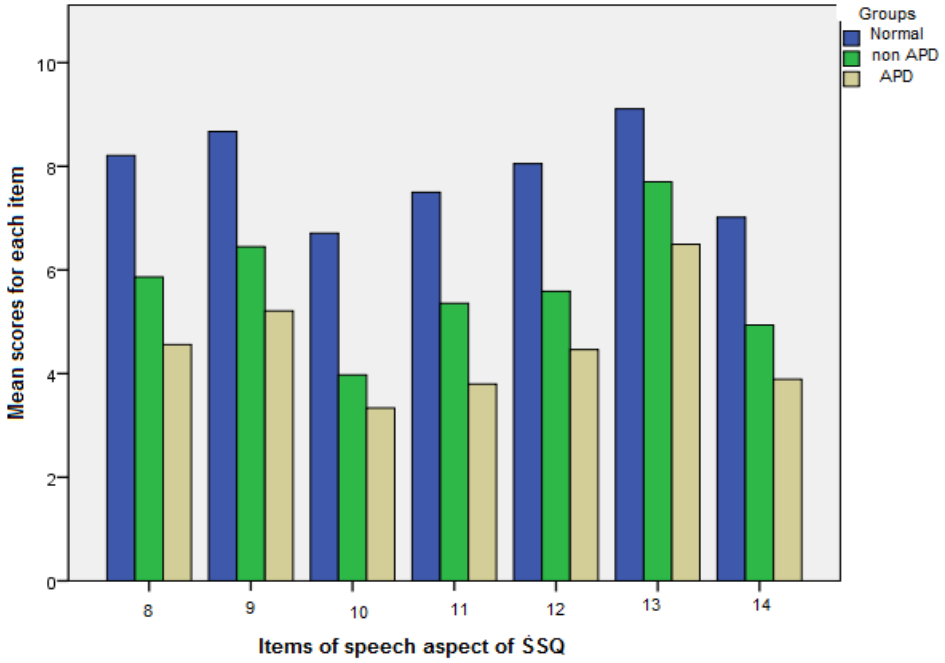


Figure 4.17: Mean scores per item (8–14) of the speech section of the SSQ questionnaire in the three groups

Figures 4.18 – 4.19 show that the mean scores for each item of the spatial section of the SSQ questionnaire in the three research groups.

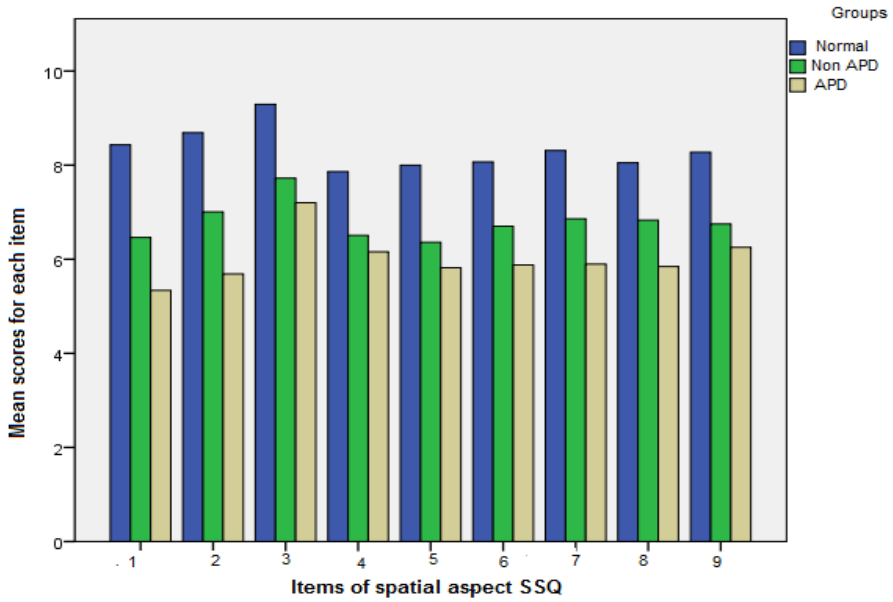


Figure 4.18: Mean scores per item (1–7) of the spatial section of the SSQ questionnaire in the three groups

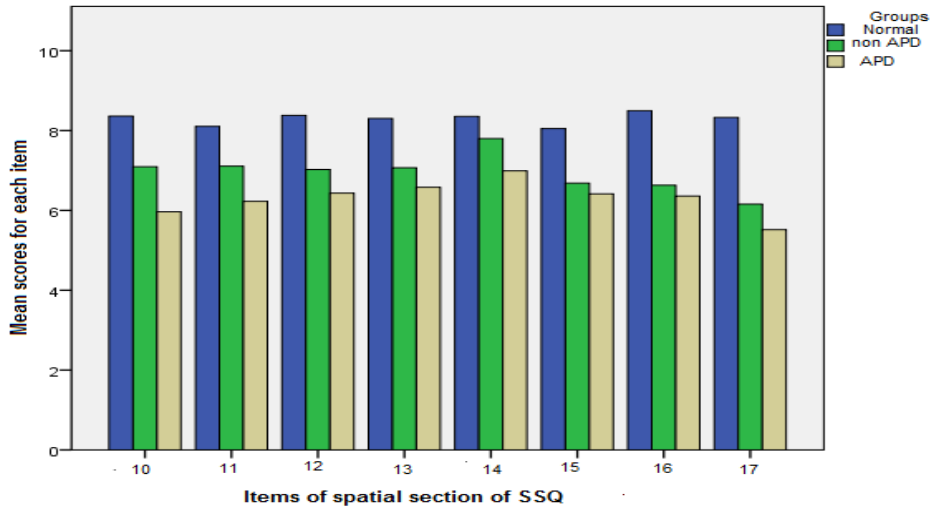


Figure 4.19: Mean scores per item (10-17) of the spatial section of the SSQ questionnaire in the three groups

Figures 4.20 - 4.21 show the mean scores for each item for the sound quality section of the SSQ questionnaire for the three research groups

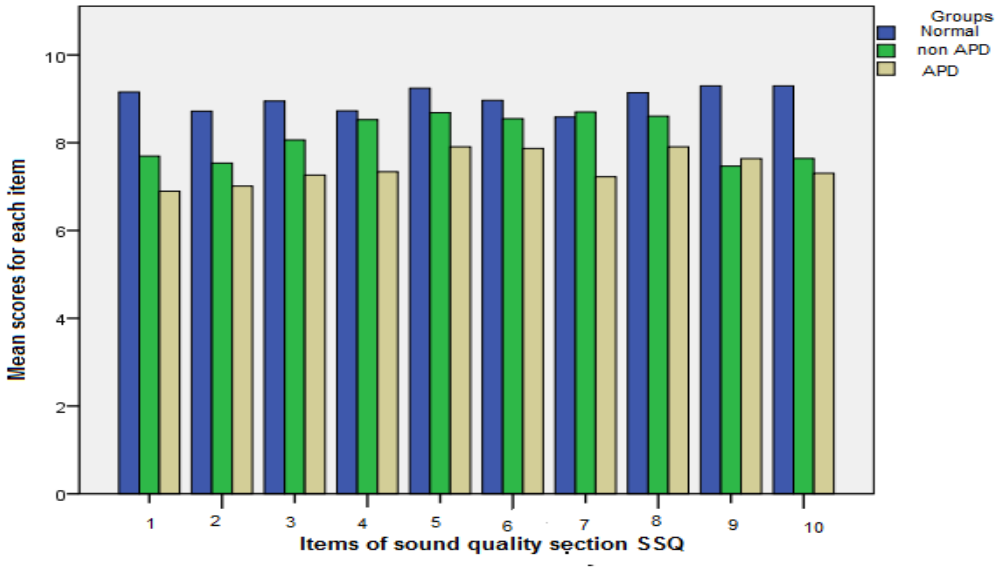


Figure 4.20: Mean scores per item (1–10) of the sound quality section of the SSQ questionnaire in the three groups

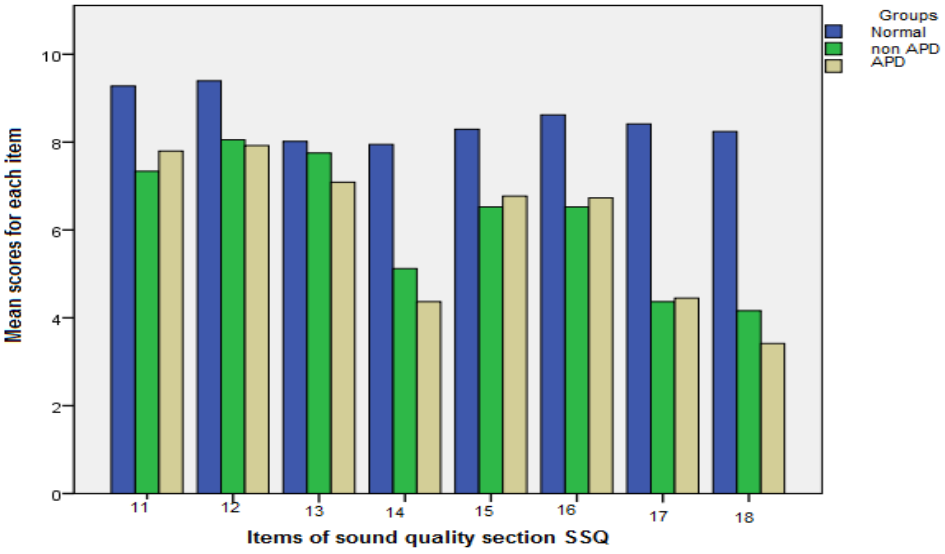


Figure 4.21: Mean scores per item (11–18) of the sound quality section of the SSQ questionnaire in the three groups

4.6.4 Hyperacusis Questionnaire Scores

Two research participants, one with clinical APD and one with clinical non-APD had incomplete data on the hyperacusis questionnaire and therefore those questionnaires were not included in the statistical analysis. The hyperacusis questionnaire score is different from the AD and SSQ ones

since higher scores indicate more severe symptoms of hyperacusis. Frequency distributions for all three groups are shown in Figures 4.22 – 4.24.

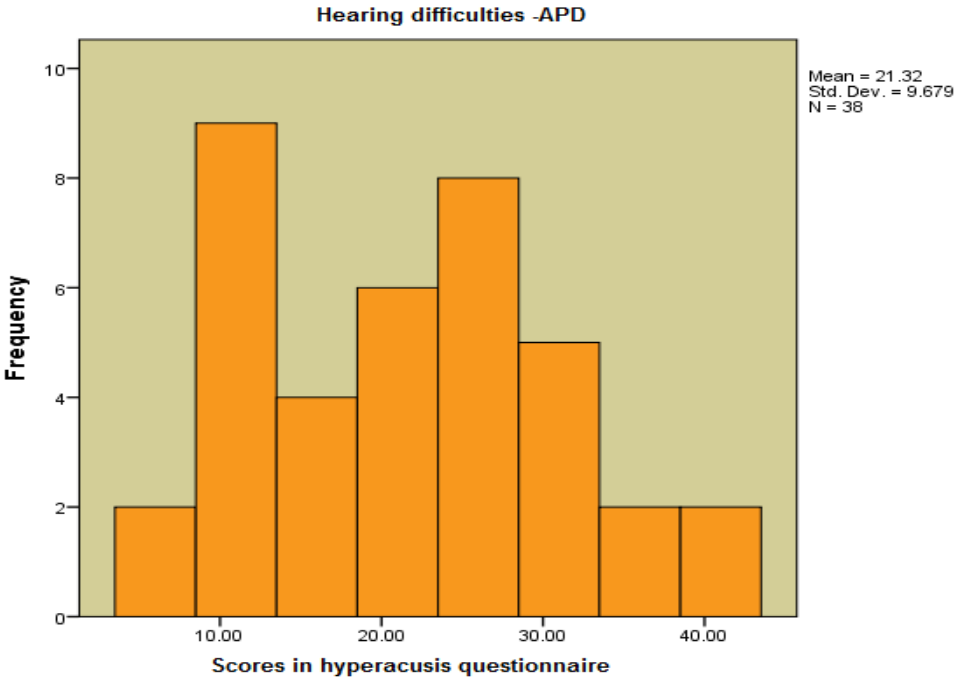


Figure 4.22: Scores in the hyperacusis questionnaire in participants with APD

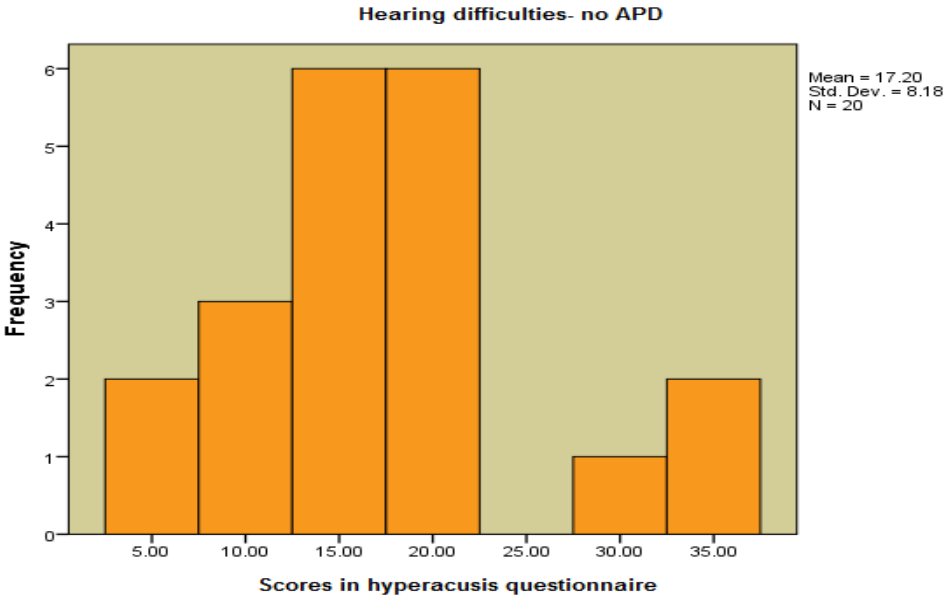


Figure 4.23: Scores in the hyperacusis questionnaire in participants with hearing difficulties but clinical non-APD

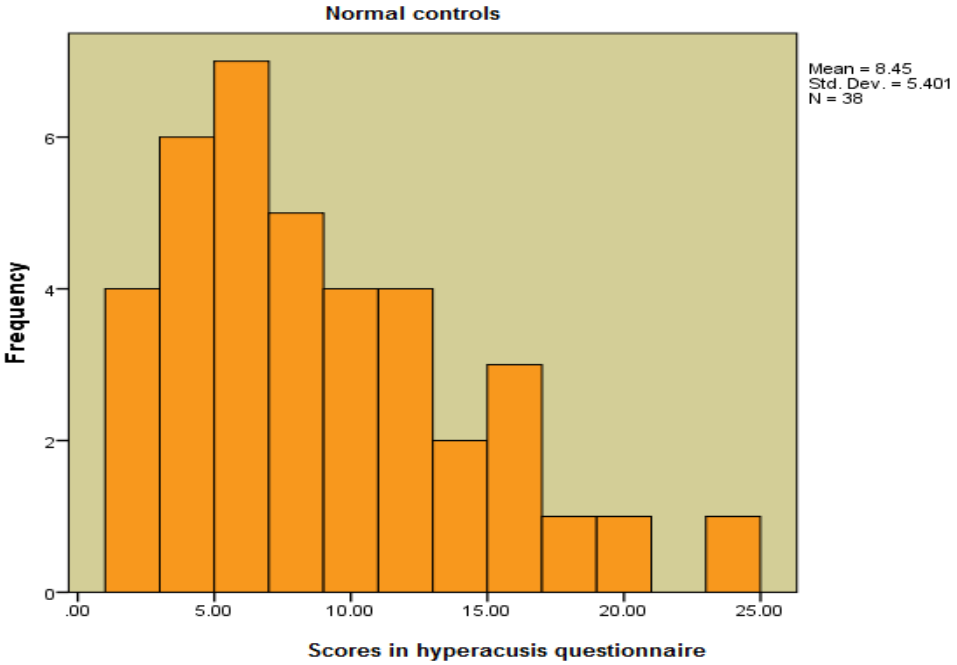


Figure 4.24:Scores in the hyperacusis questionnaires in normal controls

Table 4.10 shows the values of the mean, median and SD for participants with APD, hearing difficulties but clinical non-APD and normal controls for each domain of the hyperacusis questionnaire: (a) attentional, (b) social and (c) emotional.

Table 4.10: Values of mean, median and SD for the hyperacusis questionnaire within the 3 groups

List of abbreviations hyp, hyperacusis; AHYP, attentional hyperacusis; SHYP, social hyperacusis; EHYP, emotional hyperacusis.

Group	Value	Hyp	AHYP	SHYP	EHYP
APD (n = 38)	mean	21.3158	6.1842	8.4474	6.6053
	median	22.0000	6.0000	8.0000	6.5000
	SD	9.67891	3.13529	4.56602	3.30879
Clinical non-APD (n = 20)	mean	17.2000	4.7500	7.0000	5.6000
	median	17.0000	5.0000	7.0000	5.0000
	SD	8.17956	2.82610	3.38728	3.21837
Normal (n = 38)	mean	8.4474	2.8158	2.7105	2.7632
	median	7.50000	2.0000	2.0000	2.0000
	SD	5.40119	2.41454	2.28873	2.09806

Kruskal–Wallis testing confirms a highly significant difference among the three groups for all dimensions of the questionnaire (Table 4.11).

Table 4.11: Kruskal–Wallis in three dimensions of hyperacusis questionnaire for three groups

Hyperacusis	p-value
Hyperacusis	0.000
AHYP	0.000
SHYP	0.000
EHYP	0.000

We also conducted the Mann–Whitney non-parametric test between groups, and there were no statistically significant differences between the clinical APD and non-clinical APD groups, but there was a statistically significant difference between the clinical non-APD and normal controls (Table 4.12). Again, no further analysis was required between clinical APD and normal controls since the Kruskal–Wallis showed statistically significant differences among these groups.

Table 4.12: Mann–Whitney non-parametric test between the APD group and clinical non-APD group and between clinical non-APD and normal controls groups for the hyperacusis questionnaire and its three dimensions.

Significance levels ≤ 0.01

Hyperacusis	**APD-Clinical non-APD P value**	**Clinical non- APD-normal controls p-value**
Hyperacusis	0.119	0.001
AHYP	0.082	0.001
SHYP	0.209	0.000
EHYP	0.298	0.001

Figures 4.25 – 4.26 the mean scores for each item of the hyperacusis questionnaires for the three groups.

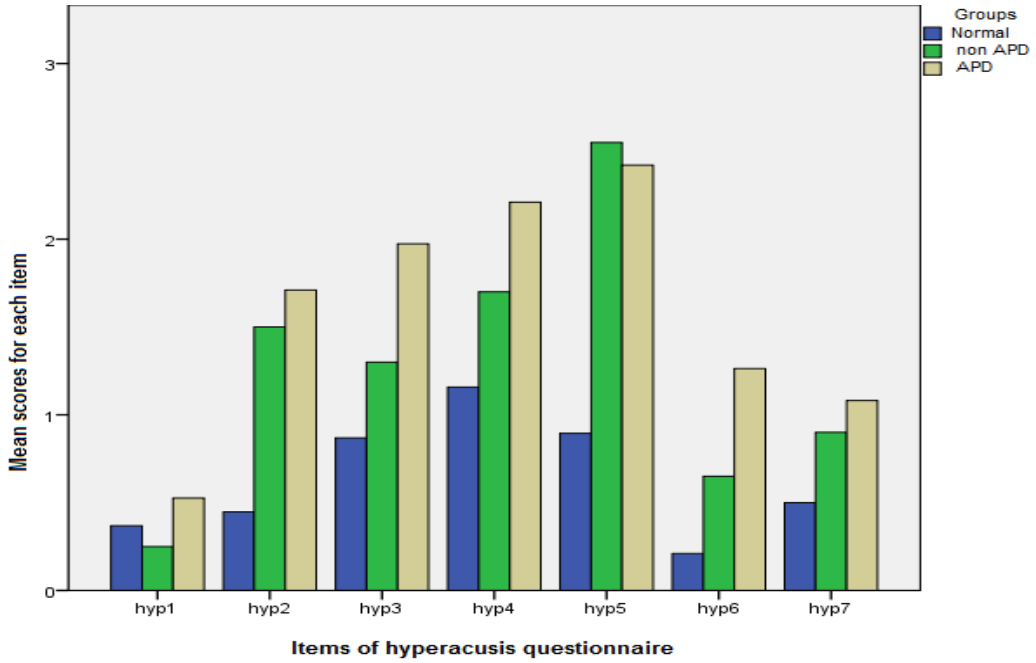


Figure 4.25: Mean scores each item of (1-7) hyperacusis questionnaire for the three groups

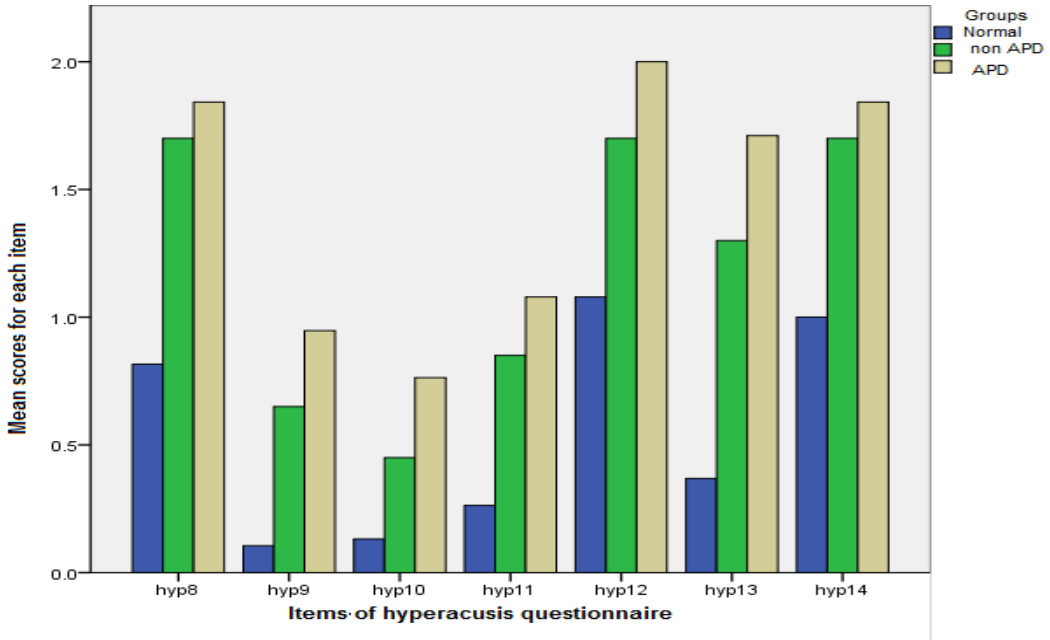


Figure 4.26: Mean scores each item of (8-14) hyperacusis questionnaire for the three groups

4.7 Relationships among AD, SSQ and Hyperacusis Questionnaires

The relationship among the Amsterdam Disability, SSQ and hyperacusis questionnaires scores was examined. There was a significant linear correlation among the three questionnaires. Spearman r_s= -0.707, p = 0.000 between AD and hyperacusis questionnaire and Spearman r_s = .763 (speech and AD), r_s =.668 (spatial and AD) and r_s =.689 (sound and AD), p = 0.000 between AD and SSQ questionnaire. The correlation was positive for the AD and SSQ and negative for the hyperacusis questionnaire and AD and SSQ. Similarly, there was a significant negative correlation between the hyperacusis and SSQ questionnaire. Spearman r_s= -.746 (speech and hyperacusis), r_s = -.510 (spatial and hyperacusis) and r_s = -.670 (sound and hyperacusis) and p = 0.000.

4.8 Questionnaires as Screening Tools

In order to see if those questionnaires can predict which patients need further assessment for APD cut-off values were calculated by using receiver operating characteristic curves (ROC). Subsequently the sensitivity, specificity and likelihood ratio of the questionnaires were calculated in predicting APD. (Figures 4.11, 4.12, 4.13). The questionnaires have low sensitivity but very high specificity that means that the questionnaires will correctly predict patients who do not have APD.

4.8.1 Amsterdam Disability Questionnaire

Figure 4.27 shows the receiver operating curve (ROC) curve for the Amsterdam Disability Questionnaire. This is a plot of sensitivity (vertical axis) against 1-specificity (horizontal axis), for different cut-off choices. The optimal cut-off value of 52.000 (i.e. a score of 52 or less) gives a sensitivity of 41% and specificity of 94.9% (1-specificity = 0.051). Likelihood ratio= sensitivity/(1 - specificity) = 8.20. Table 4.13 shows that the overall ability for this questionnaire to discriminate between individuals with or without APD, measured as the area under the ROC curve (AUC). If there is perfect

discrimination, the area under the ROC curve should be 1. For the above specificity and sensitivity, the AUC was 0.809, which is very high.

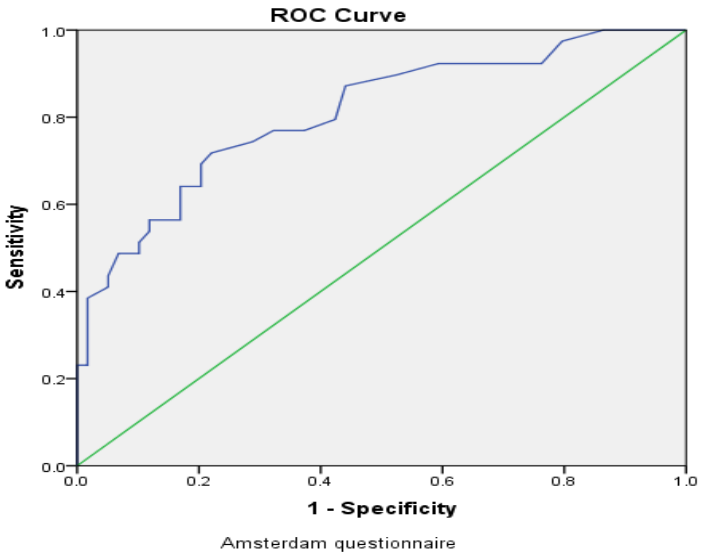


Figure 4.27: ROC for Amsterdam Disability questionnaire

Table 4.13: Area Under the Curve for AD questionnaire

Test Result Variable(s): AD

Area	Std. Error[a]	Asymptotic Sig.[b]	Asymptotic 95% Confidence Interval	
			Lower Bound	Upper Bound
.809	.045	.000	.721	.897

4.8.2 SSQ questionnaire

Figure 4.28 shows the ROC for the SSQ Questionnaire. This is a plot of sensitivity (vertical axis) against 1-specificity (horizontal axis), for different cut-off choices.

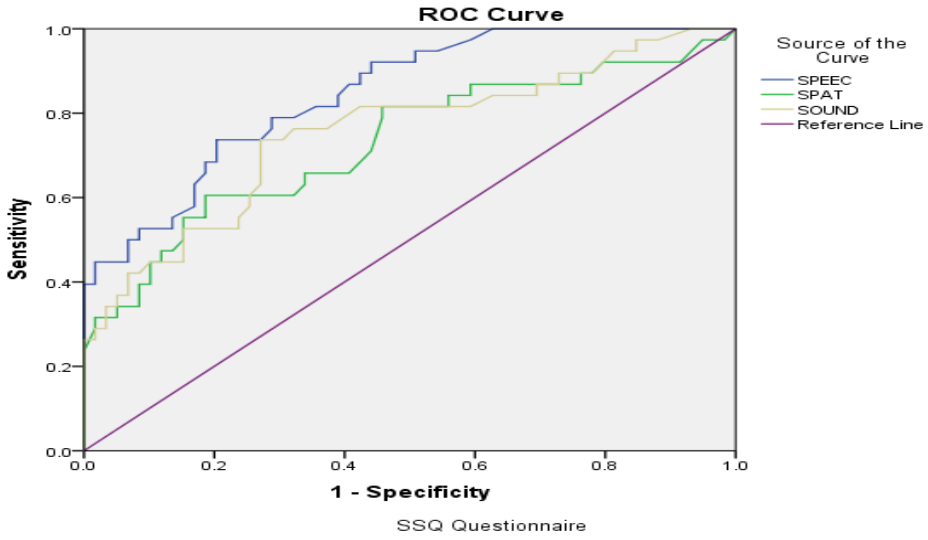


Figure 4.28: ROC SSQ questionnaire

Table 4.14: Area Under the Curve for the SSQ questionnaire

Test Result Variable(s)	Area	Std. Error[a]	Asymptotic Sig.[b]	Asymptotic 95% Confidence Interval	
				Lower Bound	Upper Bound
SPEEC	.845	.039	.000	.769	.920
SPAT	.729	.055	.000	.622	.837
SOUND	.753	.052	.000	.650	.855

For the speech aspect of the questionnaire the optimal cut off value of 51.400 (i.e. a score of 51.400 or less) gives a sensitivity of 42% and specificity of 98.3% (1-specificity = 0.017). Likelihood ratio = sensitivity/ (1-specificity) = 2.476.For the spatial aspect of SSQ questionnaire, the optimal cut-off value of 51.400 (i.e. a score of 51.400 or less) gives a sensitivity of 42% and specificity of 98.3% (1-specificity = 0.017). Likelihood ratio = sensitivity/ (1-specificity) = 2.476.

For the sound aspect of SSQ questionnaire the cut off value of 102.000 (i.e. a score of 102.000 or less) gives a sensitivity of 34.2% and 96.6% specificity (1-specificity = 0.034). Likelihood ratio = sensitivity/ (1-specificity) = 1.0.

Table.4.14 shows that the overall ability for this questionnaire to discriminate between individuals with or without APD may be measured by the area under

the ROC curve .If there is perfect discrimination the area under the ROC curve should be 1. For the above specificity and sensitivity, the AUC was 0.845, 0.729 and 0.753 for the speech, spatial, and sound aspects of the SSQ questionnaire, respectively, which is very high.

4.8.3 Hyperacusis Questionnaire

Figure 4.29 shows the ROC curve for the hyperacusis questionnaire. This is a plot of sensitivity (vertical axis) against 1-specificity (horizontal axis) for different cut-off choices.

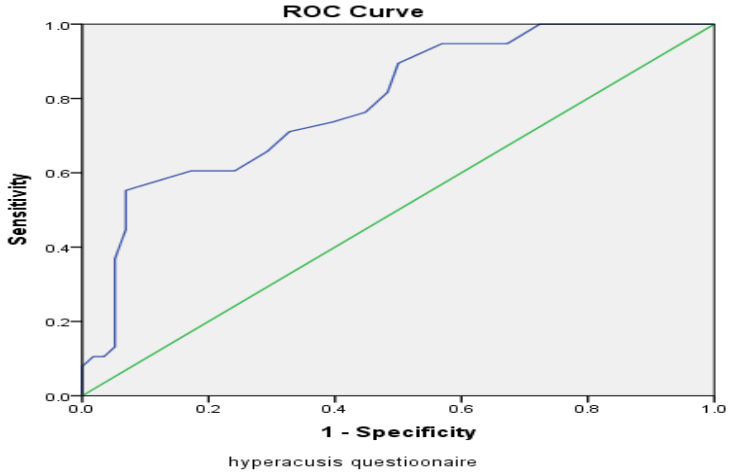


Figure 4.29: ROC hyperacusis questionnaire

Table 4.15 Area Under the Curve for the hyperacusis questionnaire

Test Result Variable(s): hyp

Area	Std. Error[a]	Asymptotic Sig.[b]	Asymptotic 95% Confidence Interval	
			Lower Bound	Upper Bound
.789	.047	.000	.698	.880

For the hyperacusis questionnaire, a cut-off value of 28.000 (i.e. score of 28 or more) gives a sensitivity of 23.7% and 95% specificity (1 – specificity = 0.052). The likelihood ratio= sensitivity/(1-specificity) = 4.55

Table 4.15 shows the overall ability for this questionnaire to discriminate between individuals with or without APD, as measured by the AUC. If there is

perfect discrimination, the AUC should be 1. For the above specificity and sensitivity, the AUC is 0.789 which is very high.

4.9 Comparison between SSQ Scores in Patients with Peripheral Hearing Loss and APD

The SSQ questionnaire was developed for adults with peripheral hearing loss, and Gatehouse and Noble (2004), in their research paper about the validation of the SSQ questionnaire in such patients, provide the mean values of each item of the SSQ questionnaire. The 153 adults who participated in their study had bilateral hearing loss of various degrees requiring hearing aids, and they completed the questionnaire prior to the fitting of the hearing aid. The research participants with hearing difficulties and clinical APD had significantly poorer scores than the research participants with hearing difficulties but clinical non-APD and the normal controls. In order to assess validity of the SSQ questionnaire in adults with APD, a comparison study was carried out of the mean values of the items of SSQ questionnaire between (i) patients who participated in 2004 study by Gatehouse and Noble on the SSQ questionnaire and (ii) the APD participants enrolled in the current study. Table 4.16 records the item-wise mean values for the two groups and the significance of the mean differences between the two groups for each item

Table 4.16: Mean values for each item SSQ questionnaire for (a) patients with hearing difficulties (Gatehouse and Noble, 2004) and (b) research participants with clinical APD; p > 0.05 no significant difference

SSQ Questionnaire	Mean value and SD for subjects with hearing loss enrolled in the Gatehouse & Noble study of 2004 (N = 153)		Mean value and SD for research subjects with clinical APD (N = 39)		P value
Speech-hearing items	Mean	SD	Mean	SD	
Talk with one person and follow TV	4.6	2.7	5.0	2.4	0.1
Talking with one person in quiet room	7.1	2.4	7.8	2.1	0.1
Having conversation with five people in quiet with vision	4.5	2.7	6.1	2.3	0.1
Having conversation with five people in noise with vision	3.4	2.3	4.2	2.6	0.1
Talking with one person in continuous background noise	4.6	2.4	4.9	2.4	0.9
Having conversation with five people in noise without vision	2.7	2.2	3.2	2.7	0.02
Having conversation in echoing environment	4.0	2.4	7.4	2.4	0.9
Ignore interfering voice of same pitch	4.9	2.4	6.9	2.4	0.9
Ignore interfering voice of different pitch	5.0	2.6	7.5	2.3	0.4
Talking with one person with TV on	3.0	2.6	5.6	2.5	0.6
Follow one conversation when many people talking	4.3	2.6	3.8	2.5	0.6
Follow conversation without missing the start of new talker	4.0	2.4	4.3	2.7	0.2
Have conversation on telephone	6.8	2.1	8.7	1.7	0.002
Follow one person speaking at telephone on the same time	2.5	1.8	6.2	1.7	0.5

Spatial hearing items	Mean	SD	Mean	SD	
Locate lawnmower	4.6	2.7	5.4	2.8	0.6
Locate speaker round a table	5.6	2.8	5.6	2.9	No difference
Lateralize a talker to left to right	7.0	2.6	7.3	2.7	0.7
Locate a door slam in unfamiliar house	6.1	2.8	6.1	2.9	No difference
Locate above or below on stairwell	5.5.	2.8	6.7	2.8	0.9
Locate dog barking	6.0	2.6	7.5	1.8	0.0002
Locate vehicle from footpath	4.9	2.8	6.9	2.6	0.4
Judge distance from footsteps or voice	4.2	2.6	7.0	2.7	0.6
Judge distance of vehicle	4.8	2.7	6.7	2.1	0.008
Identify lateral movement of vehicle	4.8	2.7	6.0	2.7	0.2
Identify lateral movement from voice or footsteps	5.0	2.7	6.3	2.9	0.4
Identify approach or recede from voice or footsteps	5.6	2.7	6.5	2.8	0.6
Identify whether vehicle is approaching or receding	5.3	2.8	7.0	1.9	0
Internalization of sounds	7.5	2.3	7.2	2.7	0.07
Sounds closer than expected	6.1	2.7	8.5	2.4	0.2
Sounds further than expected	7.3	2.2	7.2	1.9	0.1
Sounds in expected location	6.1	2.7	5.6	3.1	0.1
Sound Qualities of hearing items	Mean	SD	Mean SD		
Clarity of everyday sounds	6.6	2.7	7.0	2.7	0.9
Sounds appear jumbled	5.9	3.1	7.8	2.6	0
Music and voice as separate objects	6.3	2.7	7.5	1.8	0.0002
Identify different people by voice	7.8	2.0	7.8	1.9	No difference
Distinguish familiar music	8.3	1.9	8.0	2.2	0.6
Separation of two sounds	6.6	3.0	7.8	1.9	0.1
Identify instruments in music	6.6	3.0	7.3	2.9	0
Naturalness of music	7.2	2.6	7.5	2.1	0.3
Clarity of everyday sounds	6.6	2.7	7.8	2.7	0.02
Naturalness of others voices	6.0	2.5	7.7	2.1	0

Sound Qualities of hearing items	Mean	SD	Mean	SD	P value
Naturalness of everyday sounds	7.1	2.8	7.5	1.9	0
Naturalness of own voice	7.7	2.8	8.3	1.9	0.04
Judging mood by voice	7.5	2.5	6.6	2.3	0.3
Need to concentrate when listening	3.7	2.8	6.5	2.5	0.2
Understand when driver of a car	4.6	2.8	6.6	2.3	0.03
Understand when car passenger	5.4	2.7	6.5	1.8	0
Effort of conversation	4.0	3.1	3.6	2.6	0.06
Ability to ignore competing sounds	5.3	3.1	3.4	2.5	0.02

The above data for the speech section of the SSQ questionnaire showed that there were no significant differences between the scores of the individual items in the two groups, except for two items: ability to follow conversation in noise with 5 people and hearing on the telephone. The APD group scored better, however, for the ability to follow conversation, but the score was very low, at 3.7, and indicates significant difficulties. The scores were better for the spatial and sound quality sections of the questionnaire for both groups. For the spatial section of the SSQ questionnaire, there were two items with significant differences between the two groups (locating the dog barking and judging the distance of the vehicle). There were 10 items with significant intergroup differences in the mean values for the sound quality section of the questionnaire. Patients with peripheral hearing loss scored worse in all items apart from judging mood by voice, ability to ignore competing sounds and effort in conversation.

The above findings show that the auditory behaviour of adults with APD is similar to that of patients with peripheral hearing loss.

4.10 Discussion

The aim of this study was to characterise auditory symptoms in patients with APD. In order to provide a comprehensive picture, three validated questionnaires were used: (a) the Amsterdam Disability (AD) questionnaire, which has been used in patients with peripheral hearing loss, suspected APD

(Neijenhuis et al., 2003), and APD (Spyridakou et al., 2012; Bamiou et al., 2012); (b) the SSQ questionnaire that has been used in patients with hearing loss and (c) the hyperacusis questionnaire. We included the hyperacusis questionnaire since previous evidence has shown that patients with difficulties in hearing in noise also experience hyperacusis, and in addition, our test battery included the suppression of TEOAEs by contralateral noise, which has been found to be abnormal in patients with hyperacusis and tinnitus (Ceranic et al., 1998). In addition, the AD and SSQ questionnaires provide information about auditory complaints but no information about emotional responses and social behaviours adopted by hearing difficulties, which is overcome by the hyperacusis questionnaire to some extent.

The present study aimed at assessing the validity of the AD and hyperacusis questionnaires for assessing listening skills in neurologically normal adults with APD. Construct validity refers to the degree to which a test measures what it claims to be measuring (Cronbach and Meehl, 1955). The construct in question, defined as the 'postulated attribute of people, assumed to be reflected in test performance' (Cronbach and Meehl, 1955, p. 296), is the auditory processing ability in its broad definition by ASHA 2005, i.e. 'the efficiency and effectiveness by which the central nervous system (CNS) utilizes auditory information', as reflected by subject-reported listening ability. Construct validity, in the lack of a gold standard for APD, was initially assessed by comparing against a well-validated, 50-item hearing questionnaire, the SSQ, proposed by Gatehouse and Noble (2004), which has been validated in 153 people referred for audiological input, rated prior to hearing aid provision and showed good correlation with hearing thresholds.

The AD, SSQ and hyperacusis questionnaires were administered to a clinical population of non-neurological adults who were referred for auditory processing assessment because of hearing complaints in the presence of normal audiogram, as well as a sample of age-matched normal controls. Construct validity was then further assessed for all three questionnaires by comparing scores in the clinical vs. normal population.

The questionnaires gave significantly different results in the clinical vs. the normal group, and a good correlation with each other, demonstrating construct validity for the APD.

This research study shows that participants with APD experience a variety of auditory symptoms. Participants diagnosed with APD had significantly worse scores than participants with reported hearing difficulties and clinical non-APD.

Participants with APD have hearing difficulties in the presence of background noise, as measured by the Amsterdam Disability questionnaire and the speech aspect of the SSQ questionnaire. In both the questionnaires, the speech subscales yielded the lowest (worse) scores in the APD group and total clinical group, and the majority of the poor scores were also for individual speech-scale items. APD participants had the worst mean scores for the following questions of the Amsterdam Disability Inventory: *'Can you carry on a conversation with someone in a crowded place? 'Can you follow a conversation between a few people during dinner?'* and *'Can you carry a conversation with someone in a busy street?'* Similarly, they scored poorly in the following questions of the speech aspect of the SSQ: *'You are in a group of about five people in a busy restaurant. You cannot see everyone in the group. Can you follow the conversation?'* and *'you are in conversation with one person in a room where there are many people talking can you follow what the person you are talking to is saying?'* These results are consistent with those of other studies on adults with APD that report speech-in-noise to be the most prevalent or worst impacted listening concern of adult patients with neurological and non-neurological APD (Blaettner et al., 1989; Neijenhuis et al., 2003; Spyridakou et al., 2012; Bamiou et al., 2013).

There were no overall statistical significant differences in the mean values for items of the SSQ questionnaire between the adults with peripheral hearing loss (Gatehouse and Noble, 2004) and our study participants with clinical APD. An interesting finding of the questionnaire is that participants with APD have difficulties in ignoring changes in background noise and competing speech; this was evidenced by the fact that the clinical APD as well as the

hearing-impaired subjects (Gatehouse and Noble 2004) had the worst scores in the speech-related items related to divided address and/or rapidly shifting attention in the Amsterdam Disability questionnaire and the SSQ. Participants with APD, however, scored significantly lower scores in all aspects of the Amsterdam Disability questionnaire, including speech in noise, speech in quiet, sound recognition, localisation and detection of sound. These findings differ from those of published research studies from Neijenhuis et al. (2003) and Bamiou et al. (2012). However, their research participants differ from this research study; in the former study (Neijenhuis et al., 2003), the participants had suspected APD, and in the latter study, (Bamiou et al., 2012), they had structural brain abnormalities. Neijenhuis et al., in 2003, reported that adults with hearing difficulties and suspected APD scored worse in the SIN and sound localisation aspects of the Amsterdam Disability questionnaire. Bamiou et al. in 2012 reported that patients with stroke scored worse in sound recognition and localisation aspect of the Amsterdam Disability questionnaire.

Another interesting finding is that participants with APD scored significantly worse in the hyperacusis questionnaire. Several publications have addressed the relationship between hyperacusis, tinnitus and hearing loss. A recent review by Wagenaar et al. (2010) of tinnitus, hyperacusis and auditory processing indicates that current evidence suggests that there is probably a common central auditory neurological mechanism for tinnitus, hyperacusis and auditory processing. A recent study by Wallen et al. (2012) showed that emotional exhaustion can cause hyperacusis, as measured by uncomfortable loudness levels auditory test. The research participants with APD scored significantly higher (worse) in the following questions: '*Do you find it harder to ignore sounds around you in everyday situations?;* '*Do you have trouble concentrating in noisy surroundings?;* '*Do you have difficulty listening conversations in noisy places?'*, '*Do stress and tiredness reduce your ability to concentrate in noise'* and '*Do noise and certain sounds cause you stress and irritation?'* It is possible that the research participants with APD have hearing difficulties in the presence of background noise due to difficulties in ignoring the background noise and concentrating in speech.

However, it is difficult to decide on the basis of this study whether this reflects a problem with higher-order auditory attention or difficulty of the brain to filter out unnecessary information by means of lower bottom-up processes such as auditory streaming prior to allocation of attention. There are no published studies in which the hyperacusis questionnaire has been given to patients with APD to compare those findings. However there are publications about patients (both children and adults) with autistic spectrum disorder who experience hyperacusis and difficulty in hearing speech in noise. Children with autistic spectrum disorder (ASD) present with oversensitivity to auditory stimuli (hyperacusis) (Rosenhall et al., 1999) or/and difficulties in hearing in noisy environments. A study published by Alcantara et al. (2004) showed that individuals with Asperger's syndrome have similar speech-reception thresholds as controls in unmodulated background noise but higher by 2-4 dB for modulated noise, i.e. they cannot use the spectral and temporal dips in noise to understand speech clearly. There is some indication that this inability in Asperger's patients is associated with early sensory processing deficits in that these individuals show a delay in the development of auditory temporal-envelope processing (Alcantara et al., 2012).

Another primary aim of this research study was to identify whether the above validated questionnaires can be used as screening tools. There is a need for validated questionnaires that can be used as screening tools to identify individuals requiring further assessment for APD, (Moore et al., 2013). There was a high specificity (>90%) for all three questionnaires in predicting APD, and strong correlations were noted among the three different questionnaires. Sensitivity was poor, however, although the exact prevalence of APD is not known, it is estimated that around 10% (Saunders and Haggard, 1992) of the adults present with auditory symptoms despite normal hearing on pure-tone audiometry. It is, therefore, not anticipated that the low sensitivity of the questionnaires will lead to a huge number of unnecessary referrals, if the questionnaires were to be used as screening tools.

In contrast to paediatric studies (Cameron et al., 2006; Dawes et al., 2008; Wilson et al. 2011), this adult research study indicates that the three

validated questionnaires are reliable as screening tools for APD. A possible explanation of the above findings is that adults are better able to describe their auditory difficulties than parents or teachers who act as proxies for children; therefore, the questionnaires can help characterize the auditory profile better in the adult population compared to the paediatric one.

4.11 Conclusions

Adults with clinical APD present with a variety of auditory symptoms that include hearing difficulties in quiet and noisy environments, difficulties in localising and recognising the sound and symptoms of hyperacusis. Their listening profile is thus quite broad and needs to be taken into account when interviewing and testing these patients and also when considering means of remediation for APD. The three validated questionnaires (a) Amsterdam Disability questionnaire. (b) SSQ questionnaire and (c) Hyperacusis questionnaire can reliably identify adult patients who need further referral for APD assessment.

CHAPTER 5: PHASE 3. CORRELATION OF SELF-REPORTED HEARING DIFFICULTIES AND AUDITORY PROCESSING TESTS

5.1 Introduction

APD is classified under category H93.25 in ICD-10; however, it remains a controversial diagnosis. There is no 'gold standard' test for the diagnosis of APD, and no universal consensus on the diagnostic criteria; a wide range of diagnostic yield has been reported for the different diagnostic rules in use (Wilson and Arnott, 2013). Although there is no gold standard test for the diagnosis of APD, there are some published recommendations by the AAA (2010) and BSA (2011) on what diagnostic tests to use for APD, based on current evidence.

The AAA proposes a battery of both behavioural and objective (electrophysiological) tests. The behavioural tests are speech and non-speech tests and include tests of dichotic listening, temporal processing, auditory discrimination, monaural low redundancy and binaural function (localisation and lateralisation). The position statement from the BSA (2011) proposes that APD is characterised (and thus should be diagnosed) by deficits in both speech and non-speech tests. This has been reflected in the APD diagnostic criteria that require the finding of abnormal results in two tests (consistent with recommendations by AAA and ASHA), but one of the two tests should be non-speech (e.g. Spyridakou et al., 2012). Symptom characterisation is an important component of the diagnostic approach. It has been highlighted by both the AAA and BSA that selection of the appropriate auditory tests should be done according to the presenting symptoms, because conducting an exhaustive and time-consuming test battery is not realistic in a clinical context. In addition, test deficits may also help define the specific treatment we offer to the patients (e.g. see Practice Guidance Management of APD, BSA 2011), and for this reason, choosing the tests to conduct on the basis of symptoms reported becomes even more important.

Finally, auditory processing tests may also help quantify the patient disability. For example, it has been recently proposed that a speech-in-noise assessment is a more ecologically valid assessment for hearing impairment rather than hearing threshold loss (Thiele et al., 2011).

Auditory processing disorders are, however, very complex, and patients can present with a variety of symptoms, as shown in chapter 4 of this thesis; nevertheless, the correlation of patient symptoms with test deficits is not well understood. The following section reports on a literature review on the correlation of auditory processing tests and patient-reported symptoms.

5.2 Current Evidence of Correlation of Tests and Symptoms in Patients with APD

A literature search was carried out by using electronic databases (OVID-Medline, OVID-Embase and OVID-Cochrane). The databases were searched for the period 1992-2012 to identify published research studies regarding the correlation between symptoms and tests in patients with auditory processing disorders. With 'auditory processing disorder' as the keyword, 2112 papers published during the period 1992-2012 were retrieved. Among these papers, 306 clinical papers were selected; after exclusion of duplicate papers, non-English papers and papers not meeting the criteria listed below, only 4 primary studies were found to be suitable for the review. Published primary studies that documented the following details were considered eligible for this review: (i) diagnostic criteria of APD, (ii) symptoms reported by patients, as recorded using validated questionnaires, (iii) auditory processing disorder tests and (iv) correlation between the symptoms and tests conducted. There is a lack of the use of validated questionnaires in the adult population, and only 1 adult study was found to be suitable as per the above-mentioned inclusion criteria. Similarly and despite the use of validated questionnaires in the paediatric population, only 3 paediatric studies were noted, with no published meta-analysis or systematic reviews. Most of the current published studies are either case–control studies or clinical studies. Table 5.1 summarises the studies.

There was only one published study by Bamiou et al. (2012) for the adult population. Bamiou et al. (2012) found significant correlations between two aspects of the Amsterdam Disability questionnaire (sound localisation and sound recognition) and dichotic digits and frequency pattern tests in adults with stroke. On the other hand, in the three paediatric studies, only weak correlations were noted between tests and validated questionnaires. The CHAPS questionnaire was used in all of the paediatric studies and in the study by Wilson et al. (2011) the SIFTER questionnaire was also used. Cameron et al. (2006) and Wilson et al. (2011) did not find any significant correlation between questionnaires and APD tests. Iliadou and Bamiou (2012) found that the quiet, ideal, memory and attention aspects of the CHAPS questionnaire had moderate to strong correlations with the dichotic digits and duration pattern tests in older children. This literature review shows the paucity of published studies about the correlation of APD tests and questionnaires.

Table 5.1: Individual study characteristics

Study	No of patients	No of Controls	Age	Definition APD	Results
Cameron et al., 2006	10 cases	48	7–9.11 years	ASHA (1995)	No significant correlations between CHAPS and APD tests
Wilson et al., 2011	104 case review		6.9–14.3	ASHA (2005)	No significant correlations between CHAPS and SIFTERS and APD tests
Iliadou and Bamiou, 2012	38 APD and 20 non-clinical APD	39	11.4–12.7 Years	AAA (2010); BSA (2011)	Moderate to strong correlations between CHAPS and APD tests (DPT and DDT)
Bamiou et al., 2012	10 stroke APD	23	29–81 Years	AAA (2010); BSA (2011)	Moderate to strong correlations between AD (ADLOC and ADREG) with APD tests (FPT, DPT, LDDT)

CHAPS, Children's Auditory Performance Scale Questionnaire; SIFTER, Screening Instrument for Targeting Educational Risk; FPT, Frequency Pattern Test; DPT, Duration Pattern Test; DDT: Dichotic Digit Test; AD, Amsterdam Disability Questionnaire; ADLOC, Amsterdam Disability–localisation aspect; ADREG, Amsterdam Disability–recognition of sounds aspect; L, left

The above literature review shows the paucity of published studies about correlation between APD test results and questionnaire scores. The aims of

the present study were to assess the correlation between patient reported symptoms and auditory processing test results, so that it is possible to make informed choice of the APD tests on the basis of patient-reported symptoms and identify the test deficits that are better used as surrogate measures of patient-reported hearing disability.

5.3 Research Hypothesis

There is a correlation between auditory symptoms, as reported by validated questionnaires and auditory processing tests, in adults with hearing difficulties and normal hearing.

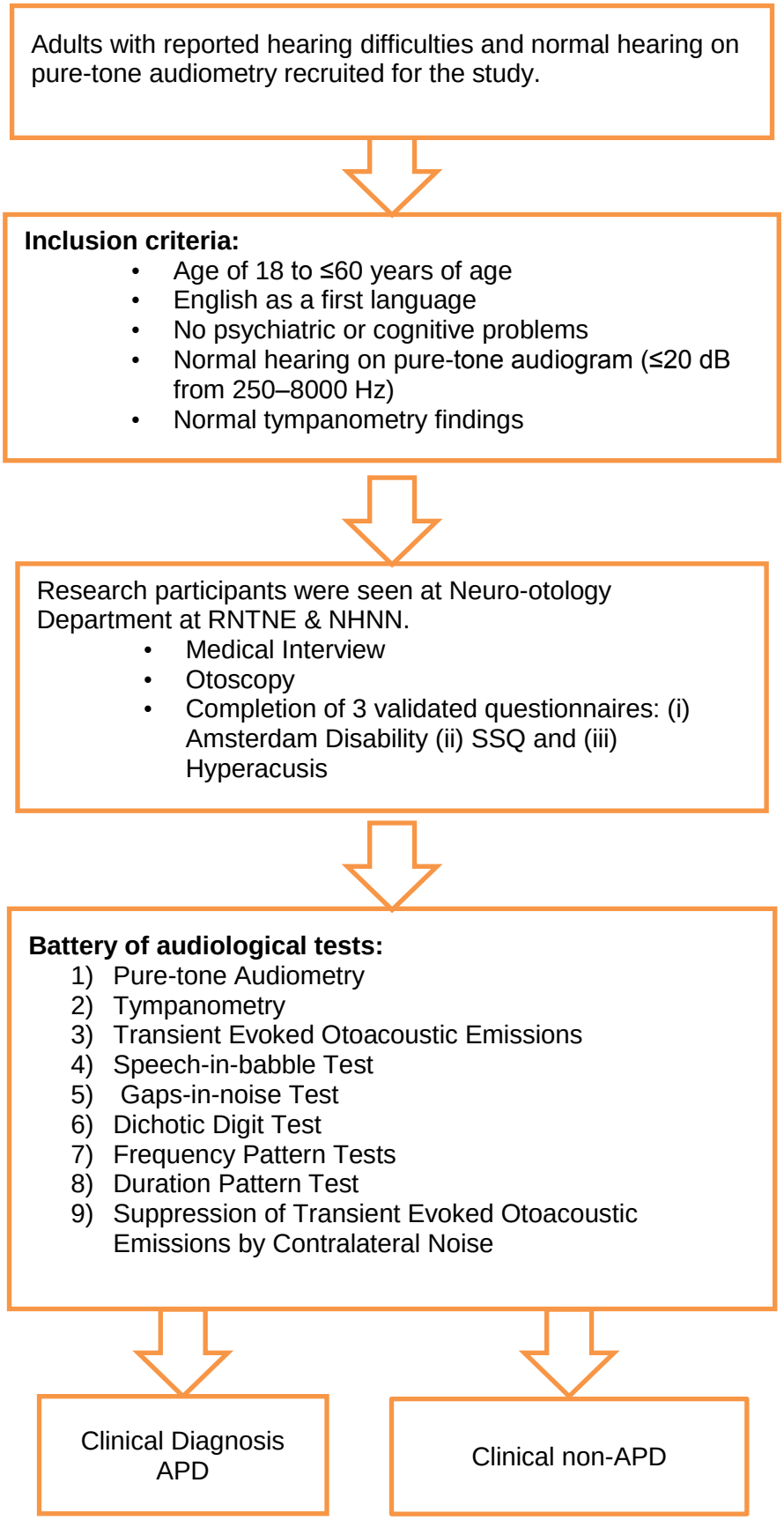
5.4 Material and Methods

5.4.1 Participant Recruitment

Participants were invited to participate in this study if they were adults who (1) sought professional advice for reported hearing difficulties but no previous clinical diagnosis of APD, (2) were referred to a direct-access audiology clinic at Whittington Health or an ENT/Audiovestibular Medicine Clinic at Royal National Throat Nose & Ear Hospital and (3) had normal hearing on pure-one audiogram.

Adults who agreed to participate in the study were interviewed at the Department of Adult Neuro-Otology at Royal National Throat Nose & Ear Hospital. Participants (age range, 18-60 years old) with English as their first language (a requirement for the accurate interpretation of the speech tests) were recruited for the research study. The following criteria were checked for: (1) normal hearing on pure-tone audiometry, (2) air conduction thresholds of ≤ 20dB on both sides at octave frequencies of 0.5–8 kHz and (3) normal middle ear function, as verified by tympanometry with normal middle ear pressure and compliance. Research participants with severe psychiatric or severe cognitive difficulties identified in the clinical interview were excluded from further assessment. Figure 5.1 summarizes the research protocol.

Figure 5.1: Research protocol



The participant's medical history was taken, including data on any otological and audiological problems, relevant medical problems, family and social history, medications and allergies. After the clinical interview and clinical otoscopy, participants were administered three validated questionnaires to complete: (a) the Amsterdam Inventory for Auditory Disability (AD) (Meijer et al., 1996), (b) the Hyperacusis Questionnaire (Khalfa et al., 2002) and (c) the Speech, Spatial and Qualities of Hearing Scale (SSQ) by Gatehouse and Noble (2004). The questionnaires have been described in Chapter 4 (Phase II).For comparison and to validate the results of the questionnaires and clinical tests, a control sample was obtained from hospital staff, students, friends and other volunteers. Similar inclusion criteria were used for the control subjects.

5.4.2 Overview of Tests Battery

All the research participants underwent the following battery of tests that have been described thoroughly in Chapter 2 of the research thesis. The SIB test has been described thoroughly in Chapter 3 (Phase 1) of the research thesis. The audiological tests were conducted in a sound-proof room.

- Pure-tone Audiometry (250–8000 Hz)
- Tympanometry
- Transient Evoked Otoacoustc Emissions (TEOAEs)
- Suppression of TEOAEs by Contralateral noise
- Central Auditory Tests test:
  - ❖ Speech-in-babble (SIB) test
  - ❖ Gaps-in-noise (GIN) test
  - ❖ Dichotic digit test (DDT)
  - ❖ Frequency pattern test (FPT)
  - ❖ Duration pattern test (DPT)

5.5 Results

5.5.1 Participant Descriptors

The study included the following subjects:

Fifty-eight research participants with reported hearing difficulties and the clinical diagnosis of APD (N = 39) or clinical non-APD (N = 19) whose data were analysed in Chapter 4. Among them, 26/39 had bilateral auditory processing test deficits; 6/39 had auditory processing deficits on the left side and 7/39 had auditory processing deficits on the right side. (MRI scans on patients with unilateral test abnormalities were all negative for structural pathology).

The data from 30 of the 38 normal controls were analysed in Chapters 2 and 3. Eight of the 38 normal controls did not complete one test in the APD test battery, and therefore, their data were excluded from the present analysis. General descriptors of these patients and controls are shown in Table 5.2

Table 5.2: General Descriptors of the Study

	APD	**Clinical non-APD**	**Normal controls**	**significance**
Number recruited	39	19	30	
Female:Male ratio (Female %)	23/16 (59%)	11/8 (58%)	17/13 (5.7%)	P = 0.315 Kruskal –Wallis
Age mean+SD	38.487± 13.2285	33.789± 12.3584	34.933 ± 9.2029	P = 0.283 One-way Anova
Dyslexia	2	--	-	
History of ear infections in childhood	1	-	4	
Mild Head Trauma	1		1	
Epilepsy	1	-	-	

5.5.2 Audiological Test Results Descriptors

5.5.2.1 Pure-tone Audiometry Results

All research participants had normal (≤20 dB) hearing thresholds on pure-tone audiometry across the frequency range of 250 Hz to 8000 Hz, for both ears. There was no significant difference among mean values of pure-tone audiometry for the right ear (p = 0.3, one-way ANOVA) and left ear (p = 0.2, one-way ANOVA) for the 3 groups or for the right and left ear in each group (p = 0; paired t-test for clinical APD and clinical non-APD groups and p = 0.8, paired t-test for normal controls) (Table 5.3).

Table 5.3: Pure-tone audiometry results for the three groups

Pure-tone audiometry mean	APD (n = 39)	Clinical non-APD (n = 19)	Normal (n = 30)	Significance (one-way ANOVA)
Right ear (Mean ±SD)	13.28±3.35	13.28±3.8	12.05±4.53	P = 0.378
Left ear (Mean ±SD)	13.64±3.35	13.63±3.39	12.16±4.34	P = 0.220
Significance (paired t test)	0	0	0.857	

5.5.2.2 Auditory processing test results

Speech-in-babble test results

Research participants with APD had significantly worse results on the SIB test. Table 5.4 and Figure 5.2 show the mean values of the SIB test among the three groups. One-way ANOVA test confirmed the significant difference in the SIB performance among the three groups, with the normal controls achieving significantly lower scores compared to those of the research participants with hearing difficulties and clinical APD and clinical non-APD. There were no statistically significant differences between the right and left ear scores for each group.

Table 5.4: Mean and standard deviations for speech-in-babble test in the three research groups

Speech-in-babble test	APD (n = 39)	Clinical non-APD (n = 19)	Normal (n = 30)	Significance (ANOVA)
Right ear (Mean±SD)	**3.081±1.58**	**2.67±1.138**	**1.079±1.88**	**P = 0.000**
Left ear (Mean±SD)	**3.148±1.73**	**2.42 ±0.93**	**0.859±1.7**	**P = 0.000**
Significance (paired *t*-test)	**0.954**	**0.583**	**0.292**	

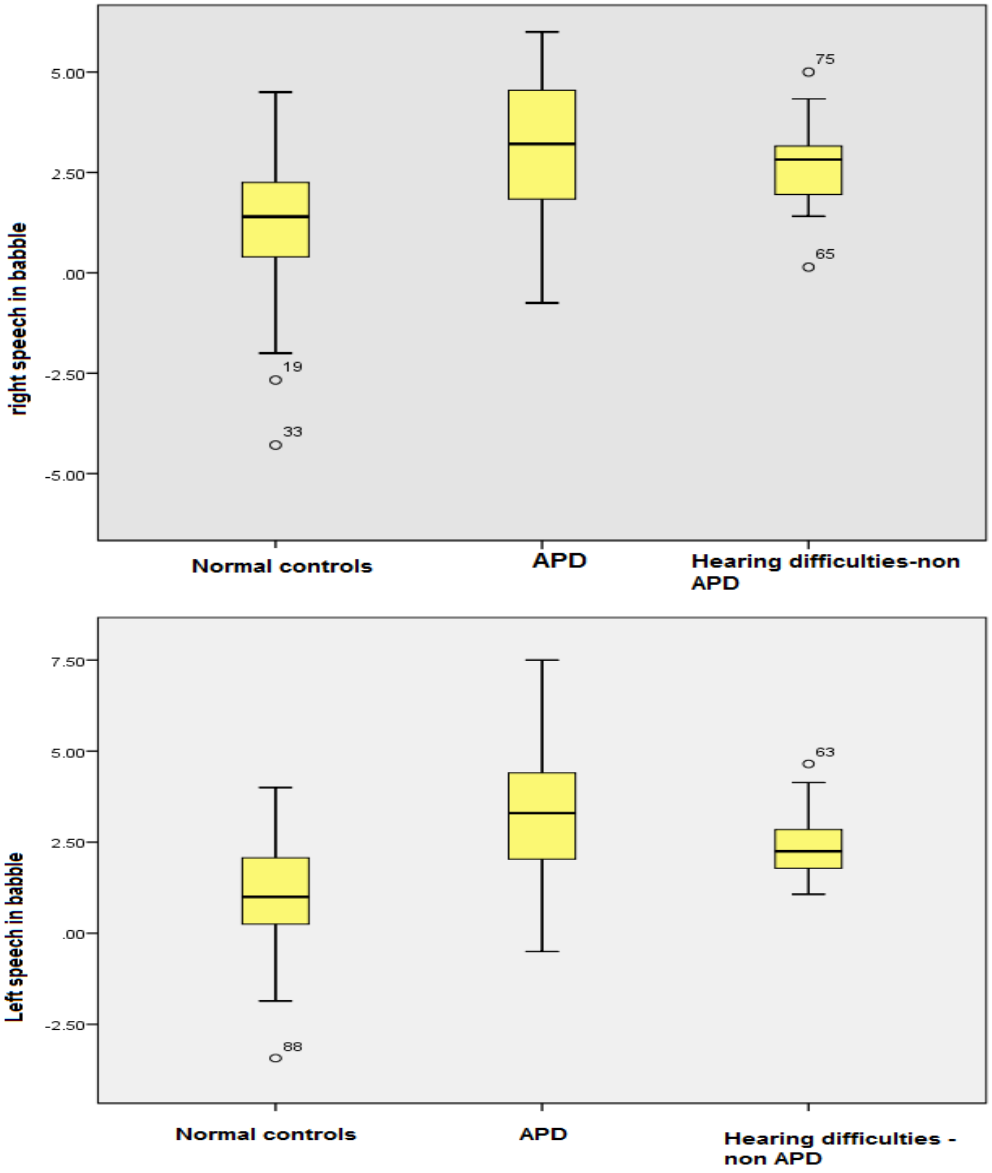


Figure 5.2: Box plot of right and left speech-in-babble scores in the three research groups: Normal controls, APD, clinical non-APD.

Gaps-in-noise test results

Table 5.5 and Figure 5.3 show the mean values of the GIN test among the three groups. Kruskal–Wallis non-parametric test confirmed significant difference in the GIN test performance among the three groups, with normal controls achieving significantly higher scores compared to the research participants with clinical non-APD and clinical APD.

Table 5.5: Mean and standard deviations for gaps-in-noise test in the three research groups

Gaps in Noise Test Mean	APD (n=39)	Clinical non-APD (n = 19)	Normal (n = 30)	Significance (Kruskal–Wallis)
Right ear (Mean±SD)	**6.656±1.447**	**5.16±1.015**	**4.53±1.408**	**P=0.000**
Left ear (Mean ±SD)	**6.90±1.518**	**5.58±1.017**	**4.43±1.357**	**P=0.000**
Significance (paired *t*-test)	**0.108**	**0.088**	**0.534**	

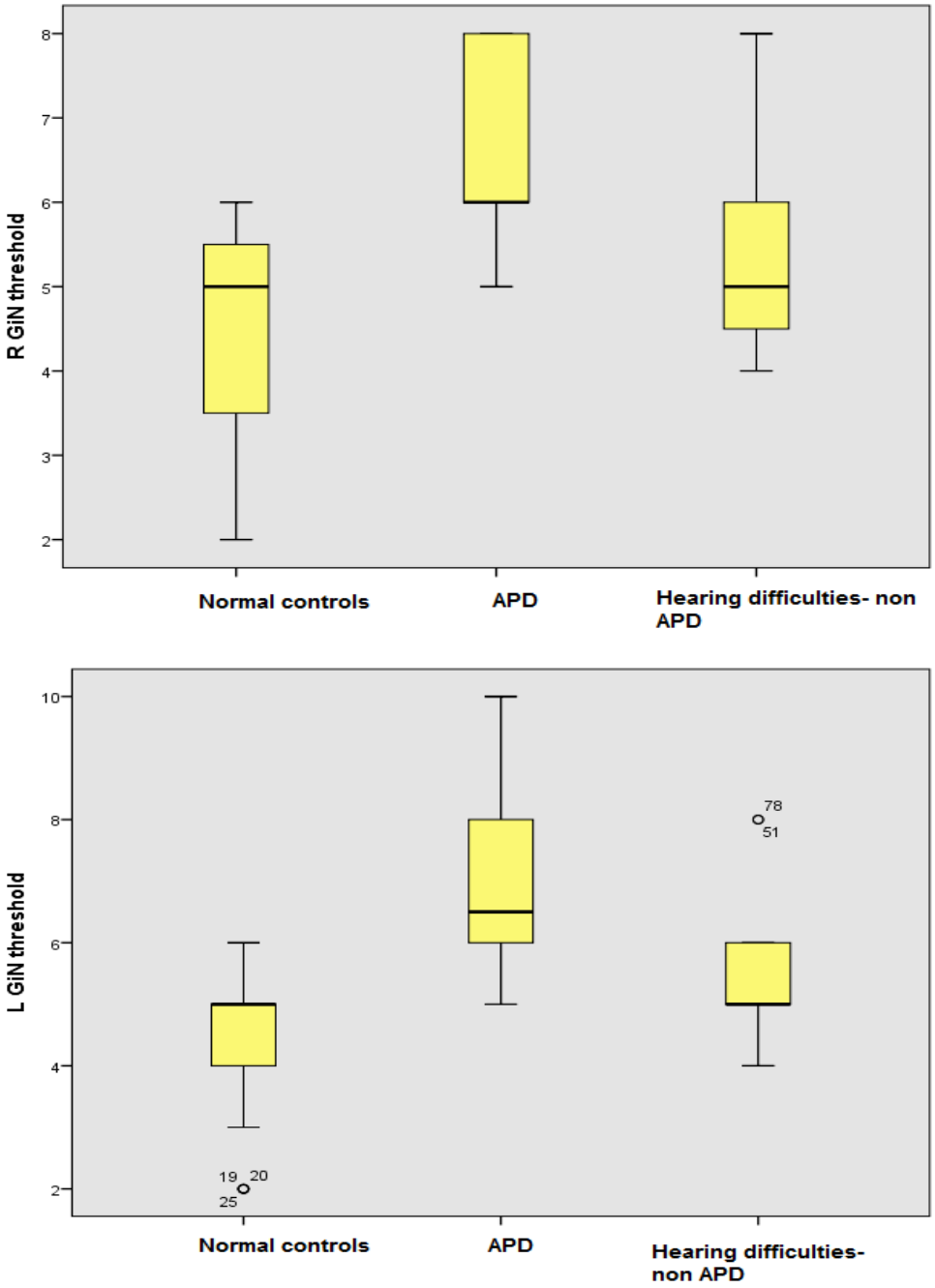


Figure 5.3: Box plot of right and left ears gaps-in-noise scores in the three research groups: Normal controls, APD, clinical non-APD.

Dichotic Digit Test

Table 5.6 and Figure 5.4 show the mean values of DDT among the three groups. Kruskal–Wallis non-parametric test confirmed a significant difference in the DDT performance among the three groups, with the normal controls achieving significantly higher scores compared to the research participants

with clinical non-APD and clinical APD. Two of the 39 APD patients did not undergo DDTs as they had dyslexia that was considered as a factor affecting the performance on that test. There were statistical significant differences between the DDT scores of the right and left ears for the APD group, with the scores being significantly worse on the left ear (p = 0.010, paired *t*-test). Similarly, the DDT scores were worse on the left ear for the adults with hearing difficulties but clinical non-APD and the normal controls but these differences were not statistically significant.

Table 5.6: Mean and standard deviations for dichotic digit test in the three research groups

Dichotic Digits Mean	APD (n = 37)	Clinical non-APD (n = 19)	Normal (n = 30)	Significance (Kruskal–Wallis)
Right ear (Mean±SD)	**91.203± 8.3028**	**97.000 ±3.2914**	**96.400±9.045**	**P = 0.002**
Left ear (Mean±SD)	**86.419±10.4406**	**95.289 ±6.5156**	**95.167±9.2376**	**P = 0.001**
Significance (paired *t*-test)	**0.010**	**0.119**	**0.154**	

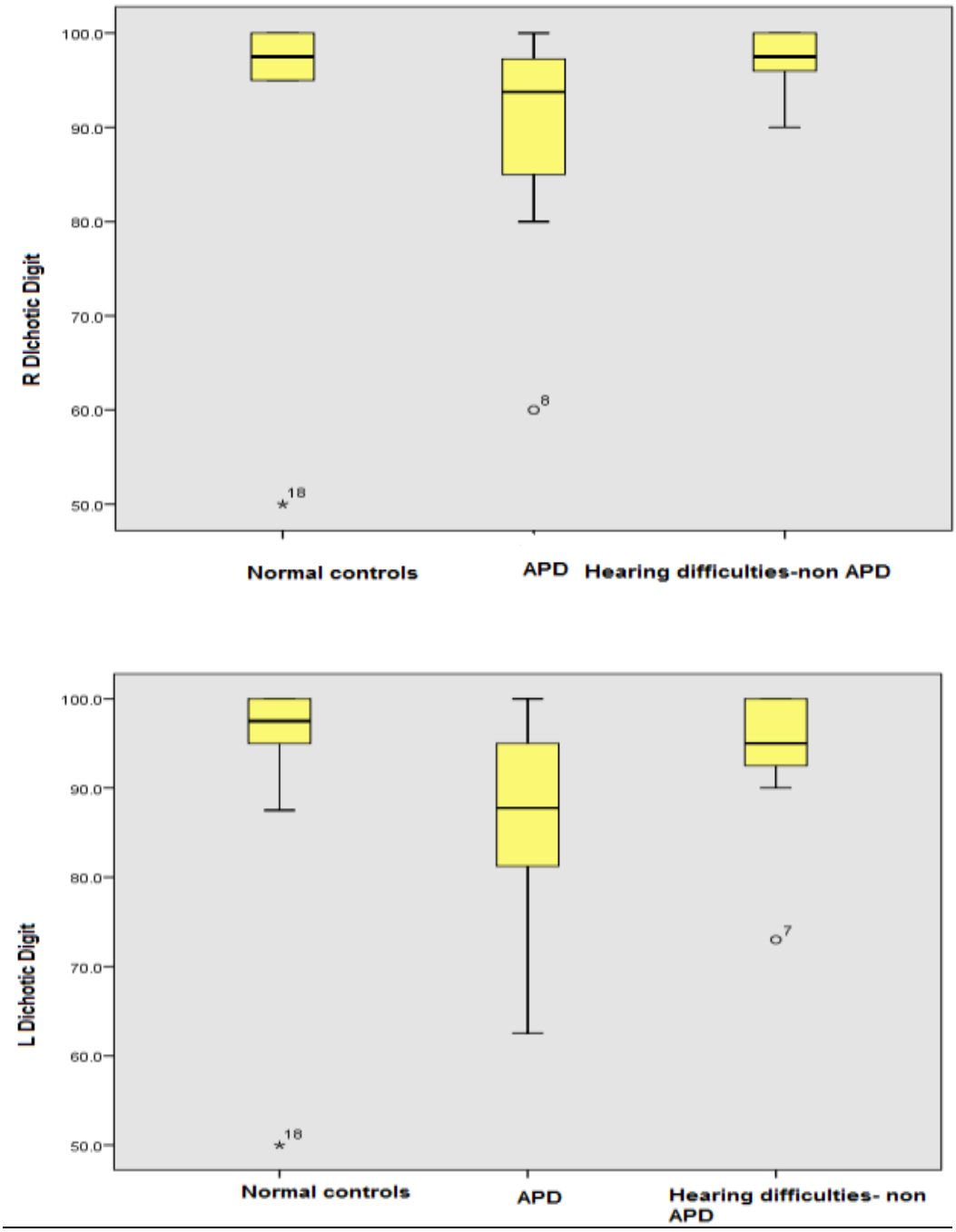


Figure 5.4: Box plot of right and left dichotic digit test scores in the three research groups: Normal controls, APD and clinical non- APD.

Duration Pattern Test

Table 5.7 and Figure 5.5 show the mean values of the duration pattern test among the three groups. Kruskal–Wallis non-parametric test confirmed the significant difference between the three groups in the DPT performance, with

normal controls achieving significantly higher scores compared to the research participants with clinical non-APD and clinical APD.

Table 5.7: Mean and standard deviations for duration pattern test in the three research groups

Duration Pattern Test	APD (n = 39)	Clinical non-APD (n = 19)	Normal (n = 30)	Significance (Kruskal–Wallis)
Right ear (Mean±SD)	**74.521±18.7847**	**91.421±9.1489**	**90.713±9.2278**	**P=0.000**
Left ear (Mean±SD)	**73.528±20.3939**	**92.032 ±9.8464**	**90.650±7.6801**	**P=0.000**
Significance (paired *t*-test)	**0.670**	**0.883**	**0.803**	

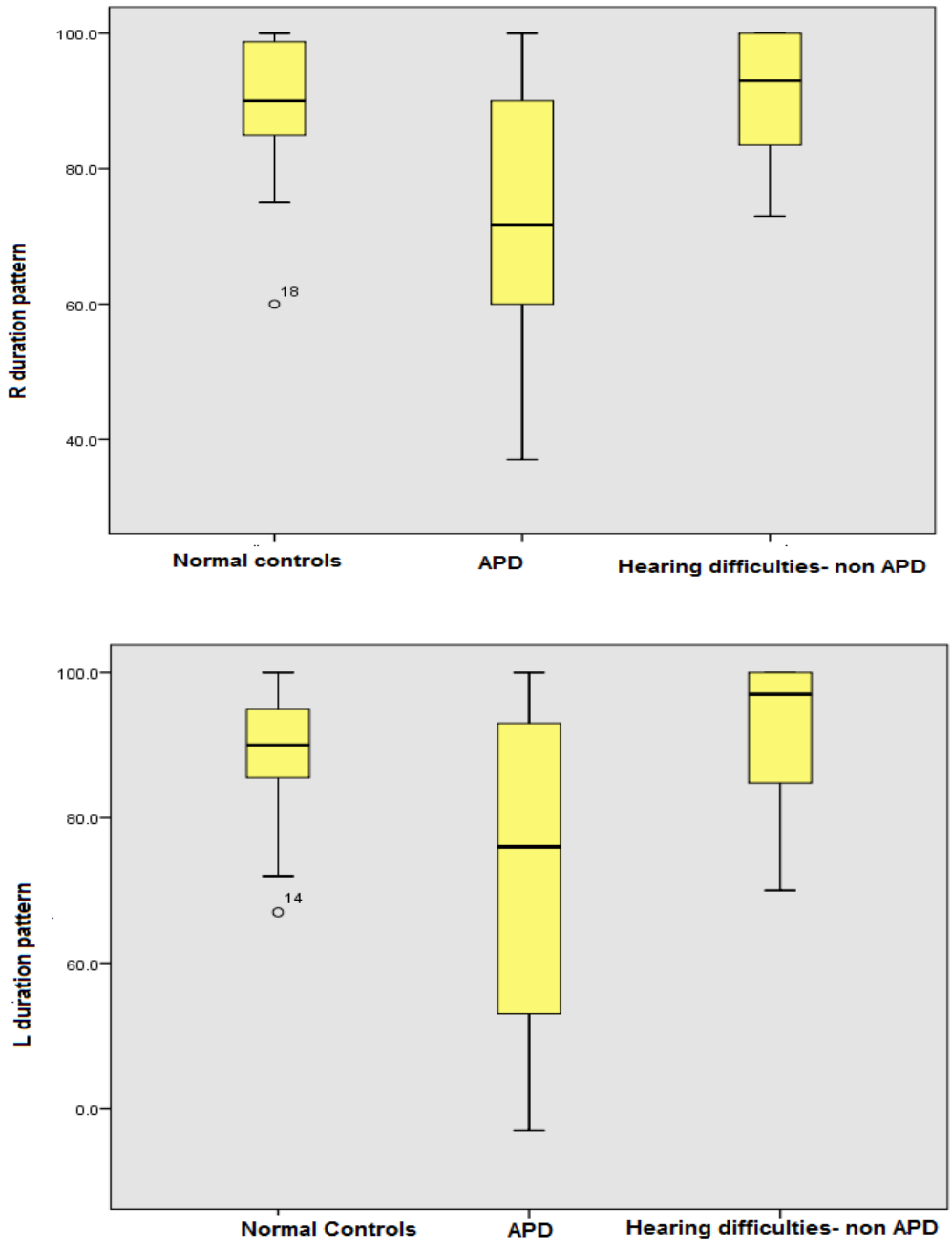


Figure 5.5: Box plot of right and left duration pattern tests scores in the three research groups: Normal controls, APD and clinical non-APD.

Frequency Pattern Tests

Table 5.8 and Figure 5.6 show the mean values of the FPT among the three groups. Kruskal–Wallis non-parametric test confirmed the significant difference between the three groups in the FPT performance, with normal controls achieving significantly higher scores compared to the research participants with clinical non-APD and clinical APD. Participants with APD had significantly worse scores on the FPT on the left ear, as shown on Table 5.8. There were no differences between the test scores of the two ears in the other two groups.

Table 5.8: Mean and standard deviations for frequency pattern test in the three research groups

Frequency Pattern Test	APD (n = 39)	Clinical non-APD (n = 19)	Normal (n = 30)	Significance (Kruskal–Wallis)
Right ear (Mean±SD)	**83.469± 18.6615**	**96.558± 5.9473**	**94.220± 6.9330**	**P = 0.002**
Left ear (Mean±SD)	**80.615± 19.8862**	**94.842 ± 10.7355**	**94.637± 7.7607**	**P = 0.000**
Significance (paired *t* test)	**0.028**	**0.538**	**0.815**	

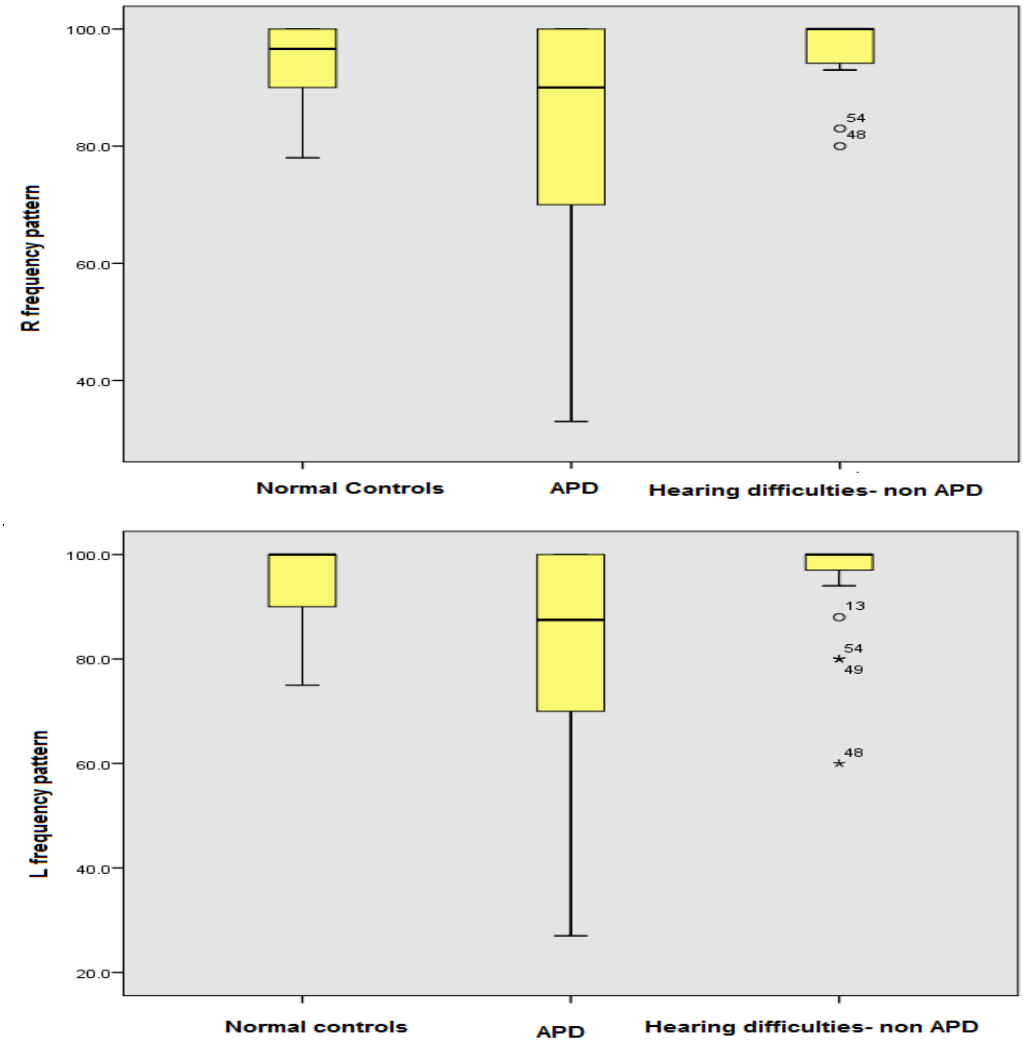


Figure 5.6: Box plot of right and left frequency pattern tests scores in the three research groups: Normal controls, APD and clinical non-APD.

Suppression of Transient Evoked Otoacoustic Emissions (TEOAEs) by Contralateral Noise

Table 5.9 and Figure 5.7 show the mean values of the three groups on TEOAEs suppression with contralateral noise. One-way ANOVA test confirmed a significant difference in the TEOAEs suppression performance among the three groups, with the normal controls, achieving significantly higher scores than those with clinical non-APD and clinical APD. There were no statistically significant differences between the right and left ear scores for each group.

Table 5.9: Mean and standard deviations for TEOAEs suppression by contralateral noise test in the three research groups

TEOAES suppression	APD (n = 39)	Clinical non-APD (n = 19)	Normal (n = 30)	Significance (ANOVA)
Right ear (Mean ±SD)	**1.109±0.7131**	**1.400±0.6334**	**2.028±1.0683**	**P = 0.001**
Left ear (Mean ±SD)	**1.172±0.8437**	**1.356 ±0.7402**	**1.810±0.9409**	**P = 0.025**
Significance(paired *t*-test)	**0.408**	**0.778**	**0.260**	

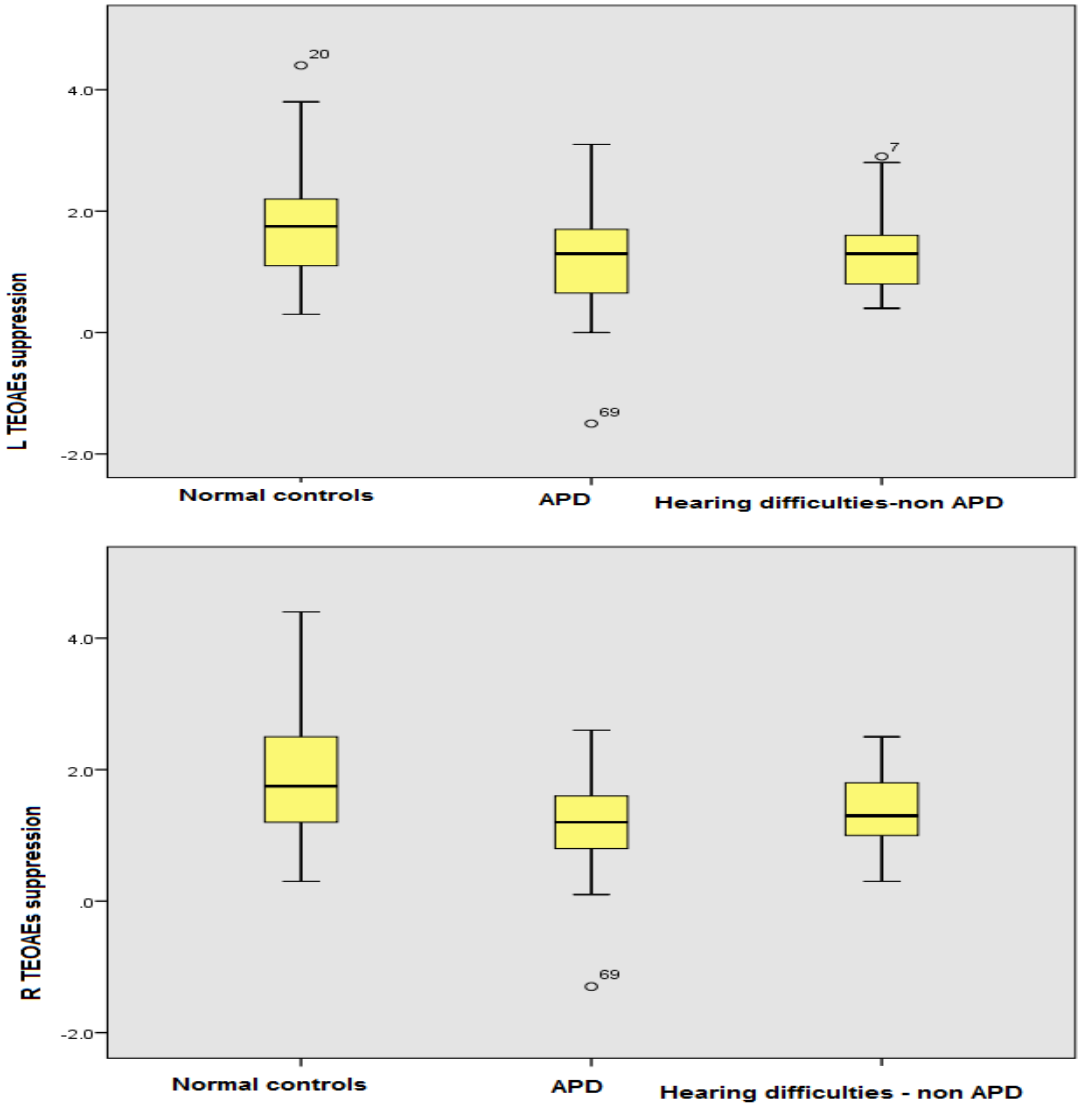


Figure 5.7: Box plot of right and left TEOAEs suppression by contralateral noise scores in the three research groups: Normal controls, APD and clinical non-APD

5.5.3 Correlations of Questionnaires and APD Tests

In order to assess correlations among the three validated questionnaires and auditory processing disorder tests, we carried out Spearman non-parametric correlation test, and the results are summarised in Table 5.10. Correlations were made for each ear separately with the questionnaire scores and also the scores in the better ear and worse ear for the monaural APD tests. The correlations are shown in Table 5.10.

Table 5.10: Correlation (Spearman rho) results between questionnaires and APD tests

** Correlation is significant at $p \leq 0.01$ *Correlation is significant at $p \leq 0.05$
Bet: better, sup: suppression, R: right, L: left

Tests		AD	Hyp	Speech	Spatial	Sound
SIB	R SIB	-.378**	.426**	-.423**	-.350**	-.386**
	L SIB	-.320**	.416**	-.431**	-.349**	-.372**
	SIB bet	-.316**	.381**	-.412**	-.351**	-.330**
	SIB worse	-.357**	.450**	-.472**	-.376**	-.408**
GIN	R GIN	-.492**	.536**	-550**	-396**	-500**
	L GIN	-.507**	.548**	-607**	-472**	-575**
	GIN bet	-.470**	.495**	-568**	-453**	-547**
	GIN worse	-.535**	.605**	-624**	-.455**	-.572**
DDT	R DDT	.268*	-.219*	.268*	.253*	.191
	LDDT	.443**	.373**	.536**	.349**	.366**
DPT	RDPT	-.240*	-.284**	.173	.129	.174
	LDPT	.229*	-.304**	.238*	.142	.208
	DPT bet	-.276**	-.261**	.204	.132	.172
	DPT worse	.223*	-.342**	.229**	.173	.223
FPT	R FPT	.138	-.074	.192	.129	.114
	L FPT	.125	-.138	.173	.069	.113
	FPT bet	.149	-.115	.183	.140	.137
	FPT worse	.109	-.097	.177	.054	.085
TEOAEs sup	R TEOAE sup	.253*	-.201	.288**	.173	.248*
	L TEOAE sup	.177	-.169	-.229**	.94	.127
	TEOAE sup bet	.138	-.113	.307**	.175	.221*
	TEOAE sup worse	.268*	-.218	.144	.061	.121

The above table shows that the SIB test results correlated moderately ($.3 < r_s < .5$, $p \leq 0.01$) with the scores of the AD, hyperacusis, and all aspects of SSQ questionnaire. There were no differences when the scores of the right, left, better or worse ear were used for the statistical analysis.

Similarly, the GIN test results correlated moderately ($.4 < r_s < .6$, $p \leq 0.01$) with the scores of all three validated questionnaires, and no differences were noted when the scores of the right, left, better or worse ear were used for the statistical analysis.

The right DDT correlated mildly ($.2 < r_s < .3$, $p \leq 0.05$) with the AD, hyperacusis, speech and spatial aspects of the SSQ. There were no significant correlations between the right DDT results and the sound quality aspect of the SSQ questionnaire. There were moderate ($.3 < r_s < .6$, $p \leq 0.01$) correlations of the left DDT results and the scores of all three questionnaires. There were no significant correlations between the frequency pattern test and any of the three questionnaires. There were no statistical significant correlations when the right, left, better or worse ear scores were used for the statistical analysis.

Mild ($.2 < r_s < .3$, $p \leq 0.05$) correlations of the right and left DPT with the scores of the AD questionnaire were noted, and the left DPT with the speech aspect of the SSQ questionnaire. There were no significant correlations with the scores of the spatial and sound quality of the questionnaire. Moderate correlations ($3 < r_s < 4$, $p \leq 0.01$) of the scores of the right, left, better and worse ears in the DPT results with the hyperacusis questionnaire.

Finally, there were moderate ($2 < r_s < .4$, $p \leq 0.01$) correlations between the scores of the TEAOEs suppression test in the right and left ears and the scores of the speech aspect of the SSQ questionnaire. There were mild ($.2 < r_s < .3$, $p \leq 0.05$) correlations of the right and worse ear TEAOEs suppression score and the scores of the AD questionnaire and sound quality aspect of the SSQ questionnaire. There were no significant correlations between the TEOAEs suppression test results and scores of the hyperacusis questionnaire or spatial aspect of SSQ questionnaire.

5.6 Discussion

The aim of this research study was to assess the correlation of diagnostic tests from the APD test battery with symptoms in adults who have hearing difficulties and normal pure-tone thresholds and visit the audiology/ENT and Audiovestibular Medicine Departments to seek medical attention. We used three validated questionnaires (i) The AD (ii) The SSQ and the (iii) Hyperacusis questionnaires to evaluate the self-reported hearing difficulties in these adults.

Study participants with abnormal results in at least one ear, in at least two tests of auditory processing (and at least one of these tests was non-speech), were classified into the clinical APD group, and the remaining patients, into the clinical non-APD group.

For our correlation statistical analysis, we used the AD questionnaire for overall disability, the three sections of SSQ questionnaire and the hyperacusis questionnaire. Weak to moderate correlations were noted between the test results and scores of the questionnaires. The SIB test, GIN test and DDT have an overall correlation with all three questionnaires and, therefore, best quantify the auditory symptoms.

The moderate correlation ($.3 < r < .5$, $p < 0.001$) of the SIB test with the questionnaires was expected since the SIB test may assess the functional hearing and the integrity and function of the overall auditory pathway from the periphery up to the cortex (George et al., 2008). George et al. (2008) showed that in the presence of normal peripheral hearing, the SIB test performance predictors include sound processing aspects such as spectral and temporal resolution and intensity-difference limens, as well as age and cognitive skills.

The GIN test results showed moderate correlation ($.3<r<.6$, $p<0.001$) with the scores of the three questionnaires. This test assesses temporal resolution (discrimination) (Jerger and Musiek, 2000; Musiek et al., 2005) that it is one of the key underlying elements for auditory processing of sound and speech (Musiek et al., 2005). Anatomically, the task involves the entire auditory

pathway up to the cortex. It is a relatively new test in the APD battery (Musiek et al., 2005) and serves as a threshold estimation test, which provides six trials for each gap duration. It also relies less on cognitive demand as the participant is asked to press a button rather than provide an oral response and may thus predominantly assess sensory processing.

The DDT is a speech test and the only binaural auditory processing test of our battery. The right dichotic digit test correlated weakly ($.2 < r < .3$, $p < 0.005$), with the questionnaires apart for the sound quality section of the SSQ questionnaire, where there was no significant correlation. The left dichotic digit test, however, correlated moderately ($3 < r < .5$, $p < 0.001$) with all the questionnaires. The dichotic digit test is a speech test that involves not only the ability to listen but also to store the information in the auditory working memory before the subject verbally labels it. The left ear score of the dichotic digit test may tap into the cognitive aspects of listening, including attention (Hugdahl et al., 2009). All three research groups scored worse on the left vs the right DDT but the APD group scored significantly worse.

The finding of the poorer score on the left side in the DDT is consistent with the findings of other research studies (Musiek 1983; Mukari et al., 2010; Bamiou et al., 2012; Schmithorst et al., 2013). Bamiou et al. (2006) showed that patients with PAX6 had interhemispheric abnormalities, which can be clinically evaluated by abnormal DDT results, but had normal monaural auditory processing disorder tests, e.g. GIN tests. These findings can be explained on the basis of the ‘callosal relay model’, which proposes that language perception takes place in the left hemisphere and that in dichotic situations, the contralateral pathway, which dominates in auditory signal transmission, takes over (Zaidel,1986). Alternatively, recent neuroimaging studies show differences in frontal eye field activation (and, thus, in attention bias) in children with right vs. left ear advantage in dichotic-word tests, as well as diffusion tensor imaging findings indicating either enhanced efferent or potentially decreased afferent connectivity of the frontal eye field with subcortical regions, which could explain the ear advantage finding at a sensory processing level (Schmithorst et al., 2013). The finding of a

moderate correlation of the left DDT results with the scores of all three questionnaires would indicate that it serves as a functional measure of listening that incorporates both attention and sensory aspects of listening.

The DPT scores correlated weakly ($.2 < r_s < .3$, $p < 0.005$) with those of the AD and the speech aspect of SSQ, but there were no significant correlations with the spatial and sound qualities of the SSQ questionnaire. There were no significant correlations of the frequency pattern tests with any of the three questionnaires. Research participants with clinical APD scored significantly worse in both duration and frequency pattern tests. A possible explanation may be that the research subjects had no structural brain abnormalities and therefore the overall score although abnormal in the participants with clinical APD was better compared to the ones with known structural abnormalities published in literature (Bamiou et al., 2006). The right temporal lobe is associated with pitch such as music and environmental sounds (Zatorre et al., 2002). A case study by Nagle et al. (2013) regarding a female patient who underwent two consecutive temporal lobe resections for epilepsy showed that following the second operation that involved resection of the superior temporal gyrus, the patient was still able to hear speech in quiet and environmental sounds but had hearing difficulties in demanding listening situations such as noisy environments. The patient scored normal in FPT. Similar findings were published by Drew et al. (2003).

The suppression of TEOAEs by contralateral noise shows weak correlations ($.2 < r_s < .3$, $p<0.05$) with the scores of the AD questionnaire and speech aspect of the SSQ questionnaire. The suppression of TEOAEs by contralateral noise on the right side shows additional weak correlations ($r = .248$, $p<0.05$) with the sound quality aspect of the SSQ questionnaire. Our findings were similar to those of other research studies (Muchnic et al., 2004; Garinis et al., 2008). Muchnic et al. (2004) reported that there was a significant difference between the suppression of TEOAEs by contralateral noise in 15 children with APD and 15 normal controls. Kumar and Vanaja (2004) showed that there was a statistical significant improvement of the speech intelligibility in ipsilateral noise perceived by children when

contralateral acoustic stimulation was applied, and this improvement correlated with suppression of TEOAEs by contralateral noise. However, a significant drawback of the latter study was that they employed English language speech test stimuli, but the children tested were not English first language speakers, and their knowledge of English language was not assessed prior to the study. These children gave lower scores compared to peers with English as the first language, and a learning effect or linguistic competency factors confounding the results cannot be excluded. Another recent study by Elgeti et al. (2008) showed that there was a significantly higher prevalence of spontaneous otoacoustic emissions (SOAEs) in children (mean age, 8 years) with poorer speech-in-noise intelligibility test scores compared to age-matched children with normal speech intelligibility. They interpreted this finding as indicative of an abnormality of the efferent system in those children, but did not perform the TEOAE suppression test. Mukari (2008) did not find a correlation between a speech-in-noise test and suppression test of distortion product otoacoustic emissions conducted in a group of older and compared with younger adult listeners. Together with the findings of previous studies, the findings of weak correlations of TEOAE suppression test with the speech aspect of the questionnaires would indicate that the lower-level electroacoustic test that assesses the function of the medial olivocochlear bundle can serve as a functional indicator of difficulty in hearing speech-in-noise. Although suppression of TEOAES assesses the medial olivocochlear system, there is also evidence (de Boer and Thornton, 2007) that there is control of the function of the efferent system by top-down neurons; therefore, abnormal suppression of TEOAEs may relate to additional top-down influences from the cortex that reflect high-order processing (de Boer and Thornton, 2007), although further research is required to elucidate this. Moderate correlations ($3 < r_s < 6$, $p < 0.01$) were noted among the results of SIB test, GIN test, left DDT and the scores of the hyperacusis questionnaire and moderate but slightly weaker correlations ($3 < r < 4$, $p < 0.001$) between the DPT results and the scores of the hyperacusis questionnaire. There were also weak correlations ($r_s = 0.219$, $p < 0.005$) between the right DDT results and the scores of the hyperacusis questionnaire. No audiological test has been developed thus far to measure

the symptoms of hyperacusis. There are, however, published papers that show abnormal suppression of TEOAEs by contralateral noise in patients with hyperacusis, and therefore, it was surprising that this research study did not show any such correlations. Ceranic et al. (1998) and Attias et al., (2005) reported that a significant number of patients present with auditory symptoms (sensitivity to loud sounds, tinnitus, difficulty in hearing speech-in-noise) following a head injury and that 65–87% of them have abnormal suppression of TEOAEs by contralateral noise. In addition, auditory complains such as difficulty in hearing SIN and hyperacusis are commonly observed in individuals with autism (Rosenhall et al., 1999; Alcantara et al., 2004). Kulesza and Mangunay (2008) examined the brains of 5 individuals with autism (age range, 5–32 years) and compared them with those of 2 controls (ages, 26 years and 29 years). They observed a significant disruption of the morphology of the medial superior olive in the individuals with autism. Although that study has shown probable involvement of the medial olivocochlear system in the auditory complaints of hyperacusis and difficulty in hearing speech-in-noise, the sample was very small; other areas of the auditory pathway were not examined and there was no information about the auditory complaints of those individuals.

The moderate correlations of the results of the SIB, GIN and left DDT tests with the hyperacusis questionnaire scores may indicate the involvement of the central auditory pathway in symptoms of hyperacusis. The strong correlations among the three questionnaires (AD, SSQ and hyperacusis), as reported in Chapter 4 of this thesis, and the moderate correlations between the results of the SIB, GIN and DDT indicate a strong relationship between difficulty in hearing speech in noise and clinical complaints of hyperacusis.

There are but a few published research studies that assess the symptoms of hyperacusis and difficulty in hearing speech in noise in adults with developmental disorders such as autism (Alcantara et al., 2004) and William’s syndrome (Blomberg et al., 2006; Elsabbagh et al., 2011). A tentative explanation for our findings could be that hyperacusis may be associated with abnormal temporal resolution (discrimination) difficulties, as

indicated by abnormal results of the GIN test and DPT. This is consistent with the findings of abnormal temporal processing abilities in individuals with loudness discomfort and Asperger's syndrome (Alcantara et al., 2004). The correlation of the SIB test with hyperacusis may reflect, to some extent, the difficulties experienced by the study subjects in ignoring background noise and/or concentrating when hearing speech. The correlation of the left DDT result with the hyperacusis questionnaire scores may also indicate difficulties with attention in these subjects.

In all, 39/58 (67.2%) patients who sought professional advice were diagnosed with APD on the basis of the current diagnostic criteria of 1 abnormal speech test result and 1 abnormal non-speech test result in one or both ears. The majority (26/39, 66.7%) of the adults had bilateral auditory processing test deficits. None of the control subjects were diagnosed with APD on the basis of these diagnostic criteria. Although the prevalence of APD in the adult population is not exactly known, it is estimated to be at around 10% (Saunders and Haggard, 1992) and is believed to increase with age in older patients, over the age of 63 up to 50% (Jerger et al., 1989). This research study shows a high prevalence of APD in the adult population, of those <60 years of age who seek professional advice due to reported hearing difficulties and having normal peripheral hearing. A possible explanation is that the research participants were recruited from a specialised ENT and Neuro-otology hospital, and the patients referred to the hospital there were significantly more troubled by their symptoms than patients who attend local community services. Another possible explanation is that this is a true reflection of the prevalence since there is a dearth of proper evidence.

Another interesting finding of this research study is that the research participants who were diagnosed with APD probably had developmental APD (BSA, 2011) or non-neurological APD. They had longstanding hearing difficulties with no known brain abnormalities, such as brain tumours or previous strokes. None of the participants had autism. Two of the study subjects with a clinical diagnosis of APD had dyslexia and 1 had epilepsy

(normal MRI). There is paucity of similar studies since most published evidence involve APD in adults with known neurological deficits (Fallis-Cunningham et al., 1998; Musiek & Lee, 1998; Musiek et al., 2005; Bamiou et al., 2006; Meneguello et al., 2006; Musiek et al., 2011; Bamiou et al., 2012: Nagle et al., 2013) or older adults with peripheral hearing loss (Jerger et al., 1989; Jerger et al., 1990; Humes et al., 2005; Mukari et al., 2010; Anderson et al., 2011). Similar to this research study, Neijenhuis et al. in 2003 published a study that evaluated a Danish APD test battery in adults and children. In their study, the adults had no known neurological disease, and the upper age limit was 57 years 11 months. As a group, the adults showed significantly more abnormalities in the APD tests than children, while their scores were more consistent, probably since they have stable auditory symptoms. About 58% of them were females similar to other adult published studies (Neijenhuis et al., 2003; Musiek et al., 1991; Lawfield et al., 2011). It is unclear whether this is a coincidence or it relates to the fact that women seek medical help more often than men. However, in the paediatric population, a recent epidemiological study by Boyle et al. (2011) showed that males are more likely to have a developmental disorder than females, and therefore, it is assumed that APD is more common in boys than in girls.

5.7 Conclusions

This research study has shown weak to moderate correlations among the SIB test, GIN test, DDT and symptoms of hearing difficulties and hyperacusis in adults younger than 60 years of age with APD. A battery of tests is needed in order to diagnose APD in such adults.

CHAPTER 6: OVERALL CONCLUSIONS

6.1 Aim and Initial Hypotheses Revisited

This research study examined the clinical symptom characteristics of adults with APD in order to enhance our understanding of the auditory profile of these disorders.

6.2 Summary of Main Findings

- Adults with APD presented with a variety of auditory symptoms reported on three validated questionnaires (AD, SSQ and hyperacusis): difficulty in hearing speech in quiet and speech-in-noise, sound recognition difficulties, problems with sound localisation and symptoms of hyperacusis. These symptoms were significantly more severe in adults with APD than in normal controls.
- Compared to adults with reported hearing difficulties but not clinically diagnosed with APD, those with reported hearing difficulties who seek professional advice and are clinically diagnosed with APD have significantly worse difficulties in hearing speech in quiet, sound localisation and sound recognition, but not significantly worse difficulty in hearing speech-in-noise or symptoms of hyperacusis.
- The three validated questionnaires showed good specificity (>90%) in identifying patients requiring an APD assessment, although sensitivity was rather low (around 40% for the AD and SSQ and 23.7% for the hyperacusis questionnaire).
- Statistically significant correlations were noted between the auditory tests and questionnaires, with moderate correlations among SIB, gap-in-noise, and dichotic digit tests with the three validated questionnaires.
- There are mild to moderate correlations among the duration pattern test and TEOAEs suppression by contralateral and aspects of the three validated questionnaires.

6.3 General Interpretation of the Findings

This research study addressed a current pressing need in quantifying the symptoms in individuals with APD by using validated questionnaires (Moore et al., 2013). There are but a handful of published research studies in the adult APD population (Neijenhuis et al., 2003; Bamiou et al., 2012) that have used a validated questionnaire. Adults with reported hearing difficulties and APD have difficulty in hearing speech in quiet and SIN, sound localisation and sound recognition. They also present with symptoms of hyperacusis. Adults with reported hearing difficulties but without a clinical diagnosis of APD have the same symptoms, albeit to a lesser extent. This was an interesting finding of this study that indicates that APD is a 'continuum', as proposed by Phillips et al. (2010). Another possible explanation for these findings is that they relate to the wide diagnostic yield and different diagnostic criteria used to define APD (Wilson and Arnott, 2013).

A standardised APD diagnostic test battery was used in this study (AAA, 2010; BSA, 2011). As part of the test battery, a newly developed monaural SIB test was used. This test was recorded in southern British accent English and employed words instead of sentences and multi-talker babble instead of white noise. Normative data were collected, and the test showed moderate correlations with all three questionnaires. The fact that the test employs monosyllabic, simple words and multi-talker babble allows for better assessment of processing sensory difficulties than speech tests employing sentences and white noise (McArdle and Wilson, 2008; Rosen et al., 2013). The test had moderate correlations with the questionnaires; this finding could be considered as indicating that it may assess overall functional elements of listening, that incorporate attention and auditory sensory of listening.

The suppression of TEOAEs by contralateral noise, which is an objective electrophysiological test, showed weak to moderate correlations with the AD and speech aspect of the SSQ questionnaire. The test is a clinical tool used to measure the function of the medial olivocochlear bundle (Collett et al., 1992) that enhances speech intelligibility in the presence of background noise (Ceranic et al., 1998; Kumar and Vanaja, 2004; Brown et al., 2010).

Our findings indicate that this test can provide useful information in patients with listening difficulties.

The three validated questionnaires were found to have high specificity, and they may correctly identify individuals requiring further assessment for APD.

Therefore, these questionnaires hold promise as screening tools for identifying patients requiring referral for APD assessment. These findings differ from those of paediatric studies indicating that validated questionnaires are not good screening tools for diagnosing APD (Cameron et al., 2006; Dawes et al., 2008; Wilson et al., 2011). One possible explanation may be that since the clinical profile of APD evolves over the age span, auditory processing and attentional/cognitive functions may have different developmental trajectories. Another explanation is that children who are assessed for APD have learning difficulties experienced in the educational environment, but adults with APD seek medical attention themselves for some abnormality.

Neijenhuis et al. (2003) proposed two different types of APD; the maturational one in children and the disordered one in adults. The study findings indicate that the three validated questionnaires can be used in adults reporting hearing difficulties but having normal pure-tone audiograms, to assess the need for further APD assessment.

The APD participants in this study were younger than 60 years of age, had normal peripheral hearing and had no known causes for APD. They had the non-neurological type of APD. This is strength of the study since by selecting adults with non-neurological APD, we could eliminate any confounding factors associated with structural brain pathology.

6.4 Limitations of the Study

Firstly, the sample size of this study, although good, is not adequate to perform further statistical analysis such as factor analysis. Secondly, only one set of APD diagnostic criteria was used (BSA, 2011); the findings could have been compared to other diagnostic criteria. Thirdly, the results of

neuropsychometry tests were not included. Finally, recruitment was from a broad clinical population and not a specific population; however, this is also a strength of the study since if offers insight into the population categories that seek medical attention for their hearing difficulties.

6.5 Future Research

The three validated questionnaires hold promise as screening tools for APD and should be assessed in a bigger study. Firstly, these questionnaires, in addition to a (normal) audiogram may help reliably identify adults with suspected APD who require further assessment/intervention. They may also help plan the management, even without further testing. Dillon et al. (2012) argues that real-life listening difficulties, in the presence of a normal audiogram, can be addressed by listening and communication tactics, e.g. preferential seating, lip reading or provision of FM system. The three validated questionnaires could thus be used to identify adults who would benefit from these interventions and to measure the outcomes of such interventions. For the purposes of selecting the disorder (or deficit)-specific driven remediation, further assessment would be required (Dillon et al., 2012; Bamiou et al., 2006). For example, speech in noise training is increasingly employed to address speech-in-noise deficits in adults, and improvements in performance after such training are partly attributable to improved sensory encoding, indicating that a “bottom-up” mechanism influenced the brain’s plasticity (Song et al., 2012). A worse baseline speech in noise test performance predicts better training outcome (Song et al., 2012), justifying the need to recommend such training to those who fail speech-in -noise tests. The questionnaires may be used as outcome measures following deficit specific treatment, and may serve as a better functional index of listening in real life than laboratory tests.

Further research is necessary to determine the correlation of difficulties in hearing speech in noise and hyperacusis and the results of potential auditory tests to investigate hyperacusis symptoms. Limited published research shows that hyperacusis may be measured by TEOAE suppression by contralateral noise (Ceranic et al., 1998; Spyridakou et al., 2012), but this

was not noted in this study. This research showed correlations between central auditory tests (SIB, gap in noise, dichotic digit and duration pattern) with hyperacusis. Further studies on other patient groups reporting hyperacusis such as traumatic brain injury patients using a test protocol similar to that of the present study may help provide further information regarding hyperacusis. Further research by including cognitive assessments, memory, attention and executive function, in particular, would also provide additional useful information about the profiles of such patients. Neuropsychometric measurements could be correlated with central auditory tests in order to obtain further information about the diagnostic validity of those tests, and also correlated with patient symptoms, in order to help select identify appropriate management strategies.

Further investigations on the clinical application of the SIB test as a speech test of the APD battery are necessary. Normative data should be collected for different accents in British English since the words have been recorded in Southern British accent.

Finally, further research extending the study to adults aged over 60 years is necessary.

REFERENCES

Aboitiz, F, Lopez, J, Montiel, J, 2003. Long distance communication in the human brain: timing constraints for inter-hemispheric synchrony and the origin of brain lateralization. Biol. Res. 36:89-99.

Ahmmed, AU, Ahmmed, AA, Bath, JR, Ferguson, MA, Plack, CJ, Moore, DR, 2014. Assessment of Children with suspected Auditory Processing Disorder: a factor analysis study. Ear Hear. 35(3): 295-305.

Alcantara, JI, Weisblatt, EJ, Moore BC, Bolton, F, 2004. Speech- in- Noise Perception in High-functioning Individuals with Autism or Asperger's syndrome. J. Child Psychol. Psychiatry, 45(6): 1107-1114.

Alcantara, JI, Cope, TE, Cope, W, Weisblatt, EJ, 2012. Auditory Temporal-Envelope Processing in High Functioning Children with Autism Spectrum Disorder. Neuropsychologia, 50(7): 1235-1251.

Alsius A, Navarra J, Campbell R, Soto-Faraco, SS, 2005 Audiovisual Integration of Speech Falters under High Attention Demands. Curr. Biol. 15(9): 839-843.

American Academy of Audiology, 2010. "Clinical practice guidelines – diagnosis, treatment, and management of children and adults with central auditory processing" Retrieved on 26th June 2014 from www.audiology.org/resources/documentlibrary/Documents/CAPD%20Guidelines%208-2010.pdf.

American Standards Association, 1960. Acoustical Terminology SI, 1-1960, American Standards Association, New York.

American Speech-Language-Hearing Association (ASHA), 1996. Task Force on Central Auditory Processing Consensus Development Central auditory processing: Current status of research and implications for clinical practice. Am. J. Audiology, 5(2): 41-54.

American Speech-Language- Hearing Association (ASHA) 2005 (Central) Auditory Processing Disorders [Technical Report]. Retrieved on 26th June 2014 from www.asha.org/docs/html/tr2005-00043.html

Anderson, K and Smaldino, J, 1999. Listening Inventories for Education: A classroom measurement tool. Hear. J. 52: 74.

Anderson, K and Smaldino, J, 2000. Children's Home Inventory for Listening Difficulties (CHILD). Educational Audiology Review, 17: 3.

Anderson, S and Kraus, N, 2011. Neural Encoding of Speech and Music: Implications for Hearing Speech in Noise. Semin. Hear. 32(2):129–141.

Anderson, S, Parbery-Clark, A, Yi, HG, Kraus, N, 2011. A Neural Basis of Speech-in-Noise Perception in Older Adults. Ear Hear. 32(6): 750-757.

Atcherson, SR, Richburg, CM, Zraick, RI, George, CM, 2013. Readability of Questionnaires Assessing Listening Difficulties Associate with (Central) Auditory Processing Disorders. Lang. Speech Hear. Serv. Sch. 44(1): 48-60.

Attias, J, Zwecker-Lazar, I, Nageris, B, Keren, O, Groswasser, Z, 2005. Dysfunction of the Auditory Efferent System in Patients with Traumatic Brain Injuries with Tinnitus and Hyperacusis. J. Basic Clin. Physiol. Pharmacol. 16(2-3): 117-126.

Baddeley, A ,1992. Working memory. Science 255(1): 556-59.

Bamiou, DE, Musiek, FE, Stow, I, Stevens, J, Cipolotti, L, Brown, MM, Luxon, LM, 2006. Auditory Temporal Processing Deficits in Patients with Insular Stroke. Neurology, 67: 614-661.

Bamiou, DE, Sisodiya, S, Musiek, FE, Luxon, LM, 2007. The Role of the Interhemispheric Pathway in Hearing. Brain Res. 56(1):170-182.

Bamiou, DE, Werring, D, Cox, K, Stevens, J, Musiek, FE, Brown MM, Luxon, LM, 2012. Patient-reported Auditory Functions after Stroke of the Central Auditory Pathway. Stroke, 43(5):1285-1289.

Baran, JA and Musiek, FE, 2003. Central Auditory Disorders in Textbook of Audiological medicine. Ed. Linda Luxon Textbook of Audiological Medicine: Clinical Aspects of hearing and balance MD Taylor & Francis Group.

Ben-David, BM, Tse, VY, Schneider, BA, 2012. Does it Take Older Adults Longer than Younger Adults to Perceptually Segregate a Speech Target from a Background Masker? Hear. Res. 290(1-2): 55-63.

Bilger, RC, Nuetzel, MJ, Rabinowitz, WM, Rzeckzkowski, C, 1984. Standardization of a Test of Speech Perception in Noise. J Speech Hear. Res. 27(1): 32-48.

Blaettner, U, Scherg, M, von Cramon, D, 1989. Diagnosis of Unilateral Telencephalic Hearing Disorders. Evaluation of a Simple Psychoacoustic Pattern Discrimination Test. Brain 112(Pt1):177-195.

Blomberg, S, Rosander, M, Andersson, G, 2006. Fears, Hyperacusis and Musicality in Williams syndrome. Res. Dev. Disabil. 27:668-680.

Boyle, CA, Boulet, S, Schieve, LA, Cohen, RA, Blumberg, SJ, Yeargin-Allsopp, M, Visser, S, Kogan, MD, 2011.Trends in the Prevalence of Developmental Disabilities in US Children, 1997–2008. Pediatrics 127(6):1034-1042.

Brand, T and Kollmeier, B, 2002. Efficient Adaptive Procedures for Threshold and Concurrent Slope Estimates for Psychophysics and Speech Intelligibility Tests. J. Acoust. Soc. Am. 111(6): 2801-2810.

Bregman AS, 1990. Auditory Science Analysis. MIT Press, Cambridge, MA

British Society of Audiology, 1992. Recommended procedure for tympanometry. Br J Audiol. 26 (4): 255-257.

British Society of Audiology, 2011. Auditory processing disorder (APD). Position Statement. Retrieved on 26th June 2014 from http://www.thebsa.org.uk/images/stories/docs/BSA_APD_PositionPaper_31March11_FINAL.pdf.

British Society of Audiology, 2011. Recommended Procedure Pure-tone air-conduction and bone-conduction threshold audiometry with and without masking. Retrieved on 26th June 2014 from http://www.thebsa.org.uk/wp-content/uploads/BSA_RP_PTA_FINAL_24Sept22_MinorAmend06Feb12.pdf

Broadbent, DE, 1954. The role of auditory localisation in attention and memory span. J. Exp. Psychol. 47:191-196

Brown, GJ, Ferry, RT, Meddis, R, 2010. A Computer Model of Auditory Efferent Suppression: Implications for the Recognition of Speech in Noise. J. Acoust. Soc. Am. 127(2): 943-954.

Brown, J and Jaffe, J, 1975. Hypothesis on cerebral dominance. Neuropsychologia. 13:107-110.

Brungart, DS, Simpson, BD, Ericson MA, Scott, KR, 2001. Informational and Energetic Masking Effects in the Perception of Two Simultaneous Talkers. J. Acoust. Soc. Am. 110: 2527-2538.

Cameron, S, Dillon, H, Newall, P, 2006. The Listening in Spatialized Noise Test: An Auditory Processing Disorder Study. J. Am. Acad. Audiol.17(5):306-320.

Cameron, S and Dillon, H, 2007. Development of the Listening in Spatialized Noise-Sentences Test (LISN-S). Ear Hear. 28: 196-211.

Cameron, S and Dillon, H, 2011. Development and Evaluation of the LISN & Learn Auditory Training Software for Deficit-specific Remediation of Binaural Processing Deficits in Children: Preliminary Findings. J. Am. Acad. Audiol. 22(10): 678-696

Carhart, R and Tillman, TW, 1970. Interaction of Competing Speech Signals with Hearing Losses. Arch. Otolaryngol. 91(3): 273-279.

Ceranic, BJ, Prasher, DK, Raglan, E, Luxon, LM, 1998. Tinnitus after Head Injury: Evidence from Otoacoustic Emissions. J. Neurol. Neurosurg. Psychiatry 65(4): 523-529.

Collet, L, Veuillet, E, Bene, J, Morgon, A, 1992. Effects of Contralateral White Noise on Click-evoked Emissions in Normal and Sensorineural Ears: Towards an Exploration of the Medial Olivocochlear System. Audiology 31(1):1-7.

Committee on Hearing and Bioacoustics and Biomechanics (CHABA), 1988. Speech Understanding and Aging. J. Acoust. Soc. Am. 83: 859–895.

Cooke, M, Green, P, Josifoski, L, Vizinho, A, 2001. Robust Automatic Speech Recognition with Missing and Unreliable Acoustic Data. Speech Comm. 34(3): 267-285.

Cooper, JC and Gates, GA, 1991. Hearing in the Elderly-The Framingham Cohort, 1983-1985: Part II. Prevalence of Central Auditory Processing Disorders. Ear Hear. 12(5): 304-311.

Cox, RM, Alexander, GC, Gilmore, C, 1987. Development of the Connected Speech Test (CST). Ear Hear. 8: 119S–126S.

Cronbach, LJ and Meehl, PE, 1955. Construct Validity in Psychological Tests. Psychol. Bull. 52(4): 281-302.

Danhauer, JL and Leppler, JG, 1979. Effects of Four Noise Competitors on the California Consonant Test. J. Speech Hear. Disord. 44(3): 354-362.

Davis A, 1989. The Prevalence of Hearing Impairment and Reported Hearing Disability among Adults in Great Britain. Int. J. Epidemiology 18: 911-917.

Davis, MH, Ford, MA, Kherif, F, Johnsrude, IS, 2011. Does Semantic Context Benefit Speech Understanding through "Top-down" Processes? Evidence from Time-resolved Sparse fMRI. J. Cogn. Neurosci. 23(12):3914-3932.

Dawes, P, and Bishop, DV, 2007 The SCAN-C in Testing for Auditory Processing Disorder in a Sample of British Children. Int. J. Audiol. 46(12): 780-786.

Dawes, P, Bishop, DVM, Sirimanna, T, Bamiou, DE, 2008. Profile and Aetiology of Children Diagnosed with Auditory Processing Disorder (APD) Int. J. Ped. Otorhinolaryngol. 72(4): 483-489.

de Boer, J and Thornton, AR, 2007. Effect of Subject Task on Contralateral Suppression of Click Evoked Otoacoustic Emissions. Hear. Res. 233(1-2): 117-123.

Dillon, H, Cameron, S, Glyde, H, Wilson, W, Tomlin, D, 2012. An Opinion on the Assessment of People who may have an Auditory Processing Disorder. J. Am. Acad. Audiol. 23:97-105

Dreschler, WA, Verschuure, H, Ludvigsen, C, Westermann, S, 2001. ICRA Noises: Artificial Noise Signals with Speech-like Spectral and Temporal Properties for Hearing Instrument Assessment. Audiology 40(3): 148-157.

Drew, R, Oyler, RF, Schaedel, T, 2003. Right Temporal Lobe Auditory-Induced Epilepsy: Functional and Audiologic Pre/post-surgical Results. J. Med. Speech Lang. Pathol. 11(2): 43-50.

Dubno, JR, Dirks, DD, Morgan, DE, 1984. Effects of Age and Mild Hearing Loss on Speech Recognition in Noise. J. Acoust. Soc. Am. 76(1): 87- 96.

Egan, JP, 1948. Articulation Testing Methods. Laryngoscope 58: 955-991.

Elgeti, A, Zehnhoff-Dinnesen, AG, Matulat, P, Schmidt, CM, Knief, A, 2008. Spontaneous Otoacoustic Emission Enhancement in Children with Reduced Speech-in-Noise Intelligibility. Audiol. Neurotol. 13(6): 357-364.

Elsabbagh, M, Cohen, H, Cohen, M, Rosen, S, Karmiloff-Smith, A, 2011. Severity of Hyperacusis Predicts Individual Differences in Speech Perception in Williams Syndrome. J. Intellect. Disabil. Res. 55(6): 563-571.

Etymotic Research, 2005. BKB Speech-in-Noise Test (Version 1.03) [Audio CD]. Elk Grove Village, IL: Author.

Evans EF, 1992. Auditory Processing of Complex Sounds: An Overview. Philos. Trans. R. Soc. Lond. B. Biol. Sci. 336 (1278): 295-306.

Fallis-Cunningham, R, Keith, RW, Warnick, RE, 1998. Central Auditory Processing in a Patient with Bilateral Temporal Lobe Tumors: Case Report. J. Am. Acad. Audiol. 9(4): 299-304.

Fikret-Pasa, S, 1993.The Effects of Compression Ratio on Speech Intelligibility and Quality (Unpublished doctoral dissertation). Northwestern University, Evanston, IL

Fisher, LI, 1976. Fisher's Auditory Problem Checklist. Cedar Rapids, IA: Grant Wood Area Educational Agency.

Gao, E and Suga, N, 2000. Experience-dependent Plasticity in the Auditory Cortex and the Inferior Colliculus of Bats: Role of the Corticofugal System. Proc. Natl. Acad. Sci. USA 97(14): 8081-8086.

Galambos R, 1956. Suppression of Auditory Nerve Activity by Stimulation of Efferent Fibres to Cochlea. J. Neurophysiol. 19(5): 424-437.

Garinis, AC, Glattke, T, Cone-Wesson, BK, 2008. TEOAE Suppression in Adults with Learning Disabilities. Int. J. Audiol. 47(10): 607-614.

Gatehouse, S and Noble, W, 2004. The Speech, Spatial and Qualities of Hearing Scale (SSQ). Int. J. Audiol. 43(2): 85-99.

George, EL, Festen, JM, Houtgast, T, 2008. The Combined Effects of Reverberation and Non-stationary Noise on Sentence Intelligibility. J. Acoust. Soc. Am. 124(2): 1269-1277.

Guinan, JJ Jr. 2006. Olivocochlear Efferents: Anatomy, Physiology, Function, and the Measurement of Efferent Effects in Humans. Ear Hear. 27(6): 589–607.

Guinan, JJ Jr. 2010. Cochlear Efferent Innervation and Function. Curr. Opin. Otolaryngol. Head Neck Surg. 18(5): 447-453.

Gustafsson, HA and Arlinger, SD, 1994. Masking of Speech by Amplitude Modulated Noise. J. Acoust. Soc. Am. 95(1): 518-529.

Helfer, KS and Vargo, M, 2009. Speech Recognition and Temporal Processing in Middle-Aged Women. J. Am. Acad. Audiol. 20(4):264-271

Higson, JM, Haggard, MP, Field, DL, 1994. Validation of Parameters for Assessing Obscure Auditory Dysfunction—Robustness of Determinants of OAS Status Across Samples and Test Methods. Br. J. Audiol. 28(1): 27-39.

Hind, SE, Haines-Bazrafshan, R, Benton CL, Brassington, W, Towle, B, Moore, DR, 2011. Prevalence of Clinical Referrals having Hearing Thresholds within Normal Limits. Int. J. Audiol. 50(10): 708-716.

Hirsh, IJ, Davis, H, Silverman, SR, Reynolds, EG, Eldert, E, Benson, RW, 1952. Development of Materials for Speech Audiometry. J. Speech Hear. Disord. 17(3): 321-337.

Howard-Jones, PA and Rosen, S, 1993. Unmodulated Glimpsing in 'Checkerboard' Noise. J. Acoust. Soc. Am. 93(5): 2915-2922.

Hugdahl, K, Westerhausen, R, Alho, K, Medvedev, S, Laine, M, Hamalainen, H, 2009. Attention and Cognitive Control: Unfolding the Dichotic Listening Story. Scand. J. Psychol. 50(1): 11-22.

Humes, LE, 2005. Do 'Auditory Processing' Tests Measure Auditory Processing in the Elderly? Ear Hear. 26(2): 109-119.

Hwang, JH, Wu, CW, Chen, JH, Liu, TC, 2006. The Effects of Masking on the Activation of Auditory-associated Cortex during Speech Listening in White Noise. Acta Otolaryngol. 126(9) : 916-920.

ICD-10 H93.25 Central Auditory Processing Disorder. Retrieved online on 26th June 2014 from http://www.icd10data.com/ICD10CM/Codes/H60-H95/H90-H94/H93-/H93.25.

Iliadou, V, Bamiou, DE, Kaprinis, S, Kandylis, D, Kaprinis, G, 2009. Auditory Processing Disorders in Children Suspected of Learning Disabilities—A Need for Screening? Int. J. Ped. Otorhinolaryngol. 73(7): 1029-1034.

Iliadou, V and Bamiou, DE, 2012. Psychometric Evaluation of Children with Auditory Processing Disorder (APD): Comparison with Normal Hearing and Clinical non–APD groups. J. Speech Lang. Hear. Res. 55(3): 791-799.

James, W, 1890. Psychology (briefer course). New York: Holt.

Jeeves, MA and Moes, P, 1996. Interhemispheric Transfer Time Differences Related to Aging and Gender. Neuropsychologia 34(7): 627-663.

Jerger, J and Jerger, S, 1975. Clinical Validity of Central Auditory Tests. Scand. Audiol. 4: 147-163.

Jerger, J, Jerger, S, Oliver, T, Pirozollo, F, 1989. Speech Understanding in the Elderly. Ear Hear. 10(2): 79-89.

Jerger, J, Oliver, T, Pirozzolo, F, 1990. Impact of Central Auditory Processing Disorder and Cognitive Deficit on the Self-assessment of Hearing Handicap in the Elderly. J. Am. Acad. Audiol. 1: 75-80.

Jerger, J and Musiek, FE, 2000. Report of the consensus conference on the diagnosis of auditory processing disorders in school-aged children. J Am Acad Audiol. 11(9):467-474

Jerger, S and Jerger, J, 1984. Pediatric Speech Intelligibility Test: Manual for Administration. St. Louis, MO: Auditec

Kalikow, DN, Stevens, KN, Elliott, LL, 1977.Development of a Test of Speech Intelligibility in Noise using Materials with Controlled Word Predictability. J. Acoust. Soc. Am. 61(5): 1337-1351.

Kandel, ER, Schwartz, JH, Jessell, TM, 2000. Principles of Neural Science, 4th ed. McGraw-Hill, New York. ISBN 0-8385-7701-6

Katz, J, 2004. The Buffalo Model Questionnaire. SWW Reports 26: 5-6.

Kawase, T and Liberman, MC, 1993. Antimasking Effects of the Olivocochlear Reflex. I. Enhancement of Compound Action Potentials to Masked Tones. J. Neurophysiol. 70(6): 2519-2532.

Kemp, DT, 1978.Stimulated Acoustic Emissions from within the Human Auditory System. J Acoust. Soc. Am. 64(5): 1386-1391.

Kennedy, V, Wilson, C, Stephens, D, 2006. When a Normal Hearing Test is just the Beginning. J. R. Soc. Med. 99(8): 417-420.

Khalfa S, Dubal S, Veuillet E, Perez-Diaz, F, Jouvent, R, Collet, L, 2002. Psychometric Normalization of a Hyperacusis Questionnaire. ORL J Otorhinolaryngol Relat Spec. 64(6): 436-442.

Kiernan, JA, Central Auditory Pathway retrieved online on 26th June 2014 from www.instruct.uwo.ca.

Killion, MC, Niquette, PA, Gudmundsen, GI, Revit, LJ, Banerjee, S, 2004. Development of a Quick Speech-in-noise Test for Measuring Signal-to-noise Ratio Loss in Normal-hearing and Hearing-impaired Listeners. J. Acoust. Soc. Am. 116: 2395-2405.

Kimura, D, 1961. Cerebral Dominance and the Perception of Verbal Stimuli. Can. J. Psychol. 15: 166-171

King, C, Warrier, CM, Hayes, E, Kraus, N, 2002. Deficits in Auditory Brainstem Pathway Encoding of Speech Sounds in Children with Learning Problems. Neurosci. Lett. 319(2): 111-115.

King, K and Stevens, D, 1992. Auditory and Psychological Factors in 'Auditory Disability with Normal Hearing'. Scand. Audiol. 21(2): 109-114.

King, PF, 1954. Psychogenic Deafness. J. Laryngol. Otol. 68(9): 623-635.

Kopetzky, SJ, 1948. Deafness, Tinnitus and Vertigo. New York: Nelson; p280

Kramer, SE, Kapteyn, TS, Festen, JM, Tobi, H, 1995. Factors in Subjective Hearing Disability. Audiology, 34(6): 311-320.

Kulesza, RJ and Mangunay, K, 2008. Morphological Features of the Medial Superior Olive in Autism. Brain Res. 1200:132-137

Kumar, G, Amen F, Roy, D, 2007. Normal Hearing Tests: Is a Further Appointment Really Necessary? J. R. Soc. Med. 100(2): 66.

Kumar, UA, and Vanaja, CS, 2004. Functioning of Olivocochlear Bundle and Speech Perception in Noise. Ear Hear. 25(2): 142-146.

Kunaratnam, N, Bamiou, DE, Cohen M, 2003. Speech in Babble versus Speech in Noise in Normal Subjects and in Patients with Neurological Lesions (MSc dissertation UCL).

Lawfield, A, McFarland, DJ, Cacase, AT, 2011. Dichotic and Dichoptic Digit Perception in Normal Adults. J. Am. Acad. Audiol. 22(6): 332-341.

Liasis, A, Bamiou, DE, Campbell, P, Sirimanna, T, Boyd, S, Towell, A, 2003. Auditory Event Related Potentials in the Assessment of Auditory Processing Disorders: A Pilot Study. Neuropediatrics 34(1): 23-39.

Liberman, AM, 1970. The Grammars of Speech and Language. Cogn. Psychol. 1: 301-323.

Loo, JH, Bamiou, DE, Rosen, S, 2013.The Impacts of Language Background and Language-related Disorders in Auditory Processing Assessment. J. Speech Lang. Hear. Res. 56(1): 1-12.

Luce, PA, Pisoni, DB, Goldinger, SD, 1990. Similarity Neighbourhoods of Spoken Words. In: Altmann G, ed. Cognitive Models of Speech Processing: Psycholinguistic and Computational Perspectives. Cambridge MA: MIT Press, pp 122–147.

Luce, PA and Pisoni, DB, 1998.Recognizing Spoken Words: The Neighbourhood Activation Model. Ear Hear. 19(1): 1-36.

Luo, F, Wang, Q, Kashani, A, Yan, J, 2008. Corticofugal Modulation of Initial Sound Processing in the Brain. J. Neurosci. 28(45): 11615–11621.

Luxon, LM. 1981. The Anatomy and Pathology of the Central Auditory Pathways. Br. J. Audiol. 15(1): 31-40.

Manell, R, Olivocochlear bundle system retrieved on 26th June 2014 from www.zaenea.com.

Mann, MD, Chapter 8. Central auditory pathway in the nervous system in action retrieved on 26th June 2014 from www.michaeldmann.net.

McArdle, R and Wilson, RH, 2008. Predicting Word-recognition Performance in Noise by Young Listeners with Normal Hearing using Acoustic, Phonetic, and Lexical Variables. J. Am. Acad. Audiol. 19(6): 507-518.

McGurk, H, and MacDonald, J, 1976. Hearing Lips and Seeing Voices. Nature 264(5588): 746-748.

Meijer, AG, Wit, HP, TenVergert, EM, Albers, FW, Muller Kobold JE, 2003. Reliability and Validity of the (Modified) Amsterdam Inventory for Auditory Disability and Handicap. Int. J. Audiol. 42(4): 220-226.

Meister, H, von Wedel, H, Walger, M, 2004. Psychometric Evaluation of Children with Suspected Auditory Processing Disorders (APDs) using a Parent–answered Survey. Int. J. Audiol. 43(8): 431-437.

Meneguello, J, Leonhardt, FD, Pereira, LD, 2006. Auditory Processing in Patients with Temporal Lobe Epilepsy. Braz. J. Otorhinolaryngol. 72(4): 496-504.

Messing, DP, Delhorne, L, Bruckert, E, Braida, LD, Ghitza, O, 2009. A Nonlinear Efferent-inspired Model of the Auditory System: Matching Human Confusions in Stationary Noise. Speech Commun. 51: 668-683.

Millen, SJ, Haughton VM, Yetkin, Z, 1995. Functional Magnetic Resonance Imaging of the Central Auditory Pathway Following Speech and Pure-tone Stimuli. Laryngoscope 105(12 Pt 1): 1305-1310.

Moore, BCJ, Tyler, LK, Marslen-Wilson, W, 2008. Introduction. The Perception of Speech: From Sound to Meaning. Philos. Trans. R. Soc. Lond. B Biol. Sci. 363(1493): 917-921.

Moore, DR, Ferguson, MA, Edmondson-Jones, AM, Ratib, S, Riley, A, 2010. Nature of Auditory Processing Disorder in Children. Pediatrics 126(2): e382-390.

Moore, DR, 2012. Listening Difficulties in Children: Bottom-up and Top-down Contributions. J. Commun. Disord. 45(6): 411-418.

Moore, DR, Rosen, S, Bamiou, DE, Campbell, NG, Sirimanna, T, 2013. Evolving Concepts of Developmental Auditory Processing Disorder (APD): A British Society of Audiology APD Special Interest Group 'white paper' Int. J. Audiol. 52(1): 3-13.

Morel, A and Imig, TJ, 1987. Thalamic Projections to Fields A, AI, P, and VP in the Cat Auditory Cortex. J. Comp. Neurol. 265(1): 119-144.

Muchnic, C, Ari-Even Roth, D, Othman-Jebara, R, Putter-Katz, H, Shabtai, EL, Hildesheimer, M, 2004. Reduced Medial Olivocochlear Bundle System Function in Children with Auditory Processing Disorders. Audiol. Neurootol. 9(2): 107-114.

Mukari, SZ and Mamat, WH, 2008. Medial Olivocochlear Functioning and Speech Perception in Noise in Older Adults. Audiol. Neurootol. 13(5): 328-334.

Mukari, SZ, Umat, C, Othman, NI, 2010. Effects of Age and Working Memory Capacity on Pitch Pattern Sequence Test and Dichotic Listening. Audiol. Neurotol. 15(5): 303-310.

Munoz-Lopez, MM, Mohedano-Moriano, A, Insausti, R, 2010. Anatomical Pathways for Auditory Memory in Primates. Front. Neuroanat. 8(4): 129

Murphy, DR, Daneman, M, Schneider, BA, 2006. Why Do Older Adults Have Difficulty Following Conversations? Psychol. Aging 21(1): 49-61.

Musiek, FE, 1983. Assessment of Central Auditory Dysfunction: the Dichotic Digit Test Revisited. Ear Hear. 4(2): 79-83.

Musiek FE, Pinheiro, ML, 1987. Frequency patterns in cochlear, brainstem, and cerebral lesions. Audiology, 26(2):79-88

Musiek, FE, Gollegly, KM, Lamb, LE, Lamb, P, 1990 Selected Issues in Screening for Central Auditory Processing Dysfunction. Semin Hear. 11:372-383

Musiek, FE, Collegly, KM, Kibbe, KS, Verkest-Lenz, SB 1991. Proposed screening test for auditory disorders: follow-up on the dichotic digit test. Am. J.Otol. 12(2):109-113

Musiek, FE, and Lamb, L, 1992 Chapter 2 Neuroanatomy and Neurophysiology of Central Auditory Processing in: Central Auditory Processing A Transdisciplinary View Ed: Jack Katz et al.

Musiek, FE, 1994. Frequency (pitch) and Duration Pattern Tests. J. Am. Acad. Audiol. 5:265-268.

Musiek, FE, and Lee, WW, 1998. Neuroanatomical Correlates to Central Deafness. Scand Audiol Suppl. 49: 18-25.

Musiek, FE, Oxholm, VB, 2003. Chapter 11. Central auditory anatomy and function; Textbook of Audiological Medicine Clinical aspects of hearing and balance Ed. Luxon, LM pp 179-193.

Musiek, FE, Shinn, JB, Jirsa, R, Bamiou, DE, Baran, JA, Zaidan, E, 2005 GIN (Gaps-In-Noise) Test Performance in Subjects with Confirmed Central Auditory Nervous System Involvement. Ear Hear. 26(6): 608-618.

Musiek, FE, Chermak, GD, Weihing, J, Zapulla, M, Nagle, S, 2011. Diagnostic Accuracy of Established Central Auditory Processing Test Batteries in Patients with Documented Brain Lesions. J. Am. Acad. Audiol. 22(6): 342-358.

Myklebust, H, 1954. Auditory Disorders in Children. New York: Grune & Stratton.

Nagle, S, Musiek, FE, Kossof, EH, Jallo, G, Boatman-Reich, D, 2013. Auditory Processing following Consecutive Temporal Lobe Resections: A Prospective Case Study. J. Am. Acad. Audiol. 24: 535-543.

Neijenhuis, K, Snik, A, van den Broek, P, 2003 Auditory Processing Disorders in Adults and Children: Evaluation of a Test Battery. Int. J. Audiol. 42(7): 391-400

Newman, CW, Jacobson, GP, Weinstein, BE, Sancibridge, SA, 1997. Computer-generated Hearing Disability/Handicap Profiles. Am. J. Audiol. 6(1): 17-21.

Nilsson, M, Soli, SD, Sullivan, JA, 1994. Development of the Hearing in Noise Test for the Measurement of Speech Reception Thresholds in Quiet and in Noise. J. Acoust. Soc. Am. 95(2): 1085-1099.

Niquette, P, Arcaroli, J, Revit, L, Parkinson, A, Staller, S, Skinner, M, Killion, M, , 2003, Development of the BKB-SIN Test. Paper presented at the annual meeting of the American Auditory Society, Scottsdale, AZ. Retrieved on 26th June 2014 from www.amauditorysoc.org/pages/abstracts/2003/pp/2003-pp-04.

Obleser, J, Eisner, F, Kotz, SA. 2008. Bilateral Speech Comprehension Reflects Differential Sensitivity to Spectral and Temporal Features. J. Neurosci. 28(32): 8116-8123.

Okada, K, Rong, F, Venezia, J, Matchin, W, Hsieh, IH, Saberi, K, Serences, JT, Hickok, G, 2010. Hierarchical Organization of Human Auditory Cortex: Evidence from Acoustic Invariance in the Response to Intelligible Speech. Cereb. Cortex 20(10): 2486-2495.

Patterson, RD and Johnsrude IS, 2008. Functional Imaging of the Auditory Processing Applied to Speech Sounds. Philos. Trans. R. Soc. Lond. B. Biol. Sci. 363(1493): 1023-1035.

Pereira, LD and Schochat, E, 1997. Processamento Auditivo Central: Manual de Avaliac¸a˜o. Sa˜o Paulo: Ed. Lovise. p. 99-149.

Phillips, DP, Comeau, M, Andrus, JN, 2010. Auditory Temporal Gap Detection in Children with and without Auditory Processing Disorder. J. Am. Acad. Audiol. 21(6): 404-408.

Pichora-Fuller, MK, Schneider, BA, Macdonald, E, Pass, HE, Brown, S, 2007. Temporal Jitter Disrupts Speech Intelligibility: A Simulation of Auditory Aging. Hear Res. 223(1-2): 114-121.

Pickles, JO and Comins, SD, 1973. Role of Centrifugal Pathways to Cochlear Nucleus in Detection of Signals in Noise. J Neurophysiol. 36(6): 1131-1137.

Plomp, R, 1978. Auditory Handicap of Hearing Impairment and the Limited Benefit of Hearing Aids. J. Acoust. Soc. Am. 63: 533-549.

Plyler, PN, Alworth, LN, Rossini, TP, Mapes, KE, 2011. Effects of Speech Signal Content and Speaker Gender on Acceptance of Noise in Listeners with Normal Hearing. Int. J. Audiol. 50(4): 243-248.

Purdy, SC, Kelly, AS, Davies, MG, 2002. Auditory Brainstem Response, Middle Latency Response, and Late Cortical Evoked Potentials in Children with Learning Disabilities. J. Am. Acad. Audiol. 13(7): 367-382.

Rasmussen, GL, 1946. The Olivary Peduncle and Other Fiber Projections of the Superior Olivary Complex. J. Comp. Neurol. 84: 141-219.

Rosen, S. 1992. Temporal Information in Speech: Acoustic, Auditory and Linguistic Aspects. Philos. Trans. R. Soc. Lond. B. Biol. Sci. 336(1278): 367-373.

Rosen, S, Souza, P, Ekelund, C, Majeed, AA, 2013. Listening to Speech in a Background of Other Talkers: Effects of Talker Number and Noise Vocoding. J. Acoust. Soc. Am. 133(4): 2431-2443.

Rosenhall, U, Nordin, V, Sandstrom, M, Ahlsen, G, Gillberg, C, 1999. Autism and Hearing Loss. J Autism Devel. Disord. 29(5): 349-357.

Sahley, TL, Nodar, RH, Musiek, FE, 1997. Efferent Auditory System: Structure and Function.1st ed. San Diego: Singular Publishing group, Inc.

Salvi, RJ, Lockwood AH, Frisina, RD, Coad, ML, Wack, DS, Frisina, DR, , 2002. PET Imaging of the Normal Human Auditory System: Responses to Speech in Quiet and in Background Noise. Hear. Res. 170(1-2): 96-106.

Samelli, AG and Schochat, E, 2008.The gaps-in-noise test: gap detection thresholds in normal- hearing young adults. Int J Audiol, 47(5):238-245

Sanders, DA, 1977. Auditory Perception of Speech: An Introduction to Principles and Problems, New Jersey: Prentice-Hall, PTR

Santi, PA and Mancini, P, 1998. Cochlear Anatomy and Central Auditory Pathways. Otolaryngology Head and Neck Surgery, Ed. C Cummings 3rd Edition, p.p. 2803–2830

Saunders, GH and Haggard, MP, 1992. The Clinical Assessment of 'Obscure Auditory Dysfunction' (OAD) - 2. Case Control Analysis of Determining Factors. Ear Hear. 13(4): 241-254.

Schmithorst, VJ, Farah, R, Keith, RW, 2013. Left Ear Advantage in Speech-related Dichotic Listening is not specific to Auditory Processing Disorder in Children: A Machine-learning fMRI and DTI Study. Neuroimage. Clin. 3: 8-17.

Scott, SK, and Johnsrude, IS, 2003. The Neuroanatomical and Functional Organization of Speech Perception. Trends Neurosci. 26(2): 100-107.

Sekiyama, K, Kanno I, Miura S, Sugita, Y, 2003 Auditory-Visual Speech Perception Examined by fMRI and PET. Neurosci. Res. 47(3): 277-287.

Shapleske, J, Rossell, SL, Woodruff, PW, David, AS, 1999. The Planum Temporale: A Systematic, Quantitative Review of its Structural, Functional and Clinical Significance. Brain Res. Brain Res. Rev. 29(1): 26-49.

Smoski, WJ, Brunt, MA, Tannahill, JC, 1992. Listening Characteristics of Children with Central Auditory Processing Disorders. Lang. Speech Hear. Serv. Sch. 23: 145-152.

Soli, SD, Vermiglio, A, Wen, K, Laroche, C, Giguere, C, Iwaki, T, et al., 2002. Development of the Hearing in Noise Test (HINT) in New Languages. Short course presented at the 14th Convention of the American Academy of Audiology, Philadelphia, PA.

Song, JH, Skoe, E, Banai, K, Kraus, N, 2012. Training to improve Hearing Speech in Noise: Biological Mechanisms. Cereb Cortex, 22(5):1180-1190

Speaks, C and Jerger, J, 1965. Method for Measurement of Speech Identification. J Speech Hear. Res. 8: 185-194.

Sprangler, KM, and Warr, WB, 1991. The Descending Auditory System in Neurobiology of Hearing: the Central Auditory System, Ed: Altschuler R.A. et al., Raven Press, New York, pp 27-45.

Springer, S and Gazzaniga, M, 1975. Dichotic Testing of Partial and Complete Split Brain Patients. Neuropsychologia 13(3): 341-346.

Spyridakou, C, Luxon, LM, Bamiou, DE, 2012. Patient Reported Speech in Noise Difficulties and Hyperacusis Symptoms and Correlation with Test Results. Laryngoscope 122 (7): 1609-1614.

Sumby, WH, and Pollack, I, 1954. Visual Contribution to Speech Intelligibility in Noise. J. Acoust. Soc. Am. 26: 212-215.

Tabri, D, Abou Chacra, KM, Pring, T, 2011. Speech Perception in Noise by Monolingual, Bilingual and Trilingual Listeners.Int. J. Lang. Commun. Disord. 46(4): 411-422.

Thiele, C, Sukowski, H, Wagener K, Kollmeier, B, Lenarz, T, Lesinski-Schiedat, A, 2011. [Hearing loss determination and assessment of the reduction in earning capacity taking speech discrimination tests in noise into account]. HNO 59(11): 1111-1117.

Tillman, TW and Carhart, R, 1966. An Expanded Test for Speech Discrimination Utilizing CNC Monosyllabic Words. North Western University Auditory Test No. 6. Brooks Air Force Base, TX: USAF School of Aerospace Medicine Technical Report.

Uppenkamp, S, Johnsrude, IS, Norris, D, Marslen-Wilson, W, Patterson, RD, 2006. Locating the Initial Stages of Speech-sound Processing in Human Temporal Cortex. Neuroimage 31(3): 1284-1296.

Wagenaar, O, Wieringa, M, Verschuure, H. 2010. A Cognitive Model of Tinnitus and Hyperacusis: A Clinical Tool for Patient Information, Appeasement and Assessment. Int. J. Tinnitus 16(1): 66-72

Wagener, KC and Brandt, T, 2005. Sentence Intelligibility in Noise for Listeners with Normal Hearing and Hearing Impairment: Influence of Measurement Procedure and Masking Parameters. Int. J. Audiol 44(3): 144-156.

Wallen, MB, Hasson, D, Theorell T, Canlon, B, 2012. The Correlation between the Hyperacusis Questionnaire and Uncomfortable Loudness Levels is Dependent on Emotional Exhaustion. Int. J. Audiol. 51(10): 722-729.

Warr, WB, 1980. Efferent Components of the Auditory System Ann.Otol. Rhinol. Laryngol. Suppl. 89: 114-120

Warr, WB and Beck, JE. 1996. Multiple Projections from the Ventral Nucleus of the Trapezoid Body in the Rat. Hear. Res. 93(1-2): 83-101.

Welsh, LW, Welsh, JJ, Healy, MP, 1985. Central Presbycusis. Laryngoscope 95(2): 128-136.

Wild, CJ, Yusuf, A, Wilson, DE, Peelle, JE, Davis, MH, Johnsrude, IS, 2012. Effortful Listening: The Processing of Degraded Speech depends Critically on Attention. J. Neurosci. 32(40): 14010-14021.

Wilson, RH, 2003. Development of a Speech- in- Multitalker Babble Paradigm to Assess Word-recognition Performance. J. Am. Acad. Audiol. 14(9): 453-470.

Wilson, RH and McArdle, RA, 2005. Speech Signals used to Evaluate Functional Status of the Auditory System. J. Rehabil. Res. Dev. 42 (4 Suppl 2): 79-94.

Wilson, RH, Mc Ardle, RA, Smith SL, 2007. An Evaluation of the BKB-SIN, HINT, Quick SIN, and WIN Materials on Listeners with Normal Hearing and Listeners with Hearing Loss. J. Speech, Lang. Hear. Res. 50(4): 844-856.

Wilson, RH, Carnell, CS, Cleghorn, AL, 2007. The Words-in-noise (WIN) Test with Multitalker Babble and Speech-spectrum Noise Maskers. J. Am. Acad. Audiol. 18(6): 522-529.

Wilson, RH, McArdle, RA, Roberts, H, 2008. A Comparison of Recognition Performances in Speech-spectrum Noise by Listeners with Normal Hearing on PB-50, CID W-22, NU-6, W-1 Spondaic Words, and Monosyllabic Digits Spoken by the Same Speaker. J. Am. Acad. Audiol. 19(6): 496-506.

Wilson, RH, and McArdle, R, 2012. Speech-in-noise Measures: Variable versus Fixed Speech and Noise Levels. Int. J. Audiol. 51(9): 708-712.

Wilson, SM, Saygin, AP, Sereno, MI, Iacoboni, M, 2004. Listening to Speech Activates Motor Areas Involved in Speech Production. Nat. Neurosci. 7(7): 701-702.

Wilson, WJ, Jackson, A, Pender A, Rose, C, Wilson, J, Heine C, Khan, A, 2011.The CHAPS, SIFTER, and TAPS–R as Predictors of (C) A Skills and (C) APD. J. Speech Lang. Hear. Res. 54(1): 278-291.

Wilson, WJ, and Arnott, W, 2013. Using different criteria to diagnose (central) auditory processing disorder: how big a difference does it make? J. Speech Lang. Hear. Res. 56(1): 63-70.

Winslow, RL and Sachs, MB, 1988. Single-tone Intensity Discrimination based on Auditory Nerve Rate Responses in Backgrounds of Quiet, Noise and with Stimulation of the Crossed Olivocochlear Bundle. Hear. Res. 35(2-3): 165-189.

Witton, C, 2010. Childhood Auditory Processing Disorder as a Developmental Disorder: The Case for a Multi-professional Approach to Diagnosis and Management. Int. J. Audiol. 49(2): 83-87.

Wong, PC, Uppunda, AK, Parrish, TB, Dhar, S, 2008. Cortical Mechanisms of Speech Perception in Noise. J. Speech Lang. Hear. Res. 51(4): 1026-1041.

Wong, LL and Soli, SD, 2005. Development of the Cantonese Hearing in Noise Test (CHINT). Ear Hear. 26(3): 276-289.

Wong, LL, Ng, EH, Soli, SD,2012. Characterization of Speech Understanding in Various Types of Noise J. Acoust. Soc. Am. 132 (4): 2642-2651.

Wood, NL, and Cowan, N, 1995. The Cocktail Party Phenomenon Revisited: Attention and Memory in the Classic Listening Selective Procedure of Cherry (1953). J. Exp. Psychol. Gen. 124(3): 243-262.

Yakovlev, PI and Lecours, AR, 1967. Regional Development of the Brain. Blackwell, Oxford, England.

Yost, WA, 2000. Chapter 14: Auditory Perception and Sound Source Determination in Fundamentals of Hearing. An Introduction, 4th edition. Academic press. Elsevier science (USA), pp. 207-225.

Zaidel, E, 1986. Callosal Dynamic and Right Hemisphere Language in: Lepore F. Pitto M, Jasper HH (Eds). Two hemispheres–one brain. Functions of Corpus Callosum. New York: Alan Liss.

Zatorre, RJ and Belin, P. 2001 Spectral and Temporal Processing in Human Auditory Cortex. Cereb. Cortex. 11(10): 946-953.

Zatorre, RJ, Belin, P, Penhune, VB, 2002. Structure and Function of Auditory Cortex: Music and Speech. Trends Cogn. Sci. 6(1):37-46

Zekveld, AA, Henslenfeld, DJ, Festein, JM, Schhonhoven, R, 2006. Top-down and Bottom-up Processes in Speech Comprehension. Neuroimage 32(4): 1826-1836.

Zhao, F, Stephens, D, 1996. Hearing complaints of patients with King-Kopetzky syndrome (Obscure Auditory Dysfunction). Br J Audiol. 30(6):397-402.

APPENDIX 1

Modified Amsterdam Inventory for Auditory Disability

Name **Date of birth**

Date tested

1. Can you understand a shop assistant in a crowded shop?

Almost always Frequently Occasionally Almost Never

2. Can you carry on a conversation with someone in a quiet room?

Almost always Frequently Occasionally Almost Never

3. Do you immediately hear from which direction car is approaching when outside?

Almost always Frequently Occasionally Almost Never

4. Can you hear cars passing by?

Almost always Frequently Occasionally Almost Never

5. Do you recognise members of your family by their voices?

Almost always Frequently Occasionally Almost Never

6. Can you recognise melodies in music or songs?

Almost always Frequently Occasionally Almost Never

7. Can you carry on a conversation with someone in a crowded meeting

Almost always Frequently Occasionally Almost Never

8. Can you carry on a telephone conversation in a quiet room?

Almost always Frequently Occasionally Almost Never

9. Can you hear from which corner of a lecture room someone is asking a question during a meeting?

Almost always Frequently Occasionally Almost Never

10. Can you hear someone approaching from behind?

Almost always Frequently Occasionally Almost Never

11. Do you recognise a presenter on TV by his/her voice?

Almost always Frequently Occasionally Almost Never

12. Can you understand text that is being sung?

Almost always Frequently Occasionally Almost Never

13. Can you easily carry on a conversation with somebody in a car or bus?

Almost always Frequently Occasionally Almost Never

14. Can you understand the presenter of the news on TV?

Almost always Frequently Occasionally Almost Never

15. Do you immediately look in the right direction when somebody calls you in the street?

Almost always Frequently Occasionally Almost Never

16. Can you hear noises in the house like running water, vacuuming, a washing machine?

Almost always Frequently Occasionally Almost Never

17. Can you discriminate between the sound of a car and a bus?

Almost always Frequently Occasionally Almost Never

18. Can you follow a conversation between a few people during dinner?

Almost always Frequently Occasionally Almost Never

19. Can you understand the presenter of the news on the radio?

Almost always Frequently Occasionally Almost Never

20. Can you hear from which corner of the room someone is talking to you in a quiet house?

Almost always Frequently Occasionally Almost Never

21. Can you hear the doorbell at home?

Almost always Frequently Occasionally Almost Never

22. Can you distinguish between male and female voices?

Almost always Frequently Occasionally Almost Never

23. Can you hear rhythm in music or songs?

Almost always Frequently Occasionally Almost Never

24. Can you carry on a conversation with someone in a busy street?

Almost always Frequently Occasionally Almost Never

25. Can you distinguish intonation and inflections in people's voices?

Almost always Frequently Occasionally Almost Never

26. Do you hear from which direction a car horn is coming?

Almost always Frequently Occasionally Almost Never

27. Do you hear birds singing outside?

Almost always Frequently Occasionally Almost Never

28. Can you recognise and distinguish between different musical instruments by their sound?

Almost always Frequently Occasionally Almost Never

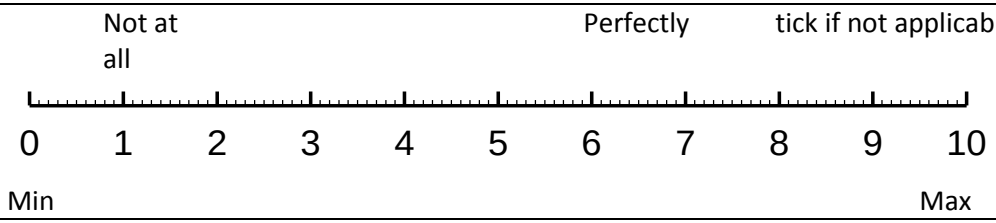
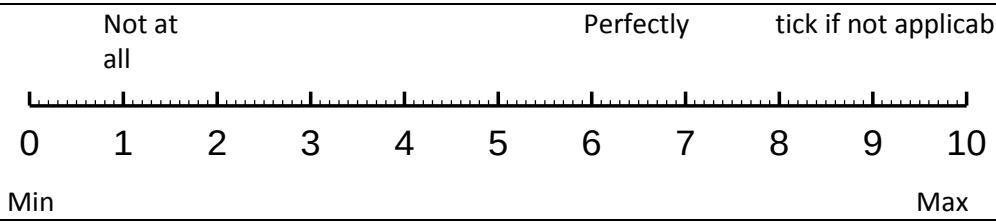
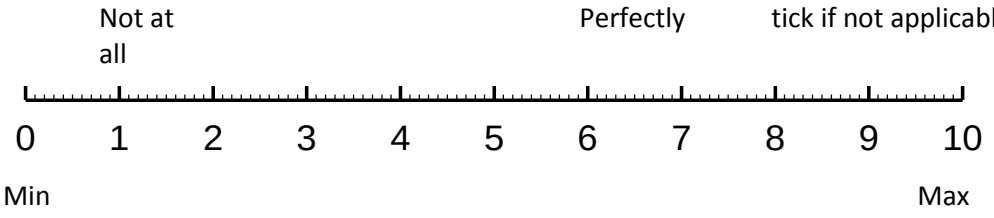
APPENDIX 2

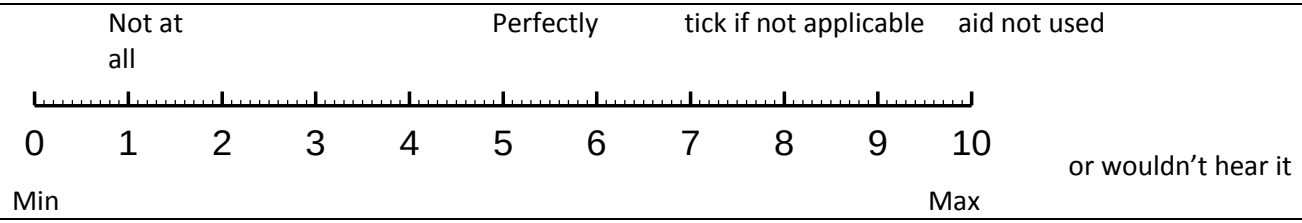
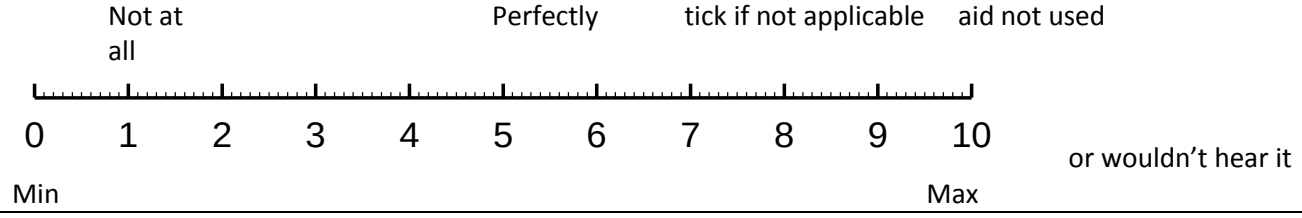
S[peech] S[patial] Q[ualities] version 3.1.2 I. Speech hearing rating scale

NAME _____ CONDITION _____ DATE _____

1. You are talking with one other person and there is a TV on in the same room. Without turning the TV down, can you follow what the person you're talking to says?	Not at all … Perfectly … tick if not applicable 0 1 2 3 4 5 6 7 8 9 10 Min … Max	aid not used or wouldn't hear it
2. You are talking with one other person in a quiet, carpeted lounge-room. Can you follow what the other person says?	Not at all … Perfectly … tick if not applicable 0 1 2 3 4 5 6 7 8 9 10 Min … Max	aid not used or wouldn't hear it
3. You are in a group of about five people, sitting round a table. It is an otherwise quiet place. You can see everyone else in the group. Can you follow the conversation?	Not at all … Perfectly … tick if not applicable 0 1 2 3 4 5 6 7 8 9 10 Min … Max	aid not used or wouldn't hear it
4. You are in a group of about five people in a busy restaurant. You can see everyone else in the group. Can you follow the conversation?	Not at all … Perfectly … tick if not applicable 0 1 2 3 4 5 6 7 8 9 10 Min … Max	aid not used or wouldn't hear it

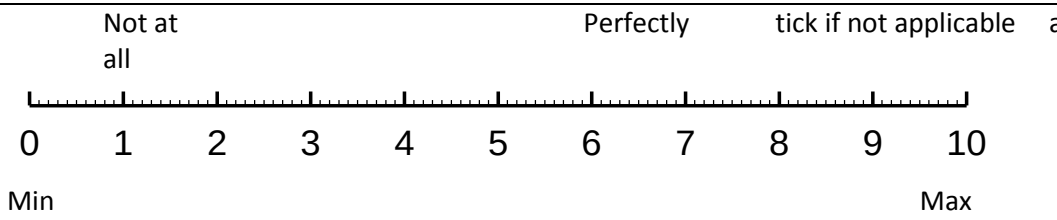
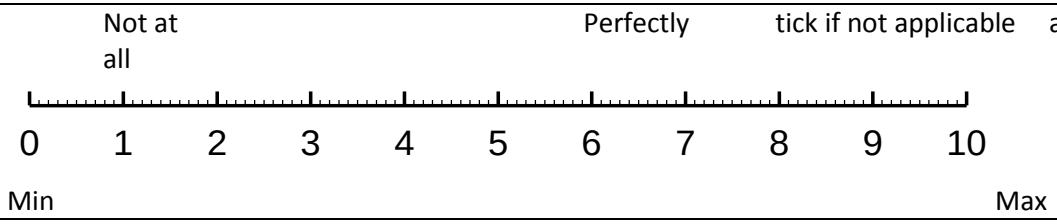
5. You are talking with one other person. There is continuous background noise, such as a fan or running water. Can you follow what the person says?	Not at all						Perfectly		tick if not applicable	aid not used			
	0	1	2	3	4	5	6	7	8	9	10		or wouldn't hear it
	Min										Max		
6. You are in a group of about five people in a busy restaurant. You <u>cannot</u> see everyone else in the group. Can you follow the conversation?	Not at all						Perfectly		tick if not applicable	aid not used			
	0	1	2	3	4	5	6	7	8	9	10		or wouldn't hear it
	Min										Max		
7. You are talking to someone in a place where there are a lot of echoes, such as a church or railway terminus building. Can you follow what the other person says?	Not at all						Perfectly		tick if not applicable	aid not used			
	0	1	2	3	4	5	6	7	8	9	10		or wouldn't hear it
	Min										Max		
8. Can you have a conversation with someone when another person is speaking whose voice is the same pitch as the person you're talking to?	Not at all						Perfectly		tick if not applicable	aid not used			
	0	1	2	3	4	5	6	7	8	9	10		or wouldn't hear it
	Min										Max		
9. Can you have a conversation with someone when another person is speaking whose voice is different in pitch from the person you're talking to?	Not at all						Perfectly		tick if not applicable	aid not used			
	0	1	2	3	4	5	6	7	8	9	10		or wouldn't hear it
	Min										Max		

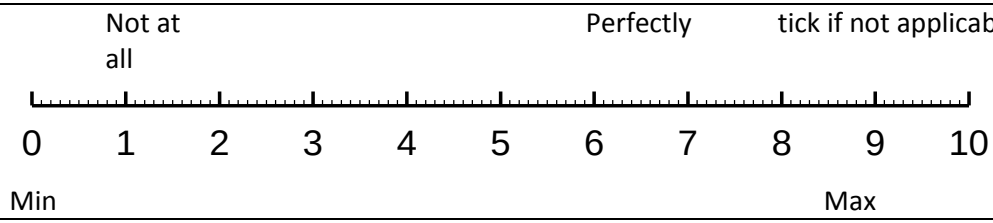
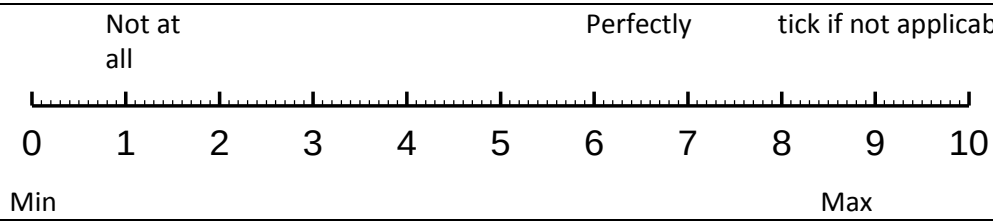
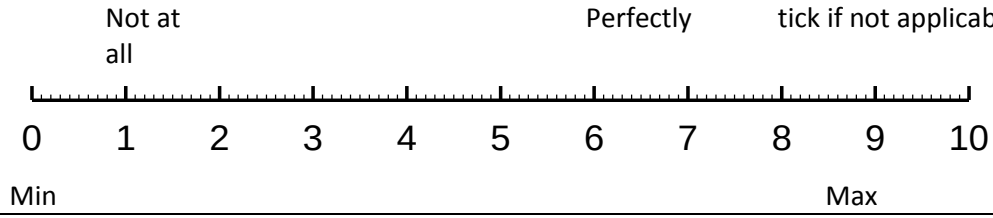
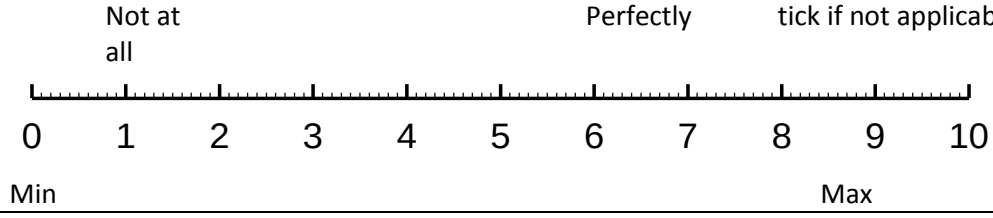
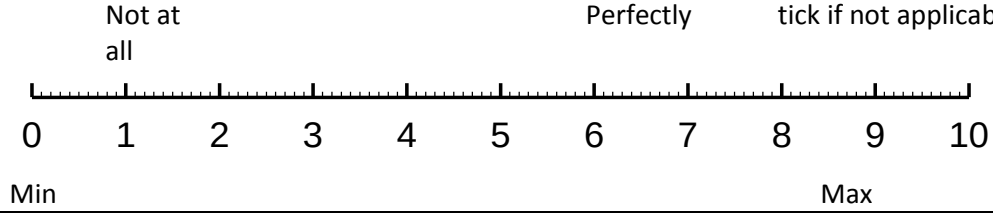
10. You are listening to someone talking to you, while at the same time trying to follow the news on TV. Can you follow what both people are saying?		tick if not applicable aid not used or wouldn't hear it
11. You are in conversation with one person in a room where there are many other people talking. Can you follow what the person you are talking to is saying?		tick if not applicable aid not used or wouldn't hear it
12. You are with a group and the conversation switches from one person to another. Can you easily follow the conversation without missing the start of what each new speaker is saying?		tick if not applicable aid not used or wouldn't hear it

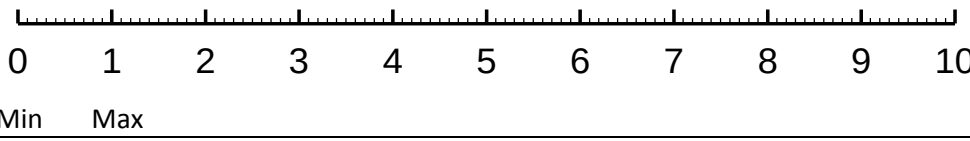
13. Can you easily have a conversation on the telephone? **[using one, none, or both aids?]**	
14. You are listening to someone on the telephone and someone next to you starts talking. Can you follow what's being said by both speakers?	

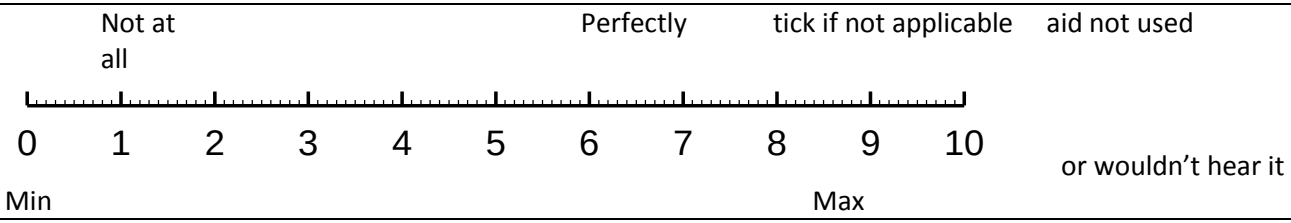
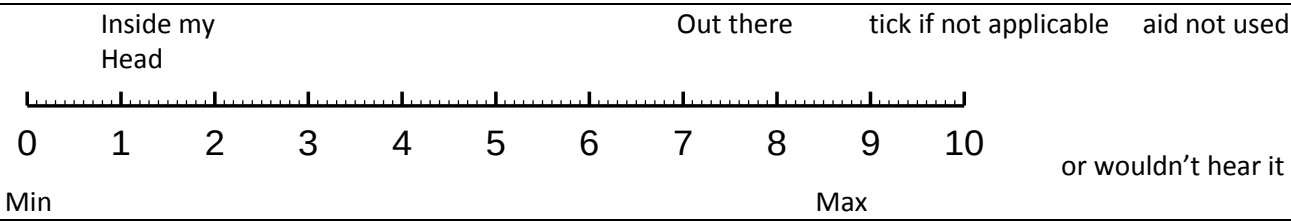
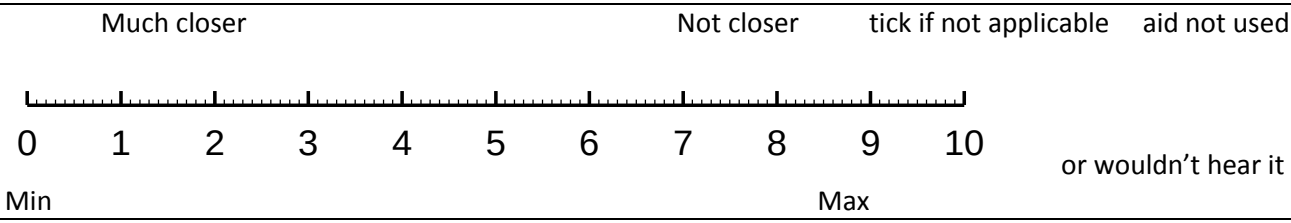
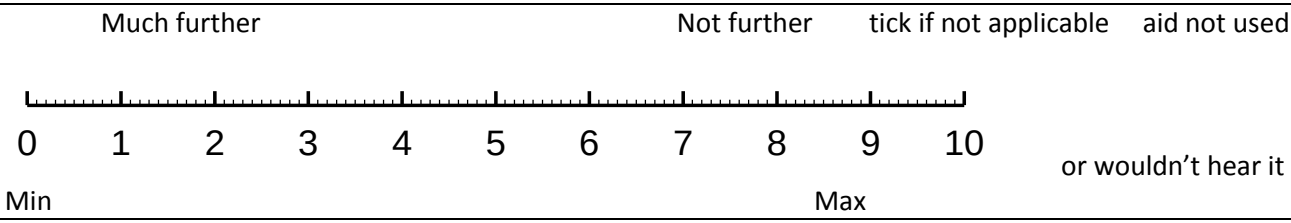
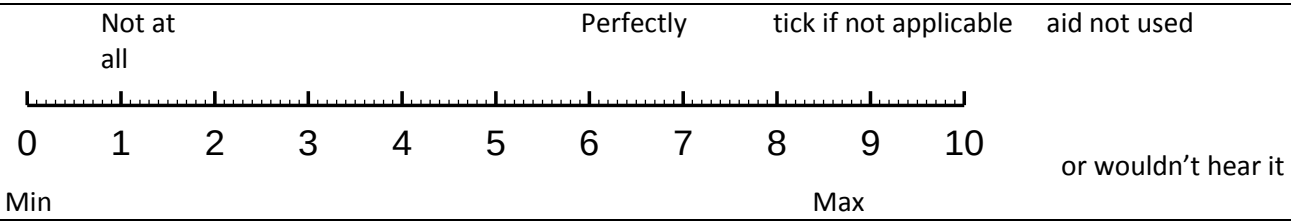
SSQ3.1 II. Spatial Rating Scale

You are outdoors in an unfamiliar place. You hear someone using a lawnmower. You can't see where they are. Can you tell right away where the sound is coming from?	Not at all	Perfectly	tick if not applicable
	0 1 2 3 4 5 6 7 8 9 10		
	Min	Max	
			aid not used
			or wouldn't hear it
You are sitting around a table or at a meeting with several people. You can't see everyone. Can you tell where any person is as soon as they start speaking?	Not at all	Perfectly	tick if not applicable
	0 1 2 3 4 5 6 7 8 9 10		
	Min	Max	
			aid not used
			or wouldn't hear it
You are sitting in between two people. One of them starts to speak. Can you tell right away whether it is the person on your left or your right, without having to look?	Not at all	Perfectly	tick if not applicable
	0 1 2 3 4 5 6 7 8 9 10		
	Min	Max	
			aid not used
			or wouldn't hear it
You are in an unfamiliar house. It is quiet. You hear a door slam. Can you tell right away where that sound came from?	Not at all	Perfectly	tick if not applicable
	0 1 2 3 4 5 6 7 8 9 10		
	Min	Max	
			aid not used
			or wouldn't hear it

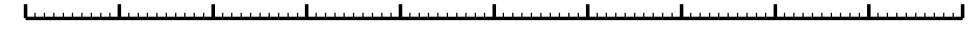
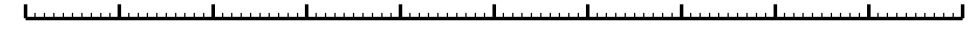
You are in the stairwell of a building with floors above and below you. You can hear sounds from another floor. Can you readily tell where the sound is coming from?		aid not used or wouldn't hear it
You are outside. A dog barks loudly. Can you tell immediately where it is, without having to look?		aid not used or wouldn't hear it

You are standing on the footpath of a busy street. Can you hear right away which direction a bus or truck is coming from before you see it?		aid not used or wouldn't hear it
In the street, can you tell how far away someone is, from the sound of their voice or footsteps?		aid not used or wouldn't hear it
Can tell how far away a bus or a truck is, from the sound?		aid not used or wouldn't hear it
Can you tell from the sound which direction a bus or truck is moving, for example, from your left to your right or right to left?		aid not used or wouldn't hear it
Can you tell from the sound of their voice or footsteps which direction a person is moving, for example, from your left to your right or right to left?		aid not used or wouldn't hear it

Can you tell from their voice or footsteps whether the person is coming towards you or going away?	Not at all  	tick if not applicable aid not used or wouldn't hear it

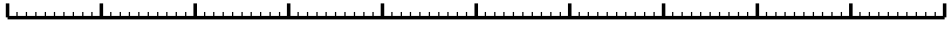
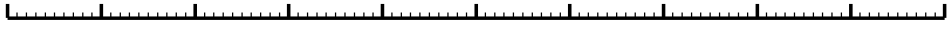
Can you tell from the sound whether a bus or truck is coming towards you or going away?	
Do the sounds of things you are able to hear seem to be inside your head rather than out there in the world?	
Do the sounds of people or things you hear, but cannot see at first, turn out to be closer than expected when you do see them?	
Do the sounds of people or things you hear, but cannot see at first, turn out to be further away than expected when you do see them?	
Do you have the impression of sounds being exactly where you would expect them to be?	

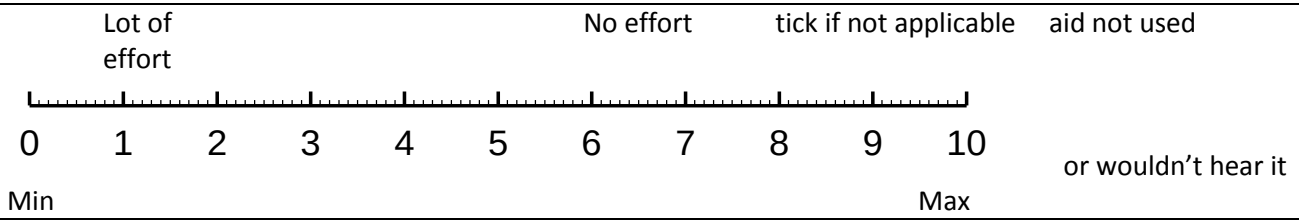
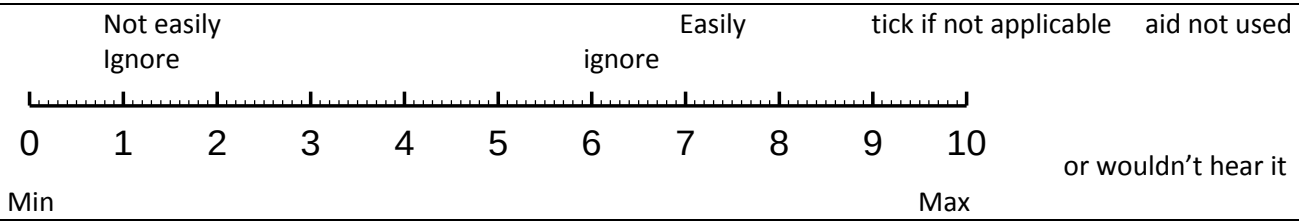
SSQ3.1 III Sound Qualities Rating Scale

1. Think of when you hear two things at once, for example, water running into a basin[a power-tool being used][a plane flying past] and, at the same time, a radio playing[the sound of hammering][a truck driving past]. Do you have the impression of these as sounding separate from each other?	Not at all — Perfectly — tick if not applicable — aid not used  0 1 2 3 4 5 6 7 8 9 10 Min — Max or wouldn't hear it
When you hear more than one sound at a time, do you have the impression that it seems like a single jumbled sound? * *If you have this experience, can you give examples of the sounds in question?	Jumbled — Not jumbled — tick if not applicable — aid not used  0 1 2 3 4 5 6 7 8 9 10 Min — Max or wouldn't hear it
3. You are in a room and there is music on the radio. Someone else in the room is talking. Can you hear the voice as something separate from the music?	Not at all — Perfectly — tick if not applicable — aid not used  0 1 2 3 4 5 6 7 8 9 10 Min — Max or wouldn't hear it

4. Do you find it easy to recognise different people you know by the sound of each one's voice?	Not at all — Perfectly — tick if not applicable 0 1 2 3 4 5 6 7 8 9 10 Min — Max	aid not used or wouldn't hear it
5. Do you find it easy to distinguish different pieces of music that you are familiar with?	Not at all — Perfectly — tick if not applicable 0 1 2 3 4 5 6 7 8 9 10 Min — Max	aid not used or wouldn't hear it
6. Can you tell the difference between different sounds, for example, a car versus a bus; water boiling in a pot versus food cooking in a frying pan?	Not at all — Perfectly — tick if not applicable 0 1 2 3 4 5 6 7 8 9 10 Min — Max	aid not used or wouldn't hear it
7. When you listen to music, can you make out which instruments are playing?	Not at all — Perfectly — tick if not applicable 0 1 2 3 4 5 6 7 8 9 10 Min — Max	aid not used or wouldn't hear it
8. When you listen to music, does it sound clear and natural?	Not at all — Perfectly — tick if not applicable 0 1 2 3 4 5 6 7 8 9 10 Min — Max	aid not used or wouldn't hear it

9. Do everyday sounds that you can hear easily seem clear to you (not blurred)?	Not at all — Perfectly — tick if not applicable — aid not used 0 1 2 3 4 5 6 7 8 9 10 Min — Max or wouldn't hear it
10. Do other people's voices sound clear and natural?	Not at all — Perfectly — tick if not applicable — aid not used 0 1 2 3 4 5 6 7 8 9 10 Min — Max or wouldn't hear it
11. Do everyday sounds that you hear seem to have an artificial or unnatural quality?	Unnatural — Natural — tick if not applicable — aid not used 0 1 2 3 4 5 6 7 8 9 10 Min — Max or wouldn't hear it
12. Does your own voice sound natural to you?	Not at all — Perfectly — tick if not applicable — aid not used 0 1 2 3 4 5 6 7 8 9 10 Min — Max or wouldn't hear it
13. Can you easily judge another person's mood from the sound of their voice?	Not at all — Perfectly — tick if not applicable — aid not used 0 1 2 3 4 5 6 7 8 9 10 Min — Max or wouldn't hear it

14. Do you have to concentrate very much when listening to someone or something?	Concentrate Hard — Not need to concentrate — tick if not applicable — aid not used  0 1 2 3 4 5 6 7 8 9 10 — or wouldn't hear it Min — Max
15. **[for long-term BL only]** If you turn one hearing aid/implant off, and do not adjust the other, does everything sound unnaturally quiet?	Too quiet — Not too quiet — tick if not applicable — aid not used  0 1 2 3 4 5 6 7 8 9 10 — or wouldn't hear it Min — Max
16. When you are the driver in a car can you easily hear what someone is saying who is sitting alongside you? **[use one aid, which one, why?]**	Not at all — Perfectly — tick if not applicable — aid not used  0 1 2 3 4 5 6 7 8 9 10 — or wouldn't hear it Min — Max
17. When you are a passenger can you easily hear what the driver is saying sitting alongside you? **[use one aid, which one, why?]**	Not at all — Perfectly — tick if not applicable — aid not used  0 1 2 3 4 5 6 7 8 9 10 — or wouldn't hear it Min — Max

18. Do you have to put in a lot of effort to hear what is being said in conversation with others?	
19. Can you easily ignore other sounds when trying to listen to something?	
20. **[long-term BL]**What are the quietest sounds that you are aware you do not hear [UNL vs BL]?	
21. Are there contexts where you definitely prefer <u>not</u> to use/to use only one hearing aid/implant?	
22. Are there contexts where you definitely prefer to use a/two hearing aid/s/implant/s?	

APPENDIX 3

Hyperacusis Questionnaire

Surname, first name: Sex: Male/Female
Age:
Profession or studies:
Place (town or area) of residence:
Telephone:
Are you or have you been exposed to noise?
Do you tolerate noise less well as compared to a few years ago?
Have you ever had hearing problems? If so, of what kind?
In the following questionnaire, put a cross in the box corresponding to the answer which best applies to you:

	No	Yes, a little	Yes, quite a lot	Yes, a lot
1 Do you ever use earplugs or earmuffs to reduce your noise perception (Do not consider the use of hearing protection during abnormally high noise exposure situations)?	☐	☐	☐	☐
2Do you find it harder to ignore sounds around you in everyday situations?	☐	☐	☐	☐
3 Do you have trouble reading in a noisy or loud environment?	☐	☐	☐	☐
4 Do you have trouble concentrating in noisy surroundings?	☐	☐	☐	☐
5 Do you have difficulty listening to conversations in noisy places?	☐	☐	☐	☐
6 Has anyone you know ever told you that you tolerate noise or certain kinds of sound badly?	☐	☐	☐	☐
7 Are you particularly sensitive to or bothered by street noise?	☐	☐	☐	☐
8 Do you find the noise unpleasant in certain social situations (e.g. night clubs, pubs or bars, concerts, firework displays, cocktail receptions)?	☐	☐	☐	☐
9 When someone suggests doing something (going out, to the cinema, to a concert, etc.), do you immediately think about the noise you are going to have to put up with?	☐	☐	☐	☐
10 Do you ever turn down an invitation or not go out because of the noise you would have to face?	☐	☐	☐	☐
11 Do noises or particular sounds bother you more in a quiet place than in a slightly noisy room?	☐	☐	☐	☐
12Do stress and tiredness reduce your ability to concentrate in noise?	☐	☐	☐	☐
13 Are you less able to concentrate in noise towards the end of the day?	☐	☐	☐	☐
14 Do noise and certain sounds cause you stress	☐	☐	☐	☐

List of Presentations and Publications

Spyridakou, C, Luxon, LM, Bamiou DE 2010 ‘Is there a correlation between auditory tests and a complaint of hearing difficulties in adults? British Association Audiological Physicians annual conference, Birmingham, March 26-27 2010 (Platform presentation)

Spyridakou, C , Luxon, LM, Bamiou, DE Correlation of reported hearing difficulties / hyperacusis and auditory tests (speech in babble and transient evoked otoacoustic emissions by contralateral noise) in adults with normal hearing. Audiology Now, American Academy of Audiology, Boston, March 28-31 2012 (Poster presentation)

Spyridakou, C, Luxon, LM, Bamiou, DE , 2012. Patient reported speech in noise difficulties and hyperacusis symptoms and correlation with test results. Laryngoscope. 122 (7):1609-14. (Publication)