

University College London
Faculty of Brain Sciences
Ear Institute

**Hearing Evaluation and
Auditory Rehabilitation
after Stroke (HEARS)**

A Thesis Presented for the Degree of
Doctor of Philosophy

By

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Declaration

I, Nehzat Koohi, confirm that the work presented in this thesis is my own. Where information has been derived from other sources, or conducted in collaboration with other researchers, I confirm that this has been indicated. All participating subjects gave informed consent and all work was carried out with the approval of Queen Square Research Ethics Committee, according to guidelines established by the Declaration of Helsinki.

The work was done under the guidance of Dr Doris-Eva Bamiou at the Neuro-otology department NHNN and the UCL Ear Institute, and Dr David Werring, at the Institute of Neurology.

Signature:

Date:

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Abstract

Stroke can affect all levels of the auditory system (from the inner ear to the central tracts), and may result in various types of auditory dysfunctions, such as peripheral hearing loss (cochlea to auditory nerve), disordered auditory processing (brainstem to cortex), and cortical deafness. Hearing-impaired stroke survivors have an increased risk of physical decline after discharge to the community. This may be attributed to restricted participation in post-acute rehabilitation programs due to the hearing impairment. Furthermore, hearing impairment may have a significant impact on listening, linguistic skills and the overall communication of the affected stroke patient. To date, no studies have sought to systematically characterise the auditory function of stroke patients in detail in order to establish the different types of hearing impairments in this cohort of patients. Such information would be clinically useful for understanding and addressing the hearing needs of stroke survivors so that appropriate management could be given to these patients in order to improve their quality of life. One of the main aims of this research was to characterise and classify the hearing impairments of stroke patients using a detailed audiological assessment test battery in order to determine the level of clinical need and inform appropriate rehabilitation for this patient population. We found that the most common type of hearing impairment in stroke subjects was the combination type, ‘peripheral hearing loss and central auditory processing disorders’, in the older subgroup (in 55%), and auditory processing deficits in the younger subgroup (in 40%). Both types of impairment were significantly higher in these groups than in controls.

Offering a comprehensive audiological assessment to all stroke patients would be a costly and time-consuming process. Therefore, a preliminary screening program for such patients needs to be identified, e.g. by means of a questionnaire, so that the full audiological assessment could be reserved for those who fail the initial screening. We aimed to determine whether a handheld hearing screener together with two validated hearing questionnaires could be used as a hearing screening tool to facilitate early identification and appropriate referral of hearing impaired stroke patients in the subacute stage. The highest test accuracy was achieved when results of the handheld hearing screener and hearing questionnaires were combined.

Auditory disability due to impaired auditory processing (AP), despite normal pure-tone thresholds, is common after stroke. However, there are currently no proven remedial interventions for AP deficits in stroke patients. Our study is first to investigate the benefits of personal frequency-modulated (FM) systems in stroke patients with disordered AP. Our results demonstrated that FM systems may substantially improve speech-in-noise deficits in stroke patients who are not eligible for conventional hearing aids.

We also evaluated the long term benefits for speech reception in noise, after daily ten-week use of personal FMs, in non-aphasic stroke patients with auditory processing deficits. We found that ten weeks of using FM systems by adult stroke patients may lead to benefits in unaided speech in noise perception. Our findings may indicate auditory plasticity type changes.

Publications and Presentations Resulting from this Work

Published journal articles

1. Research article: **Koohi** N, Vickers D, Chandrashekar H, Werring D, Bamiou DE. Hearing Characteristics of Stroke Patients: Prevalence and Characteristics of Hearing Impairment and Auditory Processing Disorders in Stroke Patients, *Journal of the American Academy of Audiology*, 2016 (in press)
2. Research article: **Koohi** N, Vickers D, Chandrashekar H, Tsang B, Werring D, Bamiou DE. Auditory rehabilitation after stroke: treatment of auditory processing disorders in stroke patients with personal frequency-modulated (FM) systems. *Disabil Rehabil.* 2016; 1-8.
3. Review article: **Koohi** N. Hearing Loss in Stroke, *Pathways: Neuroaudiology and Central Auditory Processing Disorders* June 4, 2014.

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Poster presentations

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2. Are Personal FM systems of benefit for stroke patients? *American Academy of Audiology*, Orlando, Florida USA, March 2014.
3. Hearing Evaluation and Auditory Rehabilitation after Stroke. *Neuro-rehabilitation meeting at National Hospital for Neurology and Neurosurgery*, December 2013.
4. Hearing screening in stroke patients, *British Society of Audiology*, Keele University, September 2013.

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2. Remediation of Auditory Processing Disorders in Stroke, *University of Connecticut*, April 2014.
3. Auditory processing in stroke and FM systems, *Calmen training day*, London, September 2014.
4. Hearing Evaluation and Auditory Rehabilitation after stroke, *University of Connecticut*, USA, April 2014.
5. Auditory processing remediation in stroke patients, *Annual conference of British Society of Audiology*, Keele University 2013.

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Abbreviations

ABR	Auditory brainstem responses
AIAD	Amsterdam inventory for auditory disability
AICA	Anterior inferior cerebellar artery
AN	Auditory nerve
AP	Auditory processing
APD	Auditory processing disorder
ASHA	American speech and hearing association
BM	Basilar membrane
BSA	British Society of Audiology
CANS	Central auditory nervous system
CAPD	Central auditory processing disorders
CI	Confidence interval
CN	Cochlear nucleus
FM	Frequency modulated
fMRI	Functional magnetic resonance Imaging
GIN	Gaps in noise
HG	Heschl's gyrus
HHIE	Hearing handicap inventory for elderly
IAA	Internal auditory artery
IC	Inferior colliculus
ICH	Intracranial haemorrhage
LL	Lateral lemniscus
MCA	Middle cerebellar artery
MGB	Medial geniculate body
MRI	Magnetic resonance Imaging
PCI	Posterior circulation infarct
PICA	Posterior inferior cerebellar artery
PP	Planum polare
PT	Planum temporale
PTA	Pure-tone audiometry
QoL	Quality of life
REA	Right ear advantage
SCA	Superior cerebellar artery
SIB	Speech in babble
SIN	Speech in noise
SNHL	Sensorineural hearing loss
SNR	Signal-to-noise ratio
SOC	Superior olivary complex
SRT	Stapedial reflex thresholds
TEOAE	Transient evoked otoacoustic emissions
TYMP	Tympanometry

1 Chapter 1: Introduction

1.1 Overview

Stroke is the commonest neurological conditions and is a disorder that may affect auditory brain areas (Musiek et al., 2005; Bamiou et al., 2006). The majority of stroke survivors need rehabilitation (MacDonald et al., 2000), requiring them to be adequately informed of the nature, prognosis, and proposed treatment of their illness. Hearing plays an important role in effective communication between patients and healthcare professionals (Bensing, 2000), so auditory impairment might restrict participation in rehabilitation programs, leading to a lower level of physical performance (Landi et al., 2006). Nevertheless, hearing loss is a largely neglected aspect of post-stroke management, possibly due to the potentially ‘invisible’ nature of this impairment compared to more obvious symptoms (e.g. dysphasia or motor loss).

Sensorineural hearing loss (SNHL) may be highly prevalent in stroke survivors (Edwards et al., 2006; Formby et al., 1987; O’Halloran et al., 2009). This may be due to pathology of the inner ear (Lee, 2012), auditory nerve, or cochlear nuclei, i.e. the part of the central auditory pathway before the crossing of the auditory fibres at the superior olivary complex brainstem level (Luxon, 1980). SNHL is distinctly different from ‘central deafness’, i.e. the rare and dramatic occurrence of ‘deafness’ with an additional attentional impairment component that is attributed to bilateral cortical damage in the presence of relatively preserved cochlear and neural function (Griffiths, 2010). Since the majority of stroke sufferers are usually over the age of 60, the observed association between hearing loss and stroke could be attributed to age-related changes of the inner ear or auditory nerve (Jacquin et al., 2012), while risk factors for stroke such as cigarette smoking, atherosclerosis, and others have also been associated with a more insidious onset of hearing impairment with advancing age (Yamasoba et al., 2013). Alternatively, this association could be due to the hearing pathways (see Figure 1-1) being directly affected by the stroke (Lee et al., 2009). Furthermore, if the stroke involves the central auditory pathway in the brain, patients may suffer from additional auditory processing deficits that are not reflected in tests of hearing thresholds (Bamiou et al., 2006; Bamiou et al., 2012).

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In order to inform the taxonomy for types of hearing loss used in this review, a brief overview of the auditory pathway anatomy and vascular supply will be presented before the main literature review.

1.2 Stages of Ascending Auditory Pathway

1.2.1 The Peripheral Auditory System

Hearing requires not only the ability to detect sounds in the ear, but also involves the complex processing of auditory signals encoded in the form of neural activity in the brain to derive meaningful information. The peripheral auditory system, including the eardrum, middle ear and the cochlea, enables the transformation of sound waves into neural signals for subsequent cerebral processing. Sound waves are initially detected as mechanical vibrations on the tympanic membrane. After undergoing mechanical processing in the middle ear, the vibrations are then passed to the basilar membrane (BM) in the cochlea, which as a result of its physical structure, responds differently to different sounds (Yost, 2000). Specifically, the location of maximal vibration along the length of the BM varies with sound frequency, with the high frequencies being mapped in the basal turn and the low frequencies being located in the apex. This spatiotopic encoding of sound frequency is fed forwards by hair cells, which transduce the mechanical vibrations of the BM into neural signals and pass them onto the nerve fibres of the auditory nerve [AN] (Gelfand, 1998).

Peripheral hearing loss occurs following damage to the peripheral auditory system (middle ear, cochlea and/or distal portion of the auditory nerve). It causes a complete or partial inability to detect and/or perceive sounds. In audiometry, it shows as increased sound detection thresholds.

1.2.2 The Central Auditory System

The subcortical auditory system consists of various nuclei that link the auditory nerve with the cerebral cortex, where the first and most basic central processing of sound signals is performed. The pathways flow through the brainstem, midbrain, and thalamus. The first relay station is the cochlear nuclei (CN), which along with several

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other important nuclei such as superior olivary complex (SOC) and lateral lemniscus (LL), are located in the brainstem. The pathway then diverges into the inferior colliculus (IC) in the midbrain and flows through the medial geniculate body (MGB) in the thalamus, which is the last relay station in the subcortical auditory system that connects the brainstem and the auditory cortex (Gelfand, 1998). The outputs of subcortical auditory processing are passed to dedicated auditory responsive regions in the cerebral cortex, including various areas of the temporal and inferior parietal lobes. Hearing loss (i.e. increased sound detection thresholds on pure-tone audiometry) could occur following damage to these areas of the auditory pathway, either unilaterally or bilaterally, depending on which nuclei are involved (Musiek, 2003).

For the purposes of this review, we use the terms ‘subcortical hearing loss’ to denote increased sound detection thresholds on pure-tone audiometry attributed to pathology in the subcortical auditory pathways (such as the brainstem nuclei) and ‘cortical hearing loss’ to denote increased sound detection thresholds on pure-tone audiometry with and without an attentional component that is attributed to pathology of the auditory cortices. Refer to Figure 1-1 for the schematic representation of the ascending ipsilateral and contralateral interactions in the auditory pathway.

1.2.3 Auditory Cortex

Neurons originating in the medial geniculate body (MGB) and radiating outward to the auditory areas of the brain create the ascending auditory system that proceeds from the thalamic area to the cerebral cortex. The auditory cortex plays a key role in auditory perception, although other areas of the human cerebral cortex (e.g., the frontal and parietal lobes) have also been implicated in processing sound information (Hackett et al., 2001).

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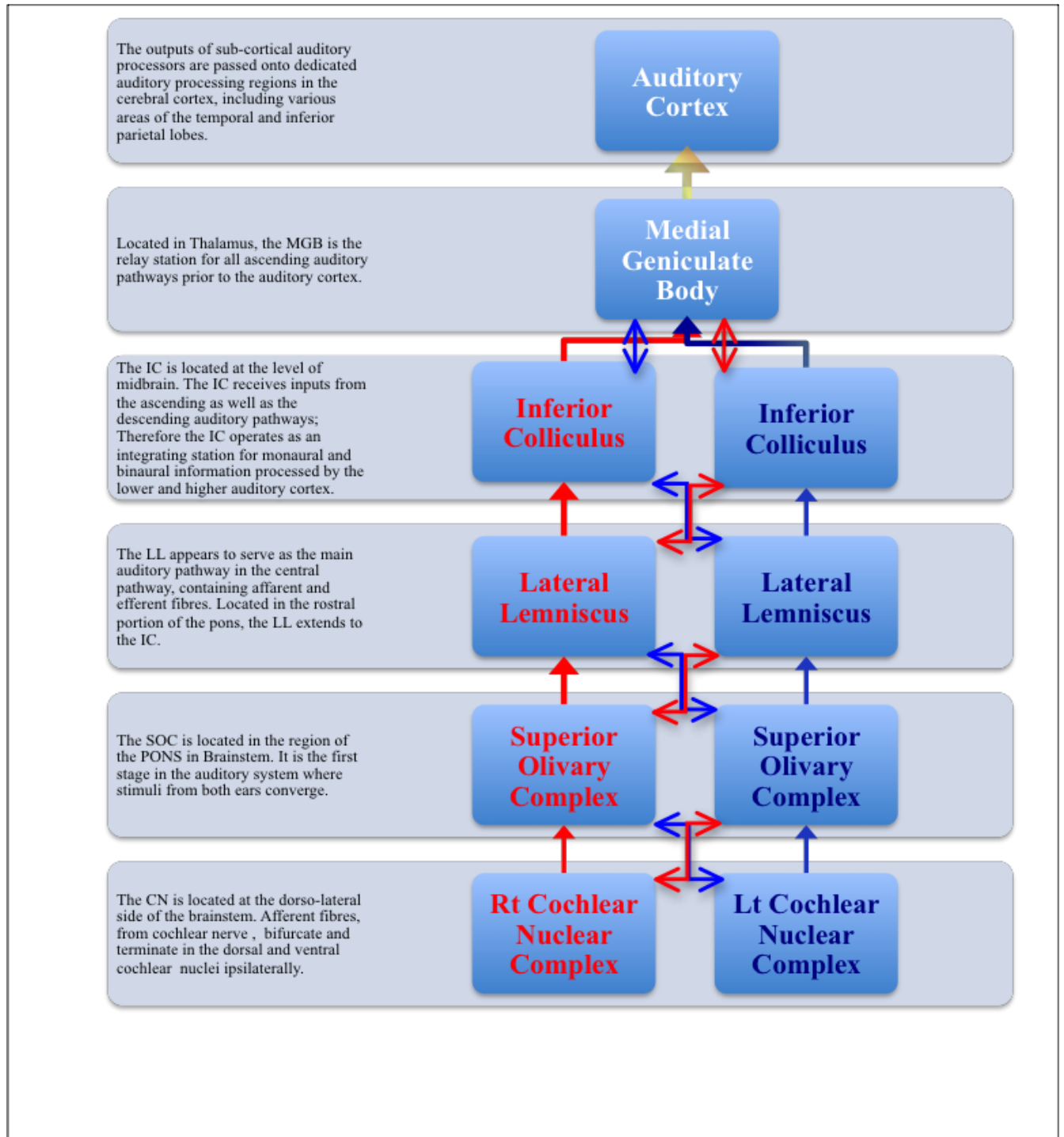


Figure 1-1: A schematic representation of the ascending ipsilateral and contralateral interactions in the auditory pathway. **KEY:** red line, right; blue line, left; IC, inferior colliculus; LL, lateral lemniscus; MGB, medial geniculate body; CN, cochlear nucleus complex; Rt, right; Lt, left.

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The auditory cortex is a highly organised processing unit, and the neural crux of hearing, language and music in human beings. It can be divided into three separate parts: the primary, secondary, and tertiary auditory cortices. These structures form concentrically around one another, with the primary cortex in the middle and the tertiary cortex on the outside. The primary cortex is responsible for basic pitch and volume perception, whilst the secondary cortex has been implicated in the processing of ‘harmonic, melodic, and rhythmic patterns’. The tertiary auditory cortex appears to integrate all aspects of sound perception to yield the overall music experience (Hackett et al., 2001).

The principal auditory area of the cortex is considered to be Heschl’s gyrus, which is located in the Sylvian fissure, approximately two-thirds posterior on the upper surface of the temporal lobe. The planum temporale (PT) is located on the cortical surface from the most posterior aspect of Heschl’s gyrus and continuing posteriorly to the end point of the Sylvian fissure. The insula (a portion of the cortex located deep within the Sylvian fissure) is yet another acoustically responsive area (Musiek, 2003).

The processing of sound involves activation of an extensive cortical network that is not confined only to the auditory cortex, but also to other acoustically responsive areas such as the adjacent temporal cortex, the inferior portion of the frontal and parietal lobes, as well as the limbic areas (Hall et al., 2003; Griffiths et al., 2004; Zatorre, 2007). The interconnection between the auditory cortex and limbic system (e.g., the amygdala and the hippocampus) through the corticolimbic projections plays a role in the perception of emotional speech and in the consolidation of auditory information to form new memories (LeDoux et al., 1983). Figure 1-2 shows a coronal view of the brain with the key auditory structures.

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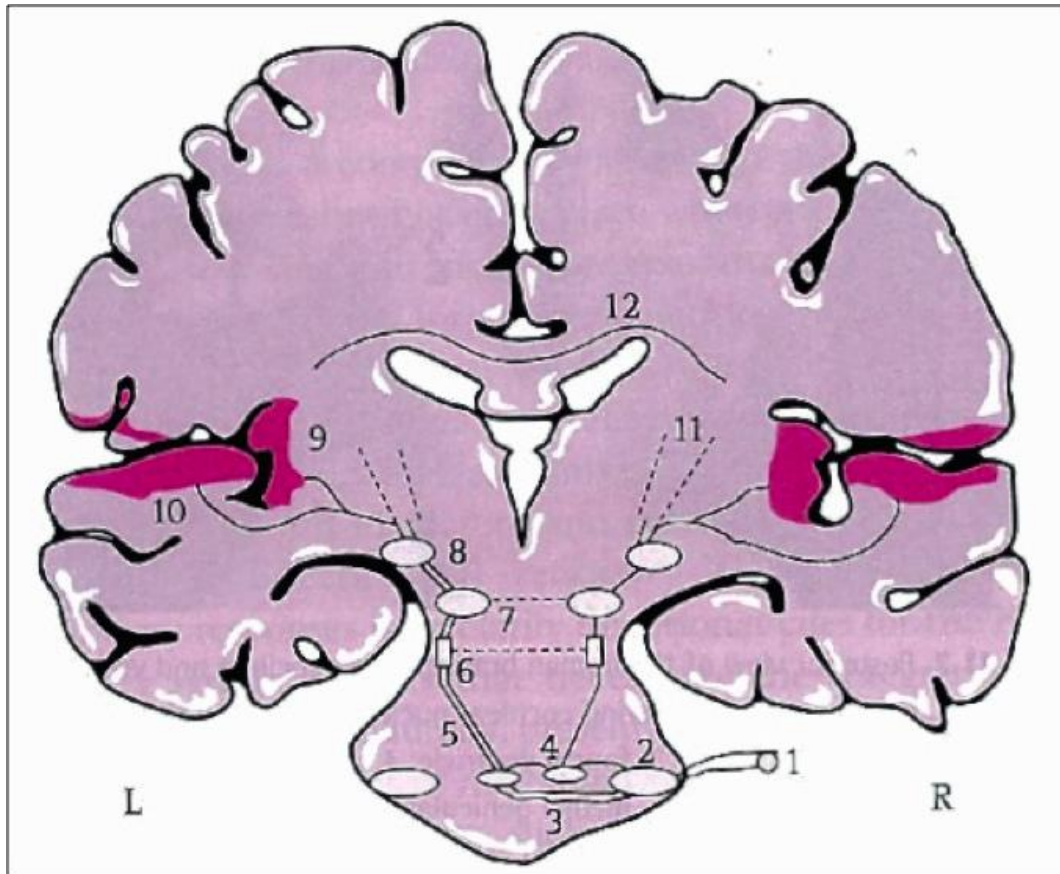


Figure 1-2: Coronal view of the brain with key auditory structures and areas defined. **KEY:** 1, Cochlear nerve; 2, cochlear nucleus; 3, stria (dorsal, intermediate, ventral); 4, superior olivary complex; 5, lateral lemniscus; 6, nuclei of lateral lemniscus; 7, inferior colliculus; 8, medial geniculate bodies; 9, insula (shaded); 10, primary auditory region in temporal and parietal lobes (shaded); 11, internal capsule; 12, corpus callosum; R, right; L, left. (Adapted from *Textbook of Audiological medicine* (p. 179), by Musiek, 2003, London: CRS Press.)

1.3 Bottom-up vs. Top-Down Auditory Processing

Selective attention is a core mechanism for perceptual and cognitive functioning (Chun et al., 2011). It has evolved out of a necessity to restrict limited processing capacity to information that is most relevant to ongoing goals and behaviours (Pashler et al., 2001). Selective attention requires both the ability to attend to relevant information and the ability to ignore irrelevant information. Top-down auditory processing serves selective attention by enhancing the cortical responses to relevant information and by suppressing cortical responses to irrelevant information in the sensory cortical regions (Gazzaley et al., 2005; Johnson & Zatorre, 2005). Auditory perception, or ‘awareness of acoustic information’, involves the complex integration

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of bottom-up sensory processes that are initiated in the cochlea, afferent and efferent neural processing in the auditory nervous system (ANS), and neural processes in diverse regions of the brain that have other specialised functions (e.g., attention, memory and vision). Functional magnetic resonance imaging studies have found that top-down and bottom-up mechanisms are sustained by partially overlapping brain networks: the top-down network would include the parietal and posterior frontal cortices, whereas the bottom-up networks would be composed of the temporo-parietal junction and the ventral frontal regions, which are mainly in the right hemisphere (reviewed in Corbetta and Shulman, 2002).

1.4 Vascular Anatomy of Peripheral and Central Auditory System

1.4.1 The Peripheral Auditory System; Functional and Vascular Anatomy of the Ear and Auditory Nerve

A continuous blood supply is a critical part of a normally functioning auditory system, and hence knowledge of vascular anatomy should not be ignored. There has been significant variability shown in the vasculature (Figure 1-3), and it can be quite complex (Waddington, 1984; Grand et al., 1997; Pai et al., 2007). However, knowledge of human anatomy can aid in understanding normal hearing function as well as clinical symptoms (Johnson & Christman, 1995).

The internal auditory artery (IAA), which usually arises from the anterior inferior cerebellar artery (AICA), supplies the inner ear. The internal auditory artery sometimes arises directly from the basilar artery, and in some cases, it is a branch of the posterior inferior cerebellar artery (PICA) (Figure 1-3). IAA divides into two main branches, the main cochlea artery and the vestibulocochlear artery. The main cochlea artery irrigates the apical three fourths of the cochlea. The cochlear ramus, which arises from the vestibulocochlear artery, feeds the basal one fourth. The internal auditory artery also supplies blood to the cochleovestibular nerve (Axelsson, 1968; Kim & Lee, 2009). Figure 1.4 shows the arterial circulation to the inner ear.

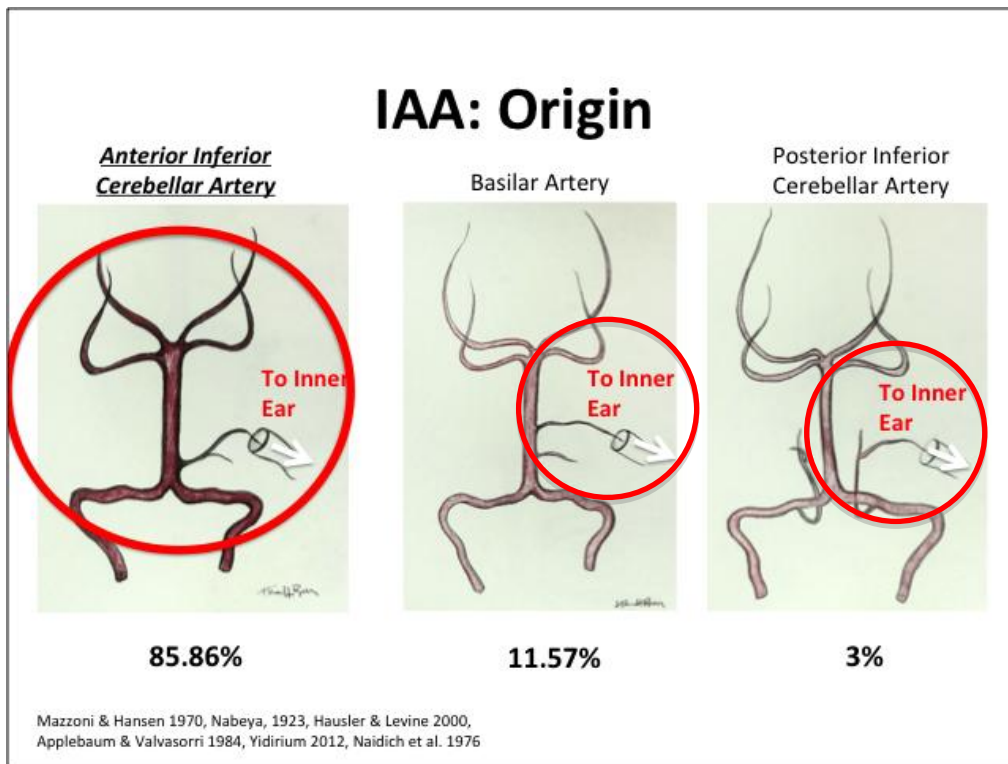


Figure 1-3: The origin of the internal auditory artery (IAA). The origin of IAA is varied but usually (in 86% of cases), the IAA arises from the anterior inferior cerebellar artery. It can also branch from the basilar artery (11.57% cases) and from the posterior inferior cerebellar artery (3% cases).

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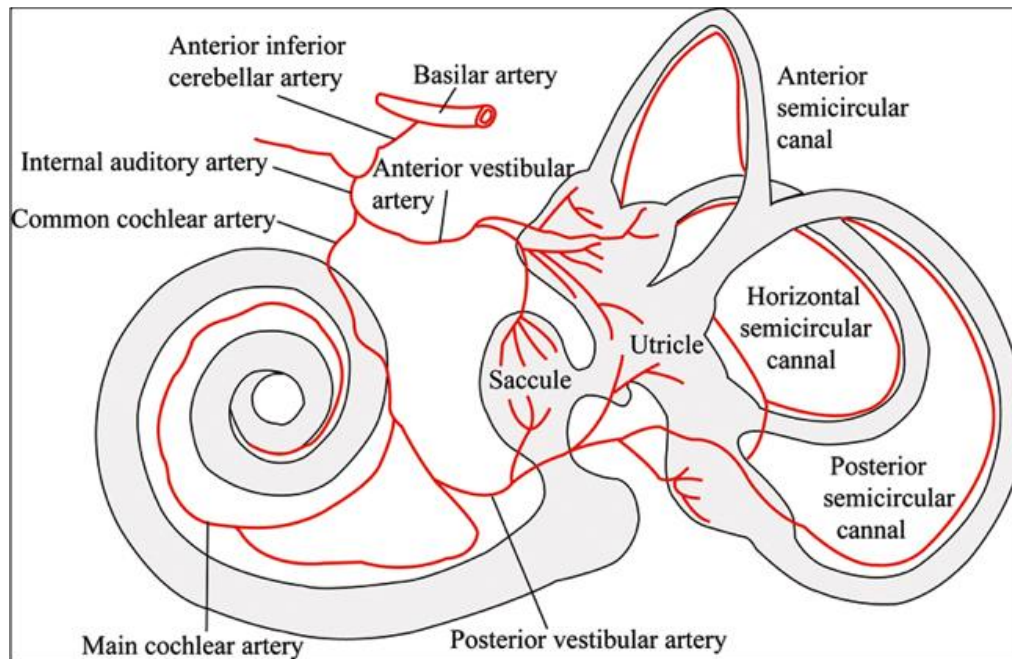


Figure 1-4: Arterial circulation to the inner ear. Reprinted from Inner Ear Dysfunction Due to Vertebrobasilar Ischemic Stroke (Kim & Lee, 2009).

1.4.2 The Central Auditory Pathway; Functional and Vascular Anatomy of the Brainstem, Medial Geniculate Body and Auditory Cortex

The main blood supplier of the brainstem is the basilar artery (Figure 1-5, p. 10). The AICA, a branch of the basilar artery, indirectly supplies the cochlear nerve (CN), cochlear nucleus, and superior olivary complex (SOC). The pontine arteries, which also originate from the basilar artery, supply the SOC and lateral lemniscus (LL) within the pons. The superior cerebellar artery supplies the LL and inferior colliculus (IC) within the upper pons/lower midbrain (Figure 1-6, p. 11), and the posterior cerebellar artery supplies the medial geniculate body (Musiek, 1983). The middle cerebral artery (MCA) is the main artery supplying the auditory cortex. The fronto-opercular vessel is a branch of the MCA that irrigates the anterior insular. The central sulcus artery supplies the posterior insula and anterior parietal lob. Heschl's gyrus, the supramarginal gyrus and the angular gyrus receive blood from the MCA and angular arteries (Waddington, 1984). Figure 1-7 (p. 12) shows the blood supply to the central auditory brainstem.

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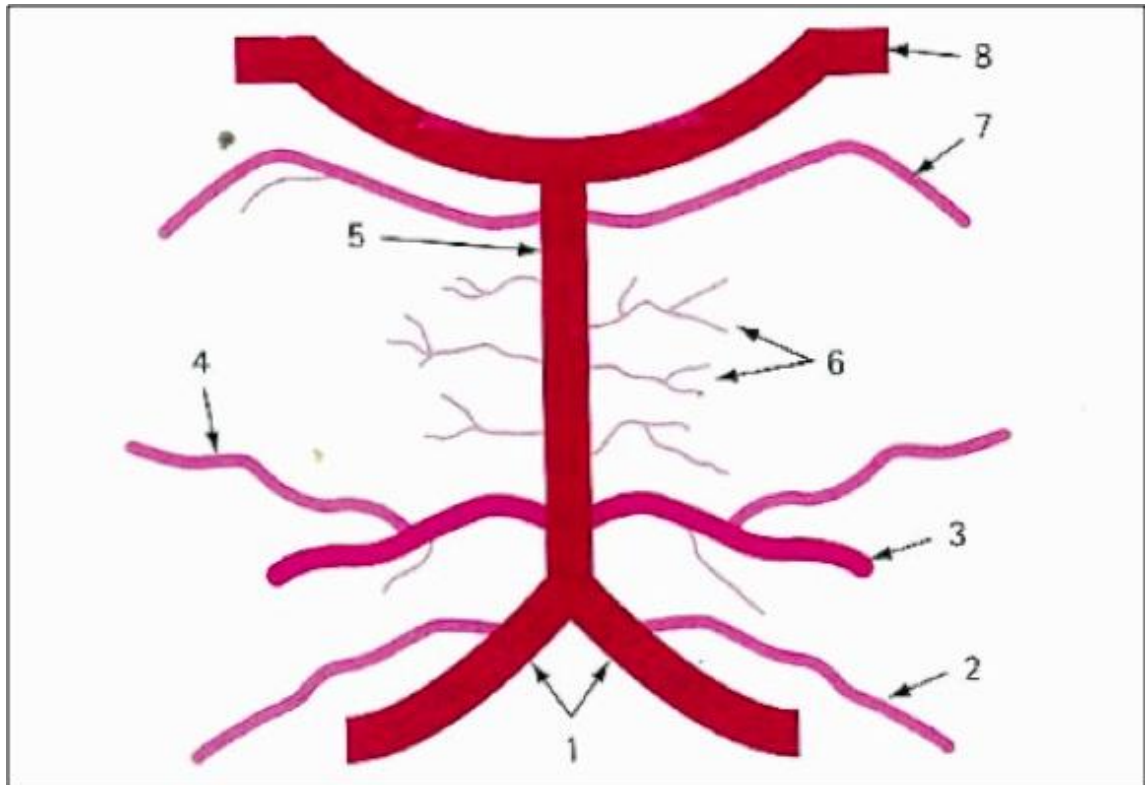


Figure 1-5: Key vessels of the rostral medulla and pons segment of the brainstem.
KEY: 1, Vertebral arteries; 2, posterior inferior cerebellar artery (PICA); 3, anterior inferior cerebellar artery (AICA); 4, internal auditory artery (IAA); 5, basilar artery; 6, pontine arteries; 7, superior cerebellar artery; 8, posterior cerebral artery. *Adapted from Audiological medicine (p. 183), by Musiek, 2003, London: CRS Press.*

Supply to Inferior Colliculus and Medial Geniculate Body

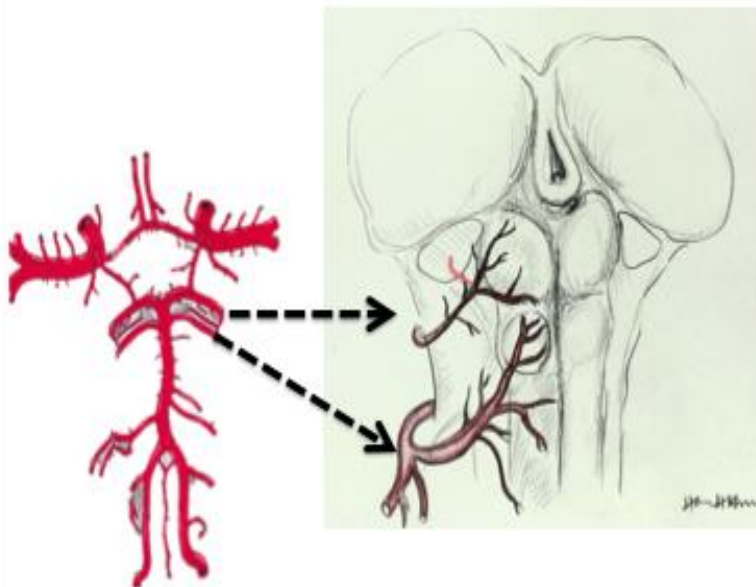


Figure 1-6: Blood supply to inferior colliculus and medial geniculate body. Adapted from a poster (Mallory Brown, American Academy of Audiology, Orlando 2014)

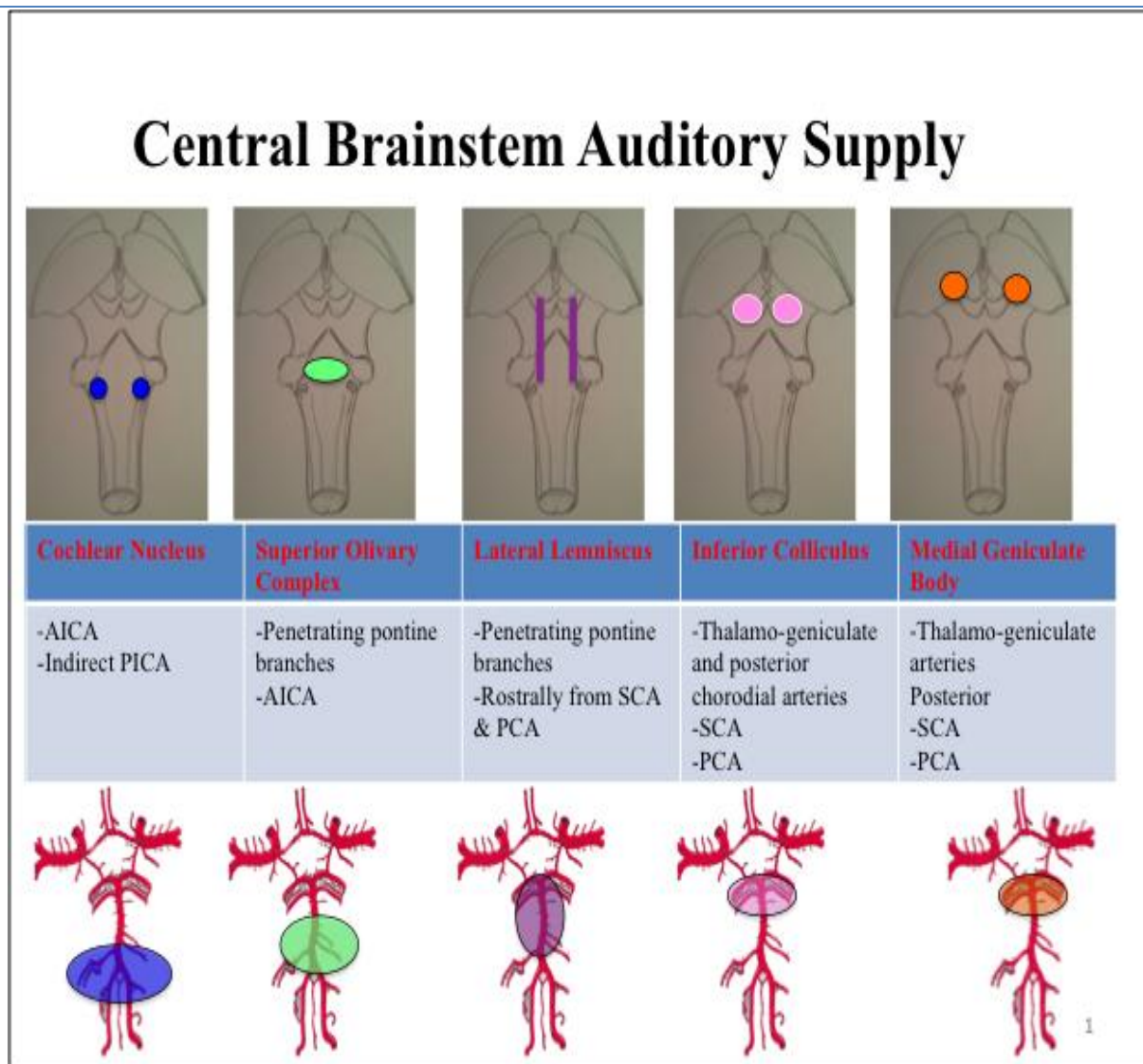


Figure 1-7: Blood supply to central auditory brainstem. KEY: AICA, anterior inferior cerebellar artery; PICA, posterior inferior cerebellar artery; PCA, posterior cerebellar artery; SCA, superior cerebellar artery. Adapted from a poster (Mallory Brown), American Academy of Audiology, Orlando 2014 (with permission)

1.5 Disorders of the Auditory System

Hearing loss most commonly indicates cochlear dysfunction, but it may also reflect either VIIIth nerve or central auditory pathology with normal cochlear function. Cochlear, VIIIth nerve or central auditory dysfunction may be part of the presentation of neurological disorders. To understand these sources of disordered hearing, the following section outlines basic concepts associated with each site of dysfunction and provides some information on a number of auditory disorders. However, disorders such as tinnitus, auditory hallucinations, etc. that are associated with central auditory hyperactivity (Musiek and Baran, 2011) were not included, as these were felt to be beyond the scope of this thesis.

1.5.1 Peripheral Hearing Impairment

Conductive hearing loss is a pathology affecting the external and middle ear that causes abnormalities in the mechanical transmission of sound waves from the environment to the cochlea. Pathology of the cochlea and VIIIth nerve gives rise to ‘sensorineural’ hearing loss, in which there is an inability to transduce the mechanical energy of sound waves into electrical activity within the cochlea or to transmit the signals along the VIIIth nerve. Sensorineural hearing loss may be further divided into that of cochlear origin and that of neural origin.

1.5.2 Auditory Neuropathy

Auditory neuropathy (AN) refers to the impairment of listening ability caused by disordered conduction in the auditory nerve with relatively preserved outer hair cell function and cochlear amplification (Starr et al., 1996; Berlin et al., 2003). Diagnosis of AN is made on the basis of a), poor auditory nerve function, b), normal outer hair cell function demonstrated by normal otoacoustic emissions, and c), poor hearing demonstrated by either abnormal pure-tone audiometry or normal pure-tone audiometry but poor speech perception, particularly in noise.

Damage to the fibres in the auditory nerve, which conveys sound information to the brain, may not affect the detection of tones as shown on the audiogram, but it can

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hinder the ability to process more complex signals. This newly recognised condition is called ‘hidden hearing loss’ because a normal audiogram can hide the nerve damage and the hearing impairment associated with it (Schaette & McAlpine, 2011; Liberman, 2015). In a study by Kujawa and Liberman (2009), mice subjected to mild acoustic trauma displayed a temporary shift in hearing thresholds but a permanent deafferentation of some 50-60% of the auditory nerve (AN) fibres in the high frequency region of the cochlea. The study (Kujawa and Liberman, 2009) showed that the dendrites swell and withdraw from synaptic connection with inner hair cells due to excessive neurotransmitter release. This suggests that deafferentation following noise damage predominantly affects the supra-threshold AN fibres, while sufficient numbers of low-threshold AN fibres remain responsive to sound. Hidden hearing loss likely causes problems with hearing in a noisy environment, a classic symptom of age-related hearing loss in humans. Normal hearing thresholds can also be accompanied by impaired function of the efferent fibres that project from the brainstem to the cochlea (Kim et al., 2002). This is particularly noteworthy, as some stroke patients, due to the micro vascular changes in the cochlea, may suffer from ‘hidden hearing loss’. One promising approach to detect such impairment is based on an existing measure of the electrical activity in auditory neurons, auditory brainstem responses (ABR). However, there are some problems associated with the use of ABR Wave I as a diagnostic test for hidden hearing loss; unlike the animal models in which the ABR can be measured accurately, in humans ABR Wave I has a relatively low amplitude and shows high variability both between and within individuals (Beattie, 1988; Lauter & Loomis, 1988). In addition to the variability due to cochlear synaptopathy itself, the variability in Wave I may be the result of a number of factors unrelated to cochlear synaptopathy. These factors include variation in sex and head size (Mitchell et al., 1989).

Hidden hearing loss is beyond the scope of the present thesis.

1.5.3 Central Auditory Impairment

Several different types of pathology (e.g., vascular pathology, trauma, demyelination) might potentially damage the auditory neural substrate within the central auditory nervous system (CANS) and thus result in audiological deficits.

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Anatomically, the CANS begins at the level of the caudal pons, specifically at the cochlear nucleus. The auditory nuclei in the brainstem are important for auditory processing for two reasons. Firstly, their role in the extraction of signals from a background of noise leads to the development of auditory separation tasks. Secondly, their role in the binaural integration of auditory information leads to the development of binaural interaction tasks (Musiek et al., 2004). However, hearing loss (apparent on the subject's pure-tone audiogram) due to processes affecting the brainstem and midbrain is rare. This is because an extensive bilateral lesion is required beyond the level of the cochlear nuclei, which is the level where partial decussation of the ascending pathway starts and which continues at several other levels beyond. Hearing loss has been reported due to lesions of the pons in the brainstem (Egan et al., 1996) and due to bilateral lesions affecting the inferior colliculus in the midbrain (Hoistad and Hain, 2003; Musiek et al., 2004).

According to the American Speech-Language-Hearing Association (ASHA) (2005), central auditory processing disorder (CAPD) is defined as deficits in the perceptual processing of auditory information in the central nervous system (CNS) that cannot be attributed to higher order language, cognition, or other related factors, along with deficits in the neurobiological activity that underlies that processing and gives rise to electro-physiological auditory potentials. Damage to the anterior lateral, frontal, and parietal lobes has been associated with auditory perceptual deficits (Griffiths et al., 2010), leading to speculation that these areas of the brain should also be considered extensions of the central auditory nervous system (Moore, 2011). In summary, CAPD can be demonstrated by poor performance in one or more of the following skills: sound localisation and lateralisation, auditory discrimination, auditory pattern recognition, temporal aspects of audition (including temporal integration, temporal ordering, and temporal masking), auditory performance in competing acoustic signals, and auditory performance with degraded acoustic signals (ASHA, 2005).

1.6 Hearing and Stroke

In the general population, a past history of stroke increases the likelihood of hearing loss. A longitudinal study of 3,526 Australian adults aged 50 years or older found that a previous history of stroke was a predictor for hearing thresholds, although it

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did not determine deterioration of hearing loss over an 11-year period (Kiely et al., 2012). This is broadly in keeping with results from a study based in Australia that analysed a population of 1,394 older adults (Gopinath et al., 2009). These researchers found that the odds of reporting a previous history of stroke in those with vs. those without hearing loss was raised but was marginally non-significant. Yet the odds of reporting stroke were significantly higher for those with moderate to severe hearing loss.

Within the stroke population, hearing loss is present in the majority of stroke patients. Formby et al. (1987) investigated hearing impairment directly associated with stroke after excluding patients who had a previous otologic history or occupational noise exposure. They reported that 61.7% of 243 stroke patients had a pure-tone average of >25 dB at the frequencies of 500, 1000, and 2000 Hz for the better ear. O'Halloran et al. (2009) tested stroke patients in a stroke ward and found that 41 out of 52 patients (79%; confidence interval (CI) 67-90%) had at least mild or greater hearing impairment. A smaller study of 60 patients with past history of stroke suggested that age, the presence of lacunar stroke, multiple bilateral ischaemic focuses, and arterial hypertension increased the risk of hearing loss (Przewozny et al., 2008).

The observed association between hearing loss and stroke could be attributed to age-related changes in the inner ear or auditory nerve (Jacquin et al., 2012), as the risk of both hearing loss and cardiovascular accidents (CVA) increases with age (Hung et al., 2011). Alternatively, stroke-related risk factors, such as cigarette smoking and atherosclerosis, which have been associated with a more insidious onset of hearing impairment with advancing age (Yamasoba et al., 2013), may directly affect the peripheral hearing organs, or the stroke event itself may damage the peripheral and central auditory pathway (Lee et al., 2009), thus giving rise to the observed hearing impairment.

Altogether, the findings from the aforementioned studies suggest that the prevalence of hearing loss in stroke survivors may be higher than the hearing loss that would be expected in the general population. However, none of the few previous studies regarding hearing impairments in stroke patients characterised auditory function in detail in order to establish the different types of hearing impairments in this cohort of

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patients. Such information would be very useful in understanding and addressing the hearing needs of stroke survivors, so that appropriate management can be given to these patients in order to improve their quality of life.

In order to inform the types of hearing loss associated with stroke, a brief overview of the definition of stroke, the classification of strokes, and the observed patterns of stroke-related hearing loss reported in case reports or series studies will be presented below, in sections 1.6.1 and 1.6.2.

1.6.1 Definition and Classification of Stroke

1.6.1.1 Definition

The World Health Organization (WHO) defines stroke as ‘a syndrome of rapidly developing clinical signs of focal (or global) disturbance of cerebral function, with symptoms lasting 24 hours or longer or leading to death, with no apparent cause other than of vascular origin’. This includes subarachnoid haemorrhage but excludes transient ischaemic attack (TIA), subdural haematoma, and haemorrhage or infarction caused by infection and tumour. It also excludes silent cerebral infarcts (Wolfe, 2000).

Stroke is typically defined in terms of pathology (ischaemia or haemorrhage), its anatomical location within the brain (e.g. left middle cerebral arterial territory) and the underlying mechanism (e.g. cardio-embolism).

1.6.1.2 Ischaemic

About 85% of all strokes are ischaemic (Ikram et al., 2012). Ischaemic stroke is the result of vessel occlusion from in situ-thrombosis, embolism or haemodynamic failure. Embolism may be from artery to artery or from the heart.

The effect of localised blood vessel occlusion will depend on the following factors: the area of the brain supplied by the vessel, the nature of the occlusion, the time that the occlusion lasts, its degree, and the anatomy of the collateral circulation.

HEARS***1.6.1.3 Haemorrhagic***

Intracranial haemorrhage (ICH) may be intracerebral, within the cerebellum or brainstem, subarachnoid, subdural, or extradural. Approximately 10% of strokes are caused by brain haemorrhage, with an annual incidence of 10-15/100,000 population (Ikram et al., 2012). The incidence increases significantly after the age of 55 years, and doubles in each decade to the age of 80 (Feigin et al., 2003). Despite being less common than ischaemic stroke, haemorrhage has a significant impact because the subsequent mortality is so high. Spontaneous ICH results from intracerebral arterial rupture, particularly from the perforating vessels, or less frequently from the venous system. The rupture of a vessel or a microaneurysm results in the sudden development of haematoma that may be of variable sizes (Losseff, 2009). These haematomas characteristically then slowly enlarge, sometimes over a matter of days, leading to progressive focal neurological deficits.

1.6.1.4 Subarachnoid Haemorrhage (SAH)

The main cause of non-traumatic SAH is rupture of an intracranial aneurysm. This accounts for 85% of cases (de Rooij, 2007). SAH is a devastating condition with an overall case fatality of 50%, with 30% of survivors being left dependent and with major neurological deficits (de Rooij, 2007). The cardinal clinical feature is the sudden onset of a headache, and is often accompanied by nausea and vomiting. Depending on the severity and location of SAH, signs of global or focal dysfunction may be found (Losseff, 2009).

1.6.2 Patterns of Stroke-Related Hearing Loss

Stroke can often include the auditory system (from the peripheral to the central tracts), resulting in various types of auditory dysfunctions such as unilateral or bilateral, peripheral and/or central hearing loss, and cortical deafness. Some dysfunctions are subtle and can only be detected by precise psychoacoustic and electrophysiological testing. This section will review the different types of hearing disorders in stroke patients classified on the basis of the site of lesion. It will include the observed hearing deficits and brief information on the vascular pathology.

HEARS***1.6.2.1 Peripheral (Cochlear and VIIIth Nerve) Hearing Loss***

Sudden hearing loss after stroke is uncommon, but it may be the initial presentation of vertebrobasilar ischemia, which is more common in the presence of vascular risk factors (Lee et al., 2002; Lee & Cho, 2003; Lee & Baloh, 2005; Kim & Lee, 2009). Anterior inferior cerebellar artery (AICA) territory stroke is the leading cause and is reported to account for 83% of cases, while posterior inferior cerebellar artery (PICA) stroke accounts for 12% (Lee & Yi, 2008). Within the different infarct territory subtypes, sudden hearing loss occurred in 87.5% of cases with isolated AICA infarct, but only in 3.4% of cases with isolated PICA infarct.

The majority of cases of sudden hearing loss after both AICA and PICA territory ischemic stroke are due to cochlear damage (Lee et al., 2002; Lee & Yi, 2008; Lee et al., 2009). Few studies have conducted electrophysiological tests to help determine whether the hearing loss is peripheral (cochlear or neural) or brainstem related (Ulbricht, 2003). Furthermore, the presence of severe to profound hearing loss confounds the interpretation of auditory brainstem evoked responses and acoustic reflexes. Despite these limitations, there is clear evidence that AICA and PICA territory strokes may lead to mixed cochlear/retro-cochlear loss, and less frequently, to retro-cochlear-only patterns of hearing loss (Lee et al., 2002).

Occasionally, the hearing loss, possibly due to initial hypo-perfusion of the internal auditory artery (IAA), can be transient and recurrent (Park et al., 2008). A case report has proposed that AICA infarction should be considered in acute audiovestibular syndrome in elderly patients with vascular risk factors even when the MRI is normal (Lee, 2008), as the current MRI cannot reliably identify labyrinthine infarction. Hearing loss caused by vertebrobasilar ischemia may improve due to improved collateral blood flow (Kido et al., 1994). On the other hand, hearing loss may worsen in the case of progressive basilar artery stenosis (Chiang et al., 2013).

Hearing loss for both AICA and PICA infarcts is mostly unilateral. However, bilateral hearing loss is also possible when there is more extensive damage (Lee, 2012; Chang et al., 2013).

Table 1-1 (pp. 25-26) shows the studies that assessed the peripheral hearing loss in stroke patients.

HEARS***1.6.2.2 Subcortical Hearing Loss due to Stroke***

Hearing loss due to brainstem and midbrain lesions is rare and has been reported in less than 1% of isolated brainstem strokes (Lee, 2008). Diagnosis of the hearing loss and differentiation between peripheral or subcortical mechanisms can be a challenge. This distinction is critically important when considering aetiology and management. Auditory brainstem responses (ABR) (testing the evoked neural response from the cochlea to the midbrain) and acoustic reflexes (testing the lower brainstem pathways) may help define the site of lesion. Below, we discuss the papers in which ABR was done as an index test to differentiate between peripheral and subcortical hearing loss in stroke patients.

Hearing deficits after superior cerebellar artery (SCA) ischemic infarction are usually contralateral (Murakami et al., 2005). The SCA branches penetrate into the superior cerebellar peduncle, the dentate nucleus, and about two thirds of the cerebellar deep white matter (Marinkovic et al., 1995). In SCA infarction, the ischemic lesion occurs in the area where fibres from the nucleus have already crossed, and therefore sensory hearing loss is observed on the contralateral side (Doyle et al., 1996; Murakami et al., 2005).

Only animal studies, previous to Doyle's study (1996), had shown an abolition of ABR waves three and five contralaterally when the damage was created unilaterally in the lateral lemniscus (Wada & Starr, 1983). Later, Murakami et al. (2005) reported another case of SCA infarction syndrome with a contralateral hearing loss.

Hearing deficits after SCA infarction can also be bilateral. Cerrato et al. (2005) reported a case in which bilateral hearing loss (left more than right) was one of the dominant symptoms at presentation. The brain MRI showed lacunar infarction of the superior cerebellar artery territory, including the right lateral lemniscus and inferior colliculus. Audiometry showed hearing loss that was more pronounced on the left side than on the right side. Using ABR testing, the left inter-wave III-V interval was prolonged. The authors attributed the hearing deficits on the side contralateral to the stroke to the fact that acoustic fibres are mostly crossed at the level of the inferior colliculus. Finally, there are case studies showing hearing loss ipsilateral to stroke-related hearing deficits. Lee and Yi (2008) reported two patients with upper

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brainstem infarction that was seen on the MRI who had hearing loss ipsilateral to the stroke. One of these two cases had a cochlear type hearing loss, while the other probably had a combined cochlear and neural hearing loss.

There are reports of hearing loss after haemorrhagic brainstem stroke. Cohen et al. (1996) reported a bilateral symmetrical hearing loss in a patient with medial brainstem involvement and unilateral hearing loss in a patient with a brainstem lesion prior to the decussation in the pons.

Nakane et al. (2006) described the case of a patient with haematoma that extended from the lower to the upper part of dorsal pons, with damage to the cochlear nuclei and trapezoid body. This patient presented with quadriplegia and bilateral hearing loss, with only wave I present on both sides in the auditory brainstem responses test. However, Goyal and colleagues (2010) reported a case of central pontine haemorrhage due to capillary telangiectasia who had bilateral hearing loss but normal ABR. The hearing loss had resolved 6 months later. The authors proposed that the hearing deficit was due to disruption of the ventral acoustic striae that decussates in the trapezoid body.

Hearing loss may also present due to stroke of higher-level subcortical structures. Musiek and Baran (2004) reported the case of a patient with a subarachnoid bleed affecting both inferior colliculi. The patient's auditory presentation was monitored for 10 months. He suffered from total 'central' deafness during the first week post-admission, but the hearing had recovered considerably two and a half weeks after admission. Eventually, audiological testing showed a progressive recovery, with pure-tone thresholds ending up within the normal range. Although the auditory evoked potentials improved, they did not recover to the normal status.

Table 1-2 (p. 27) shows hearing losses reported in brainstem stroke.

1.6.2.3 Cortical Hearing Loss ('Cortical Deafness') due to Stroke

The term 'cortical deafness' is often used to refer to deafness following damage to the primary and secondary cortices in Heschl's gyrus (HG) and the association cortex in the planum temporale (PT) without any involvement of peripheral hearing, the auditory nerves, or the brainstem auditory pathway tracts (Griffiths, 2010). However, in most reported cases of cortical deafness in the literature, areas of the sub-cortex

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were also compromised, and patients showed auditory response variability (Tanaka et al., 1991). Cortical deafness may have attentional components, yet even when these are taken into account, hearing loss is still present (Griffiths, 2010). Several cases may show no hearing recovery, while some improve over the first few weeks to months after the stroke (Griffiths, 2010).

Auditory deficits caused by cortical lesions are mostly due to ischemic stroke (Buchman et al., 1986). We herein review the studies investigating cortical deafness due to stroke in which the audiological findings have been presented (Table 1-3, p. 28).

Graham et al. (1980) presented a case with cortical deafness after bi-temporal embolic infarction. Pure-tone audiometry showed no response from either ear up to 110dB HL. ABR waves were within normal limits and stapedial reflexes were present bilaterally, confirming intact peripheral and brainstem pathways. However, cortical and middle latency responses were absent. A transmission CAT head scan showed left and right temporal cortex infarction, which resulted in total deafness.

The majority of patients with cortical deafness due to functional abnormalities of the pulvinar may suffer from some degree of attentional deficit (Pandya, 1995). Thus, obtaining accurate hearing thresholds may be a challenging task for clinicians, as patients are required to sustain attention for a simple task. Audiological examinations that evaluate the peripheral auditory system, the auditory nerve, and the brainstem are thus highly essential for the diagnosis of cortical deafness.

1.6.3 Summary of the Different Types of Hearing Loss in Stroke Patients on the Basis of the Site of Lesion

1.6.3.1 Ischaemic Stroke of the Vertebrobasilar Territory

- AICA and PICA infarction: predominately cochlear type hearing loss, but can also be mixed cochlear/retrocochlear, and less frequently, retrocochlear only
- Mostly unilateral hearing loss; however, there are a few case reports of bilateral hearing loss when there has been more extensive damage

HEARS***1.6.3.2 Ischaemic Stroke of the Upper Brainstem and Midbrain***

- SCA infarction: unilateral (contralateral to the lesion) hearing loss of retrocochlear origin. However, there are a few case reports of bilateral hearing loss. Prolonged or absent ABR waves

1.6.3.3 Subarachnoid Haemorrhage and Haemorrhagic Lesions

- Hearing loss (predominantly bilateral) of retrocochlear origin may be present due to involvement of the cochlear nuclei, olivary complex, and/or trapezoid body from the haemorrhage within the brainstem territory

1.6.3.4 Cortical Deafness

- Mostly due to ischaemic stroke, following damage to the primary and secondary cortices in Heschl's gyrus (HG) and association cortex in the planum temporale (PT), without any involvement of peripheral hearing, the auditory nerve, or the brainstem auditory pathway tracts; may also be due to some degree of attentional deficit
- Behavioural responses to sounds can be absent or inconsistent, pure-tone audiometry varies from severe to profound hearing loss, often normal ABR but absent cortical evoked responses. Audiometric thresholds in some cases may improve.

1.6.4 Limitations of the Stroke-related Hearing Loss Studies

One of the challenges in considering the available data on hearing loss in brainstem and subcortical stroke is the lack of consistency in using thorough audiological testing on such patients. Only a few studies have included the full audiological battery of tests (i.e. pure-tone audiometry, stapedial reflex thresholds, electrophysiological measurements such as auditory-evoked brainstem responses, and otoacoustic emissions) to demonstrate if the hearing loss was caused by damage to the auditory pathway in the brainstem. These case studies indicate that although rare, hearing loss can be an initial symptom of brainstem infarction. Pure-tone

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detection may be affected by the brainstem and other subcortical involvement. This would depend on the site and size of the lesion, and also on how soon the hearing sensitivity is measured after the damage occurred (Heffner & Heffner, 1986). The rarity of cases of hearing loss after brainstem/subcortical stroke is due to the fact that the ascending pathway partially decussates in the brainstem. Thus an extensive bilateral brainstem lesion is required to cause hearing loss, and such lesions are rarely compatible with life (Griffiths, 2010).

Furthermore, audiological assessment procedures were not consistently employed in the majority of the cortical-lesions-related hearing loss studies, even where objective measures would have led to a more complete definition of the auditory deficits. Consequently, the degree of cortical hearing loss in stroke patients may have been overestimated.

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Table 1-1: Studies assessing the peripheral hearing loss in patients with ischaemic posterior circulation stroke (continues on following two pages)

Study	Presence of Hearing loss	Study design	Type of stroke	Test results	Lesion shown on MRI/CT Scan
Gur et al., 2006	Bilateral hearing loss in 2 cases and unilateral in other 3 (the degree of HL was not reported)	Case series	Ischeamic	ABR showed absent Wave 2 cases and absent wave other 3 cases	Infarction in unilateral Middle Cerebellar Peduncle in all cases (Angiogram confirmed SCA in 3 cases)
Lee & Baloh, 2005	Bilateral deafness in both cases (Degree was not reported)	Case report	Ischeamic	-	Occlusion of proximal segment of the basilar artery in patient 1 and arterial dissection in patient 2
Lee & Cho, 2003	SNHL in 11 patients ranged from mild to profound. Ten unilateral and 1 bilateral SNHL	Case series	Ischeamic	Absent ABR waves in 5 (unilaterally), delayed in 6 normal ABR. Six abnormal SRTs and 6 normal. Severe normal speech score and abnormal.	Infarction in middle cerebellar peduncle in 11 patients and infarction in anterior inferior cerebellum in 1 patient
Lee & Baloh, 2003	Unilateral SNHL in 4 and bilateral, 2 mild, 2 moderate and 1 severe SNHL	Case series	Ischeamic	Normal ABR in all except 4 with unilateral abnormal ABR SRTs	Case 1: infarction in left middle cerebellar peduncle and lateral pons; case 2: infarction right middle cerebellar peduncle and anterior cerebellum; case 3: right dorsolateral pontine middle cerebellar peduncle and anterior inferior cerebellar hemisphere; case 4: infarction left middle cerebellar peduncle and dorsolateral pons; case 5: right middle cerebellar peduncle and dorsolateral pons
Lee et al., 2002	Moderate bilateral SNHL first visit; mild to moderate SNHL follow up visit	Case report	Ischeamic	Moderate SNHL of 55 days normal speech score and on the first visit. PTA improved after 15 days.	Severe stenosis of the middle third of the basilar artery and blockage of the right distal vertebral artery
Matsushita et al., 1993	Unilateral moderate SNHL	Case report	Ischeamic	Normal SRTs and ABRs	MRI result 2 day after onset of HL: small infarct in right lateral tegmentum of the lower PONS
Son et al., 2007	Unilateral moderate hearing loss	Case report	Ischeamic	No speech discrimination on left	Complete occlusion of left MCA and left vertebrobasilar artery

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Toyoda et al., 2002	Unilateral moderate hearing loss	Case report	Ischemic	Absent ABR waves unilaterally, normal speech score and normal SRTs	MRI result 9 day after the onset of hearing loss: infarction in middle cerebellar peduncle
Ito et al., 2008	Unilateral SNHL (the degree was not reported)	Case report	Ischemic	Sudden unilateral SNHL but hearing improved spontaneously before the occurrence of AICA infarction. Delayed wave I on right ABR	High intensity lesions were in the right dorsolateral pons and middle cerebellar peduncle
Gerace et al., 2008	Unilateral severe SNHL. No improvement in hearing 8 month after the onset	Case report	Ischemic	Normal ABR and SRTs	Infarction in left middle cerebellar peduncle and left cerebellum
Lee, 2008	Mild to moderate cochlear hearing loss in 4 and severe to profound combined cochlear and retrocochlear loss	Case series	Ischemic	4 patients had normal ABR or delayed absolute latencies (the inter-peak latencies were normal). No ABR response in other three patients (profound hearing loss)	Cerebellar infarct in the territory of medial branch of posterior inferior cerebellar artery in 5 patients and two patients had infarction in the brainstem
Lee et al., 2009	Profound hearing loss in the left ear	Case report	Ischemic	Absent waves on left ABR	MRI test result at the onset of hearing loss: Normal. MRI test result 4 days after the onset of sudden HL: infarction in left lateral pons, middle cerebellar peduncle and inferior-lateral cerebellum.
Kim et al., 2009	Severe to profound unilateral SNHL	Case report	Ischemic	Audiological test results revealed absent or decreased auditory and vestibular function	First visit MRI result: Normal. Follow-up MRI result: Infarction in middle cerebellar peduncle (n=3), Dorsolateral pons (case=3), and anterior inferior cerebellar hemisphere (n=2)
Kido et al., 1994	Severe hearing loss in the right ear. Hearing improve dramatically 12 days after the onset of HL suggest the recanalization of circulation disturbance or the development of collateral circulation	Case report	Ischemic	-	Infarction in AICA and PICA territory

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Table 1-2: ‘Central’ hearing loss reported in brainstem stroke

Study	Presence of Hearing loss	Study design	Test results	Type of stroke	Lesion shown on MRI/CT Scan
Matsuda et al., 1993	Mild to moderate low frequency hearing loss in the right ear	Case report	Prolongation of wave I latency on the right side compared to the left.	Ischeamic	CT scan showed a 4.5 cm high-density area in right cerebellar peduncle
Cohen et al., 1996	Low frequency hearing loss	Case report	Abnormal ABR; Wave V being constantly involved. Abnormal acoustic reflexes and masking level difference	Ischeamic	Damage to the medial superior olivary nuclei and trapezoid body
Deplanque et al., 1998	Moderate to severe hearing loss in the left ear and severe to profound on the right	Case report	Prolonged wave I and absent waves III and V on ABR. Normal MLR (indicating intact subcortical area)	Ischeamic	Left sided infarction in the lateral inferior pons and in the middle cerebellar peduncle
Vitte et al., 2002	Mild hearing loss in the right ear and moderate in the left.	Case report	ABR thresholds were within normal limits.	Ischeamic	Bilateral lesion of inferior colliculi (involving the tectum of the mesencephalon mostly the left side)
Musiek et al., 2004	No respond to loud sounds initially but patient regained hearing after 10 months.	Case report	All ABR waves were present but the morphology of wave was poor. Absent MLR and LLR. Absent P300 waves initially but waves were present after 9 weeks.	Haemorrogic	Damage to inferior colliculus and inferior portion of superior colliculus but the pons was spared in this patient
Nakane et al., 2006	Bilateral SNHL (degree not reported)	Case report	ABR showed normal waves I and abolished waves III and V on both sides	Ischeamic and haemorrogic	Large hematoma located in the lower to upper part of the dorsal pons extending widely to the dorsal pons

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Table 1-3: Report of cortical deafness in stroke patients

Study	Presence of Hearing loss	Study design	Test results	Type of stroke	Lesion shown on MRI/CT Scan
Graham et al., 1980	No response from left & right up to 110 dB nHL. Responded to loud noises after 7 months	Case report	Normal ABR, Normal MLR, Absent CERA	Ischeamic	Transmission CAT scan showed discrete area of low attenuation in both temporospatial regions and in the right occipital region.
Kneebone et al., 1981	Initially no response to sounds; after 1 year a mild hearing loss persisted.	Case report	Normal ABR Absent CERA but after a year the CERA responses had returned	Ischeamic	Bilateral temporospatial infarction
Woods et al., 1984	Initially no response to sound	Case report	Normal ABR Normal later responses (latency \approx 100ms), even to sub-threshold stimuli	Ischeamic	R & L superior temporal lobe infarcts (more extensive on right and extending to temperoparietal junction (involving HG on both sides
Bahls et al., 1988	No consistent response to tested frequencies up to 100dB	Case report	Normal ABR & MLR Absent LLR thresholds (to 300ms)	Ischeamic	Right superior temporal lobe infarction involving HG and adjacent frontal and inferior parietal cortex. Left superior temporal lobe infarction involving HG and adjacent parietal cortex
Mendez & Geehan, 1988	Hearing thresholds > 70 dB initially. Thresholds of 30-40 in the right ear and 20-25 dB in the left after two weeks	Case report	Normal ABR Absent MLR thresholds	Ischeamic	Right & Left superior temporal gyrus infarcts
Tanaka et al., 1991	Severe hearing loss across all tested frequencies with marked variability in thresholds	Case report	Normal ABR Main component mid-latency response not recorded. Variable and inconsistent long latency responses	Ischeamic	Right deep white matter infarcts of temporal lobe below insula, especially posterior part HG partially involved Left deep white matter infarcts of temporal lobe below insula, especially posterior part HG spared
Szirmai et al., 2003	Deafness after haemorrhages on right, then left, after four-year interval.	Case report	Normal ABR	Ischeamic and haemorrogic	Right hemisphere haemorrhage involving superior temporal gyrus and underlying white matter (first event). Left hemisphere sub-insular infarct (second event)
Musiek et al., 2007	Severe to profound hearing loss bilaterally	Case report	Normal ABR Absent MLR and LLR	Ischeamic and haemorrogic	Bilateral CVA involving Heschi's gyrus and some adjacent neural tissue on both sides of the brain.

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Table 1-4: Studies that have assessed the prevalence of hearing loss in stroke patients

Study	Study design	Setting and timing	Aims	# of patients	Type of stroke	Audiological battery	Type of hearing impairment	Results
Formby et al., 1987	Observational case series	Rehabilitation ward within 2 weeks and up to 1 month post-stroke (acute stage)	The prevalence of hearing loss among stroke patients	243	Cerebrovascular lesion (right & left)	Only otoscopy & pure-tone audiometry (75% tested w/ portable audiometry, 25% w/ diagnostic audiometry)	Not specified	Hearing loss detected in 61.7% of stroke patients
Graves et al., 1995	Observational case series	Stroke rehabilitation ward, acute stage	The incidence and extent of hearing loss in patients admitted for stroke rehabilitation	110	Not specified	Otoscopy and portable pure-tone audiometry	Not specified	53% of patients failed the hearing-screening test.
Edwards et al., 2006	Observational case series	Stroke ward, within 5 days	To assess the systematic use of hearing screening.	53	Ischemic stroke	Sound repetition screening (combination of high- and low-pitched sounds; subjects were asked to repeat them)	Not specified	42% of patients identified with hearing loss; 86% of which were not identified before the hearing screening.
O'Halloran et al., 2009	Observational case series	Stroke unit, acute stage	To investigate relationships between communication related impairments & difficulty communicating health care needs re: capacity w/ assistance & performance	52	Ischemic and haemorrhagic	Portable audiometry	Not specified	79% of patients identified with a mild or greater hearing loss.

1.7 Prevalence of Hearing Impairment in the General Population

1.7.1 Prevalence of Hearing Loss in Adults

The World Health Organization reported that there are 360 million people in the world with disabling hearing loss, which was defined as hearing loss greater than 40 decibels (dB) in the better hearing ear in adults. This represents 5.3% of the world's population. Adult onset hearing loss is one of the leading causes of years lived with disability [YLD] (WHO 2001). In 2000, hearing loss accounted for 4.7% of total YLD due to all causes, with the total global YLD for hearing loss estimated at 24.9 million (Mathers et al., 2003). Davis et al. (1998) reported that 16% of the adult population (17-80 years) in Great Britain have bilateral, and about one in four a unilateral or bilateral, 'significant' level of hearing impairment. Significant was defined as at least 25 dB HL averaged over the frequencies 0.5, 1, 2 and 4 kHz. They reported that 60% of adults aged 61-80 years old and 10% of adults aged 18-80 years old have some type of hearing loss (Davis, 1998). A report by Davis et al. (1995) estimated a population prevalence in 18-80 year olds as 0.7% for hearing in the better ear having thresholds > 75dB HL averaged across 0.5, 1, 2, and 4 kHz. In a study by Turton & Smith (2013), estimates of severe or profound bilateral hearing loss were 6.7% of the local clinical population and 0.7% of the general population.

In an epidemiology study of hearing loss in adults aged 48-92 years in Beaver Dam, Wisconsin (Cruickshanks et al., 1998), the prevalence of hearing loss was 45.9%. Of those with a hearing loss, 58.1% had a mild hearing loss, 30.6% had a moderate loss, and 11.3% had a marked loss. Consistent with the results of other studies (Plomp & Mimpen 1979; Wilson & Strouse 2002; Smits et al. 2006; Dawes et al., 2014) Cruickshanks (1998) reported the odds of hearing loss increased with age (odds ratio [OR] = 1.88 for 5 years, 95% confidence interval [CI] 1.80-1.97). In particular, the prevalence of hearing loss increases after the age of 55 years old (Dawes et al., 2014). A recent population-based study reports that based on audiometric data for Canadians, 19% of the people aged 20 to 79 (4.6 million) had at least a mild hearing loss in frequencies that are important for understanding speech (Feder et al., 2015).

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They demonstrated that their finding far exceeded the percentage who self-reported hearing difficulties, fewer than 4%. The large disparity between measured and self-reported prevalence in their study suggests that hearing loss is often unrecognised. Their results are consistent with the population-based studies conducted in the United States (Lin et al., 2011), Great Britain (Davis, 1989) and Australia (Wilson et al., 1999).

1.7.2 The Prevalence of AP Deficits in Adults

There are only a few studies assessing auditory processing disorders in adults aged 18-60 years old without structural brain abnormalities (e.g., Neijenhuis et al., 2003; Helfer and Vargo, 2009). Helfer and Vargo (2009) suggested that certain aspects of hearing begin to decline in middle age. They examined speech understanding ability and temporal processing in middle-aged adults with normal or near-normal pure-tone thresholds. Tests used were a speech-in-noise test, a gaps-in-noise test, and the Speech, Spatial, and Qualities of Hearing Scale questionnaire. Their results documented subtle age-related changes in auditory processing in this population. In another study by Neijenhuis et al. (2003), sixty-eight percent of adult patients with suspected CAPD and with normal pure-tone audiograms who complained of hearing difficulties had abnormal results in the central auditory test battery (auditory sequencing, word recognition in noise, auditory closure, and auditory patterning). Nevertheless, the prevalence of CAPD in adults is still unclear, because there is currently no 'gold standard' method to measure this deficit. Still, CAPD is thought to increase with age, and earlier studies estimated that approximately 10% (Saunders and Haggard, 1989) of the adult otological referrals to ENT in the UK complain convincingly of difficulties understanding speech in a noisy environment despite having 'normal' hearing thresholds on the pure-tone audiogram. A more recent study by Hind et al. (2011) found a lower percentage, only 0.9%. Hind et al. reported that out of a total population of 4,757 adult audiological referrals with an age range of 15 to 71 years, there were 43 adults with normal hearing but with complaints of understanding speech in noise.

In the general population, Katz (2005) found that the prevalence of auditory processing disorders was 20%, whilst DiMaggio & Geffner (2003) quoted a figure of

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12%. Published studies about the prevalence of CAPD in older adults have proposed a prevalence ranging from 23% (Cooper and Gates, 1991) to 50% (Jerger et al., 1989) in patients over the age of 63. However, the above-mentioned studies only included those individuals with a pure-tone audiometry average of less than 30 dB HL. It must be noted that a central hearing disorder may very well co-exist with a peripheral hearing impairment. The presence of age-related peripheral hearing loss may contribute to older adults' auditory symptoms and may also affect the central auditory nervous system. Furthermore, these studies mainly used test batteries that included only speech stimuli. One must consider that performance might reflect language, memory, and attention factors as well as true auditory function. Thus to minimise the potential confounding effects of language and to detect the true prevalence of CAPD, behavioural central auditory tests that employ non-speech stimuli (stimuli that are not highly dependent on attention and memory), such as gaps in noise (GIN) with a low cognitive demand and good reliability (Musiek et al., 2005), should be selected. Overall, there is a paucity of published studies regarding disordered auditory processing for this group of adults. More importantly, no studies have looked at the prevalence of AP in the stroke population despite the fact that if a stroke involves the central auditory pathway in the brain, patients may suffer from additional auditory processing deficits.

1.8 Hearing Loss Sequelae

1.8.1 Hearing Loss, Cognition and Dementia

Elderly individuals with hearing loss have an increased rate of developing dementia and more rapid cognitive decline than their non-hearing-impaired counterparts (Gurgel et al., 2014). Gates et al. (2011) reported that central auditory dysfunction is found in patients with mild memory impairment and is a precursor to Alzheimer's Disease (AD). Lin and Albert (2014) proposed a model of the possible mechanisms that might support a link between hearing loss and cognitive aging. One explanation is that greater cognitive demands (mental effort and attention) may be required to process complex sounds in the brain if the signal is poor or degraded. As a result, the increased demands of auditory processing exhaust the listener's limited pool of

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cognitive resources. Fewer resources remain available for other complex tasks such as language comprehension, memory, walking etc. This may result in permanent neuroplastic changes in the brain. Another explanation is that common abnormal biological processes (e.g., hypertension and diabetes) may result in degeneration and loss of both auditory and cognitive function (Helmkamp, Talbott, & Margolis, 1984; Talbott et al., 1990). A third possible explanation is that communication problems caused by hearing loss can lead to reduced social engagement and loneliness in older adults (Chen, 1994; Gopinath et al., 2012). These reductions increase the risk of cognitive decline. Poor social engagement likely contributes to impaired cognitive and physical functioning through both psychological and physical effects (Seeman & McEwen, 1996; Berkman, Glass, Brissette, & Seeman, 2000; Seeman, 2000).

A study by Mellon et al. (2015) indicated that over 50% of stroke patients exhibit cognitive impairment six months post-stroke. Their findings support emerging evidence of the importance of secondary preventive strategies to avert post-stroke cognitive decline and a transition into dementia (Mellon et al., 2015). Greater attention to improving lifestyle and addressing the medical risk factors for cognitive decline is urgently needed for stroke patients. Hearing health care may need to be considered in the stroke population, as the prevention and mitigation of hearing loss may play a significant role in these efforts.

1.8.2 Hearing Loss and Social Isolation

Hearing difficulties may place increased demand on cognitive processes and resources (Schneider, Pichora-Fuller, & Daneman, 2010). Hearing difficulties can cause social isolation and even depression, increasing the risk for cognitive decline (Fulton et al., 2015). Communication in noisy environments such as restaurants, social gatherings, meetings, etc. could be a challenging task for any listener. Thus, it is not surprising that many individuals with hearing and/or cognitive impairment withdraw from these situations. This could result in social isolation or avoiding participation in social gatherings with family, friends, or colleagues. A strong association between hearing loss and social isolation has been shown in older individuals (Mick et al., 2014), and as the degree of hearing loss increases, so do the odds of being socially isolated. Older adults with hearing loss are more likely to

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experience depressive symptoms, lower self-efficacy and mastery, more feelings of loneliness, and a smaller social network than normally hearing peers (Kramer & Kapteyn, 2002; Gopinath & Hickson, 2012; Gopinath & Schneider, 2012). Furthermore, studies have found that adults with stroke have an increased risk of depression and social isolation (Ayerbe et al., 2011; Venna, 2014). In a study by Dawes and colleagues (2015), hearing aid use was shown to be associated with better cognition.

1.9 Screening for Hearing Impairment

A moderate degree of hearing impairment in adults is a highly prevalent major public health problem with a large impact on people's lives. It is often neglected for far too long before access to any hearing services is achieved (Bagley, 1998). That is to say, typically, those who are referred for hearing assessment recognise that they have had a hearing problem for around 10 years or more, are aged in their mid-seventies, and have a substantial hearing problem. The older that people are when they present for assessment and intervention, the more difficult they find adaptation to and care of their hearing aids (Davis et al., 2007). A simple systematic screening, using an audiometric screening instrument, is likely to provide substantial benefit and may be cost-effective. The main purpose of a hearing screening test is to identify patients with a possible hearing impairment who require further investigation. As will be discussed in Chapter 2, a thorough audiological assessment should include a battery of behavioural and electrophysiological tests, which are often time consuming.

To date, only four studies have attempted to screen hearing in a stroke population (Formby et al., 1987; Graves et al., 1995; Edward et al., 2006; O'Halloran et al., 2009), but none specifically assessed for the presence of AP deficits. Edward et al. (2006) conducted a study on patients with acute stroke to determine whether the systematic use of brief screening measures would more efficiently detect cognitive and sensory impairment than standard clinical practice. Edward et al. demonstrated that up to 42% of stroke patients may fail a hearing-screening test, with 86% of these unidentified prior to the screening. However, they did not use a routine audiometric test to determine the presence of hearing loss, but instead employed a non-standardised sound repetition test as a 'hearing screening tool'. This brief bedside

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test assessed the ability to hear a combination of high- and low pitched sounds used in everyday conversation without the benefit of lip reading. Patients were asked to repeat the sounds *sa*, *se*, *si*, *so*, and *su* while the person vocalising the sounds blocked the view of his or her lips. Each sound heard correctly was given a score of 1. A score of 4 or less indicated a functional impairment. This test may demand attention and working memory, and therefore their findings may reflect the possibility that there are false positives that may have inflated the level of impairment in their sample. Furthermore, the sensitivity and specificity of this tool is unknown. O'Halloran and colleagues (2009) screened the hearing of 49 stroke patients at bedside using a portable audiometer with noise occluding headphones. They identified 79% of stroke patients as having a mild or greater hearing impairment in the acute stage of stroke. The numbers above could be underestimated or exaggerated due to methodological issues, e.g., the type of hearing screening employed, testing conducted in the acute stage, testing in noisy wards, etc. Formby et al. (1987) measured pure-tone air conduction thresholds in 243 stroke patients using a portable audiometer. The patients' ages ranged from 30 to 103 years old. They restricted their sample to patients who had neither remarkable otologic histories nor significant occupational noise exposure prior to stroke (as revealed by questioning the patient and/or family). They were all tested in a rehabilitation ward.

The intensity and complexity of the diagnostic process mandate the need for a screening instrument that will indicate individuals at risk of not only peripheral hearing loss but also of auditory processing deficits prior to the initiation of assessment. There is no universal 'gold standard' behavioural assessment instrument to diagnose AP deficits, reducing the certainty with which sensitivity and specificity can be identified. Ideally, screening instruments for AP deficits should identify a high proportion of those with the disorder with a relatively brief and inexpensive procedure that is easy to administer, and optimally is not influenced by non-auditory factors such as language and cognition.

More details on this subject are presented in the introduction of Chapter 4.

1.10 Auditory Rehabilitation

1.10.1 Audiological Management for Peripheral Hearing Loss

The hallmark management strategy for patients with peripheral hearing loss is the use of hearing aids. Many other rehabilitation options such as assistive listening devices and hearing therapy can also be considered when managing patients with peripheral hearing loss. Mulrow et al. (1992) showed the sustained social, mental, and emotional benefits after 12-months' use of hearing aids in a group of 192 elderly (over 64 years old) hearing-impaired patients. Although the group was quite homogeneous and 70% of patients had hearing loss of 40 dB or less (considered a mild hearing loss), the patients saw significant benefits from baseline to post hearing aid fitting. Benefits in the area of the quality of life (QoL) of the individual have been shown for those who wear hearing aids (Mulrow et al., 1990; Mulrow et al., 1992). In a study by Dawes and colleagues (2015), hearing aid use was shown to be associated with better cognition. However, they attributed this association with increased audibility in daily life rather than 'reduction of the adverse effects of hearing loss on social isolation or depression' (Dawes et al., 2015, pp 6-7).

Counselling regarding the use of hearing aids and the establishment of reasonable expectation of the benefits available from hearing aids in various listening conditions is also a critical component of any hearing aid fitting. Furthermore, there is a growing body of evidence that hearing therapy accompanying hearing aid fitting in adults yield better QoL outcomes (Kricos et al., 1996; Hickson et al., 2007).

1.10.2 Rehabilitation for Auditory Processing Deficit

Intervention for AP deficits is multidisciplinary, and test results help to determine appropriate strategies for each patient. The goal of AP rehabilitation is to improve the functional deficits of individuals with specific impairments that impact social and communicative abilities. Generally, a comprehensive management program for CAPD should focus on the following areas (Bellis, 2003; Bamiou et al., 2006):

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1. Remediate the disorder by means of techniques designed to enhance discrimination and associated neuro-auditory function (e.g. auditory training).
2. Improve the accessibility of auditory information by changing the environment (e.g., signal enhancement strategies and speaker based adaptations).

Auditory training (AT) is regarded as one of the pivotal components in AP rehabilitation. AT involves listening exercises that are designed to improve the function of the auditory system by capitalising on the brain's neural plasticity. Changes in the neural substrates are often associated with behavioural changes (Musiek et al., 2002). These changes can be measured in terms of listening performance, auditory and language processing assessments, and possibly in neuroimaging and neurophysiological tests (refer to Chapter 5 for more details).

Environmental modifications (for example, the addition of sound-absorbing materials such as carpets or floor rugs, and curtains, which can help reduce reverberation) may not always be sufficient for improving the listening conditions. An alternative to providing an effective listening environment is the use of assistive listening devices, such as personal or sound field frequency modulated (FM) systems. These wireless systems take advantage of the transmission of the speech signal (as sensed from a microphone worn near the speaker's mouth) via an FM radio wave to the receiver through a transmitter (see Chapter 5 for more details). FM systems help address the acoustic problem of distance and reduce the effects of background noise and reverberation, leading to SNR enhancement and better speech clarity (Crandell et al., 2004).

While there is some evidence to suggest that these manoeuvres help, there are no robust trials to support them. CAPD is an expanding field, and there is need for systematic, validated tests and studies to assess the efficacy of interventions.

1.11 Current Practice: Auditory Symptoms, Deficits, Assessment and Rehabilitation of Auditory Function after Stroke

The UK Royal College of Physicians' (2012) national clinical guidelines for stroke recommended that stroke patients be assessed shortly after admission for their ability to hear and to determine whether they need hearing aids, while a broad recommendation is made that any person who appears to have perceptual difficulties should have a formal perceptual assessment followed by intervention. Despite these recommendations, assessment of full auditory function (peripheral as well as central) after stroke is often neglected in current clinical stroke settings. It is not known to what extent recommendations for hearing assessment are adhered to for every patient in everyday clinical practice. Anecdotal experience indicates that this does not happen routinely in a systematic manner. Restoration of physical function in stroke is widely researched, with evidence demonstrating significant improvements following physical rehabilitation (Van Peppen et al., 2004). However, worldwide, strategies for the restoration of auditory function receive significantly less attention. Auditory rehabilitation post-stroke is arguably the 'lost dimension' of stroke rehabilitation.

1.12 Summary of the Literature Reviewed

1.12.1 Hearing Impairment in Stroke

- Stroke patients have an increased risk of impaired hearing due to cochlear and/or neural hearing loss and/or to disordered auditory processing within the brain. This may result directly from the stroke or may be a combined effect of vascular and age-related deterioration.
- Stroke can directly cause hearing loss depending on the type and the affected area along the auditory pathways. Hearing loss is largely seen in posterior circulation strokes and can produce sensorineural, subcortical (brainstem), or cortical components.

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- As stroke may also involve the auditory pathways in the brain, stroke patients may likewise suffer from additional auditory processing deficits that are not reflected by audiometric thresholds. Stroke patients may not declare any hearing complaints prior to a hearing questionnaire being administered, indicating that patients do not associate their perceived difficulties with their hearing.
- Stroke patients who are hearing impaired have an increased odds risk (1.83) of physical decline after discharge to the community.

1.12.2 Hearing Loss due to Stroke

- Peripheral hearing loss is observed in the vast majority of Anterior Inferior Cerebellar Artery infarction but rarely in Posterior Inferior Cerebellar Artery infarctions. Such hearing loss may occur in isolation. It could also be a prodromal symptom that responds well to early treatment.
- Brainstem and higher subcortical lesions involving the ascending auditory pathways may also affect the hearing thresholds, depending on the site and size of the lesion.
- Finally, hearing loss is also reported in patients with lesions in primary and secondary auditory cortices. However, the so-called cortical deafness may partly be due to attentional deficit in stroke patients. Recovery may or may not occur in such patients.

1.12.3 Hearing Evaluation in Stroke

- Hearing is not routinely assessed after stroke. Furthermore, because of other severe symptoms, patients may not be aware of their hearing loss at the time of their stroke. Hearing loss after stroke may be an important unmet need for stroke patients, and further research into its prevalence, patterns, detection, and treatment is required. Our review highlights the need for systematic, routine auditory evaluation of patients with stroke, in particular after posterior circulation strokes.

1.12.4 Auditory Rehabilitation

- The goal for auditory rehabilitation is to improve the functional deficits of individuals with specific impairments that are impacting social and communicative abilities. Restoration of physical function in stroke is widely researched. However, strategies for remediating auditory dysfunction receive significantly less attention, with auditory rehabilitation post-stroke arguably the ‘lost dimension’ of stroke rehabilitation.

1.13 Justification and General Aims of Current Investigations

The primary aims of this thesis were twofold. The first aim was to evaluate hearing function in a population of adults with stroke in two main areas: **a**, to determine the type of hearing impairment and compare the prevalence of different types of hearing impairment with a control group, and **b**, to evaluate the sensitivity and specificity of a hearing screening protocol. The second aim was to investigate the possibility of auditory rehabilitation for stroke patients with auditory processing disorders within two main areas: **a**, to investigate the immediate benefits of personal frequency-modulated (FM) systems in stroke patients with auditory processing disorders, and **b**, to investigate the long-term effect of FM systems after prolonged use in stroke patients with CAPD.

Although the MRI results and site of lesion for all stroke patients in this study were presented (Chapter 3), it is beyond the scope of this thesis to investigate the vascular pathology of the hearing impairment in our study sample. Rather, the main aim of the evaluation stage was to investigate what types of auditory impairments exist in stroke survivors and how frequent they are. Below we describe more detailed aims for each category.

1.13.1 Hearing Evaluation after Stroke: Current Studies'

Limitations and Challenges

Despite the potentially detrimental effects of stroke on the patient's hearing, auditory processing, communication, and quality of life, the audiological presentation after stroke remains under-investigated. It is still unknown how many patients in stroke units in the UK have hearing impairment that requires rehabilitation.

The aforementioned studies on the prevalence of hearing loss in stroke patients provides empirical evidence to indicate that stroke patients should be systematically assessed for hearing loss that may otherwise be missed. However, assessing patients for hearing disorders when they are in hospital, as was done in previous studies, can be challenging. For example, patients admitted into hospital with suspected stroke can be seriously medically unwell and have high levels of fatigue (Weir & Cadilhac, 2007). In addition, they often undergo multiple medical tests and procedures and are assessed by a wide range of different healthcare professionals, typically over the relatively short period of their inpatient stay (Weir & Cadilhac, 2007). It can often be both inappropriate and/or practically difficult to attempt to administer separate hearing assessments with these patients in addition to their other tests. Furthermore, auditory recovery at the chronic post-stroke stage has been reported previously (Musiek, 1980; Rey, 2007). Therefore, it is necessary to assess these patients' hearing in the chronic stage of stroke. At present, there is little, if any, information on the prevalence of hearing impairment in stroke patients in the **chronic** post-stroke stage.

When determining the appropriate management that could be given to stroke patients in order to improve their quality of life, it is important to note that hearing impairment could be of central origin; it is not mediated solely at the periphery. However, there are no studies, to our knowledge, that have systematically characterised the type of hearing impairment in this population. The major flaw with previous studies regarding hearing impairment in stroke patients is that full audiological assessments (i.e. with the full battery to assess the central auditory tracts in conjunction with the routine assessments) have not been conducted in order to classify the hearing impairment in this cohort of patients. When hearing impairment

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with central origin is present, its characteristics may vary (Polster and Rose, 1998), may go undetected unless specifically sought for (Blaettner et al., 1989), and may impact patient communication in everyday life in the chronic stage of stroke, as reported by patients (Bamiou et al., 2012). These patients may require a range of rehabilitation and remediation beyond those of conventional approaches.

Suggesting a wide-ranging auditory assessment to all stroke patients would be an expensive and inefficient procedure. Therefore, a preliminary screening test for such patients is required so that the full audiological assessment could be reserved for those who fail the initial hearing screening. However, there are no studies to date validating a hearing screening protocol that can be used in the stroke population.

We proposed to examine hearing in detail and to characterise the different types of hearing impairment in stroke patients in a systematic, observational, case-control study with the ultimate aim of developing a better taxonomy of hearing impairment in stroke patients. We also aimed to determine whether a handheld hearing screener together with two validated hearing questionnaires could be used as a hearing screening tool to facilitate early identification and appropriate referral of hearing impaired stroke patients in the subacute stage.

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To recap, the main aims of the evaluation stage were:

Auditory Assessment

- To assess the status of auditory impairment in stroke patients in the post-stroke subacute stage in order to identify the prevalence of all types of hearing impairment in this cohort.
- To compare the prevalence and type of hearing impairment in the stroke patients with the age-matched controls.

Patient Reported Hearing Difficulty and Validating an Auditory Screening Protocol

- To examine the sensitivity and specificity of a handheld hearing screener in stroke patients, using the ASHA protocol ('gold standard': the results of pure-tone audiometry).
- To examine the sensitivity and specificity of the HHIE questionnaire in stroke patients ('gold standard': information from different audiological tests was combined to construct the reference standard outcome).
- To examine the sensitivity and specificity of the AIAD questionnaire in stroke patients ('gold standard': information from different audiological tests was combined to construct the reference standard outcome).
- To evaluate the effectiveness of combined screening tools (handheld hearing screener, HHIE questionnaire, and AIAD questionnaire) in identifying the different types of hearing impairment ('gold standard': information from different audiological tests was combined to construct the reference standard outcome).

The secondary aim was:

- To explore auditory symptom differences among stroke patients with normal hearing, peripheral hearing loss, combination hearing impairment (peripheral and CAPD), and CAPD.

1.13.2 Auditory Rehabilitation after Stroke

Patients may receive conventional hearing aids if an apparent peripheral hearing loss is detected. However, hearing aid amplification for a patient with auditory processing deficits may not alleviate this specific disorder. As discussed previously, auditory disability due to impaired auditory processing, despite normal pure-tone thresholds, is common after stroke, but there are currently no proven remedial interventions for AP deficits in stroke patients. In addition, there are no formal investigations of a long-term treatment strategy in adult stroke patients with AP deficits but normal hearing. (More details are in Chapter 5.) We aimed to examine the effectiveness of personal frequency-modulated (FM) systems in stroke patients with disordered AP. Also, the present thesis evaluates the long-term potential benefits in speech-perception of personal FM system when used daily over ten weeks by non-aphasic stroke patients with a diagnosis of auditory processing deficits. It investigates whether auditory plasticity occurs after the prolonged use of FM systems.

To recap, the main aims of the auditory rehabilitation stage were:

Auditory Rehabilitation

- To examine the effectiveness of personal frequency-modulated (FM) systems in stroke patients with disordered auditory processing.
- To evaluate the potential benefits in speech-perception of personal FM systems when they are used daily over ten weeks by non-aphasic stroke patients with a diagnosis of auditory processing deficits.

1.14 General Hypotheses

The possible presence of various auditory impairments in the stroke population, alongside the above presented review, leads to four broad hypotheses, presented below. (The chapters within which each hypothesis is investigated are indicated in brackets).

- i. (a) The percentage of hearing impairment in stroke patients, in the chronic post-stroke stage, would be higher than the control group, given that stroke can cause hearing loss. (b) Given the possible involvement of central auditory pathways in stroke, it is also expected that the incidence of the central type of hearing impairment would be higher in the stroke group compared to the control group. (c) Given the high prevalence of hearing loss in older adults and of a possible predated hearing impairment in this population, along with the involvement of central auditory tracts, this study expects to observe different types of hearing impairments in younger and older stroke groups. One type is the isolated AP deficit with normal hearing thresholds in the younger group. The other type is a combination of peripheral and central impairment in the older group due to the combination of age-related hearing loss and the auditory central impairment as a consequence of the stroke (Chapter 3).
- ii. (a) The combination of a handheld hearing screener together with the AIAD and HHIE questionnaires is expected to be a sensitive and specific hearing-screening tool for detecting any type of hearing impairment in the stroke population (all types of vascular pathology) in the chronic post-stroke stage. (b) The scores of self-reported auditory symptoms, as assessed on validated hearing questionnaires in stroke patients who are diagnosed with CAPD, are expected to be significantly worse than those of stroke patients who do not fulfil the diagnostic criteria for CAPD (Chapter 4).
- iii. Non-aphasic stroke survivors without any cognitive impairments and with difficulties hearing speech-in-noise due to disordered auditory processing despite normal pure-tone thresholds would show an immediate improvement in understanding speech in background noise with binaural frequency modulated (FM) systems in a laboratory testing environment (Chapter 5).

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iv. The non-aphasic stroke group is expected to demonstrate improved speech-perception in noise performance, whether aided and unaided, after wearing the FM systems for ten weeks in comparison to the performance of a control group of stroke patients who have not been wearing an FM system (Chapter 6).

The investigations of this thesis will seek to test each of these hypotheses using appropriate methods that are described in Chapter 2. It is hoped that the findings will provide insight into both the hearing function and the rehabilitation of stroke patients.



2 Chapter 2: Materials and Methods

All materials and methods used in the following four chapters are set forth in details in this section.

2.1 Thesis Structure

This research project was divided in three separate studies (Study 1, Study 2, and Study 3: Phases I & II) that are presented in Chapters 3 to 6. More detailed descriptions of the participants, methods, and statistical analyses are given in each chapter.

Chapter 3 describes the type of hearing impairments and identifies the prevalence of all types of hearing impairments in the stroke cohort in comparison to the non-stroke control group.

Chapter 4 describes the performance of a hearing screening tool for identifying hearing impairments in individuals with stroke, the auditory characterisation of stroke patients with different types of hearing impairment as reported by validated questionnaires, and the differences in the questionnaire scores between each group of hearing types in this stroke cohort.

Chapters 5 and 6 (Study 3: Phases I & II) describe the evaluation of the potential immediate (Chapter 5) and long-term (Chapter 6) benefits in speech-perception in noise with personal FM systems in non-aphasic stroke patients with auditory processing deficits.

Chapter 7 presents a summary of the findings and conclusions.

2.2 Ethics Approval

The Ethics Committee of the National Hospital for Neurology and Neurosurgery approved the Hearing Evaluation and Auditory Rehabilitation after Stroke (HEARS) study (Project Identification number 11/0469 and REC ref 11/LO/1675). We obtained written informed consent from all the stroke and control participants.

HEARS**2.2.1 Amendment**

The London Queen Square National Health Service Ethics Committee approved an amendment (11/LO/1675 AM03). Frequency Modulated systems (FMs) were given to any participants who wished to use the FM systems after their second visit, at the end of the ‘FM treatment trial’.

2.3 Setting

This study was supported by the NIHR clinical research network. Patients were recruited by a research nurse from the stroke research network (SRN) team, from the National Hospital for Neurology and Neurosurgery [NHNN] stroke unit, and the hyper-acute stroke unit [HASU] at the University College London Hospitals [UCLH]. For the hearing evaluation stage (studies 1 and 2, with the results provided in Chapters 3 and 4), the participants were tested at the NHNN, and for the rehabilitation stage (study 3, with the results provided in Chapters 5 and 6), at the Royal Nose Throat & Ear Hospital [RNTNEH].

In addition to the recruited stroke patients mentioned above, healthy adult volunteers were recruited from friends, colleagues and staff members of the UCLH and NHNN. The control group members were tested at the neuro-otology department, NHNN.

2.4 Study Population**2.4.1 Stroke**

Sixty-five consecutive stroke patients (see the CONSORT flowchart presented in Figure 2-2, p. 52) who met the study inclusion criteria were recruited from the NHNN stroke unit and hyper-acute stroke unit [HASU] at the UCLH.

The inclusion and exclusion criteria were as follows:

Inclusion criteria:

- a. Adults aged between 18 and 80 years old.

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b. Clinical history of a single stroke verified by magnetic resonance imaging (MRI) of the brain.

Exclusion criteria:

a. Severe aphasia.

b. Cognitive impairment as shown on the Montreal Cognitive Assessment (MoCA).¹

c. Psychiatric illnesses, other neurological disorders (except stroke), and severe concurrent medical illnesses.

Of the 65 stroke patients, a final fifty were recruited to study 1 (see Figure 2-2 for more details). The patients were tested at the department of Neuro-otology, NHNN Queen Square, within three to twelve months post-onset stroke. Because one of the aims of this study was to characterise the type of hearing impairment, those with severe or greater hearing loss, as shown on the audiogram, were excluded after the completion of pure-tone audiometry. Some of the audiological assessments, such as gaps-in-noise and auditory-evoked brainstem responses, cannot be interpreted if a severe or greater hearing loss exists. Of these 50 stroke patients, three had a severe or greater hearing loss (pure-tone average). A further five were excluded as their second Montreal cognitive assessments (MoCA) were not within normal limits. A final 42 patients were included in the study. Of these 42 stroke patients, ten fulfilled the FM feasibility study inclusion criteria (see Figure 2-2) and were invited to participate in the rehabilitation study. One declined due to other research involvement. Nine patients attended the clinic on a second occasion to complete the feasibility study (Phase I) test protocol. Of these nine patients, four participants agreed to take part in the FM Phase II study. (More details are in Figure 2-2).

2.4.2 Control Group

Forty healthy controls (without a history of stroke) were recruited from the hospital staff, colleagues, hospital visitors and friends. All healthy volunteers who agreed to

¹ The MoCA was completed as a routine cognitive assessment in the acute stage before the point of discharge. If a mild or greater cognitive impairment was detected the test was re-administrated 3 months after the stroke in the UCLH stroke follow-up clinic. The SRN only referred those with no impairments or mild cognitive impairments. We reviewed the second MoCA assessment and excluded those showing cognitive impairment.

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take part in the study were given a participant information sheet and signed a written consent form. Known hearing loss was not an exclusion criterion. However, those with other than presbycusis hearing loss would have been excluded (the cause of hearing loss was asked in the medical interview). None of the controls received an MRI scan.

The inclusion and exclusion criteria for the control group were as follows:

- a. Adults aged between 18 and 80 years old
- b. No cognitive impairments, psychiatric illnesses, neurological disorders, vascular diseases, or diabetes, as reported by the volunteers themselves during the initial medical interview

2.4.3 Age Range

The histogram in Figure 2-1 (following page) shows the distribution of the participants in the stroke and healthy control groups. The mean age of the participants in the stroke and healthy groups (18-80 years old) were 58.19 years (SD=15.06) and 53.8 years (SD=15.33) respectively, with no statistically significant difference found between the two groups (Kruskal-Wallis rank sum test, $p = 0.172$).

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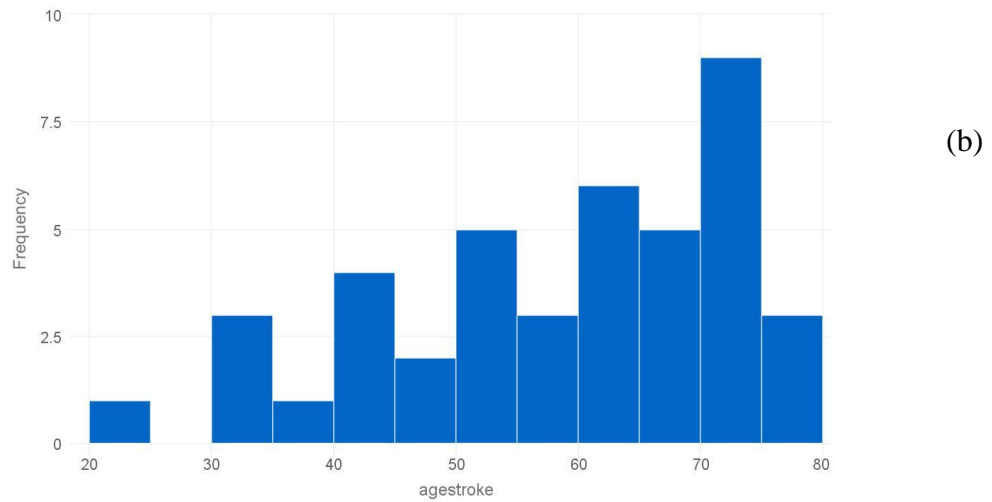
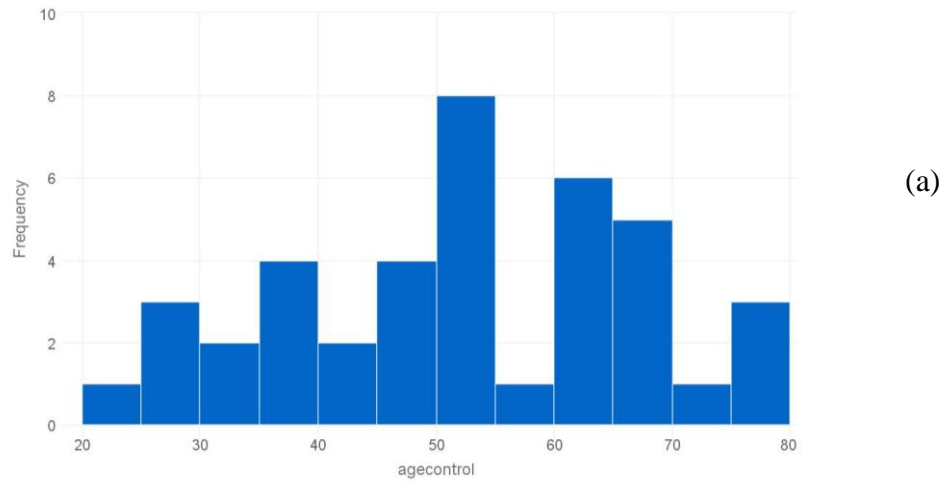
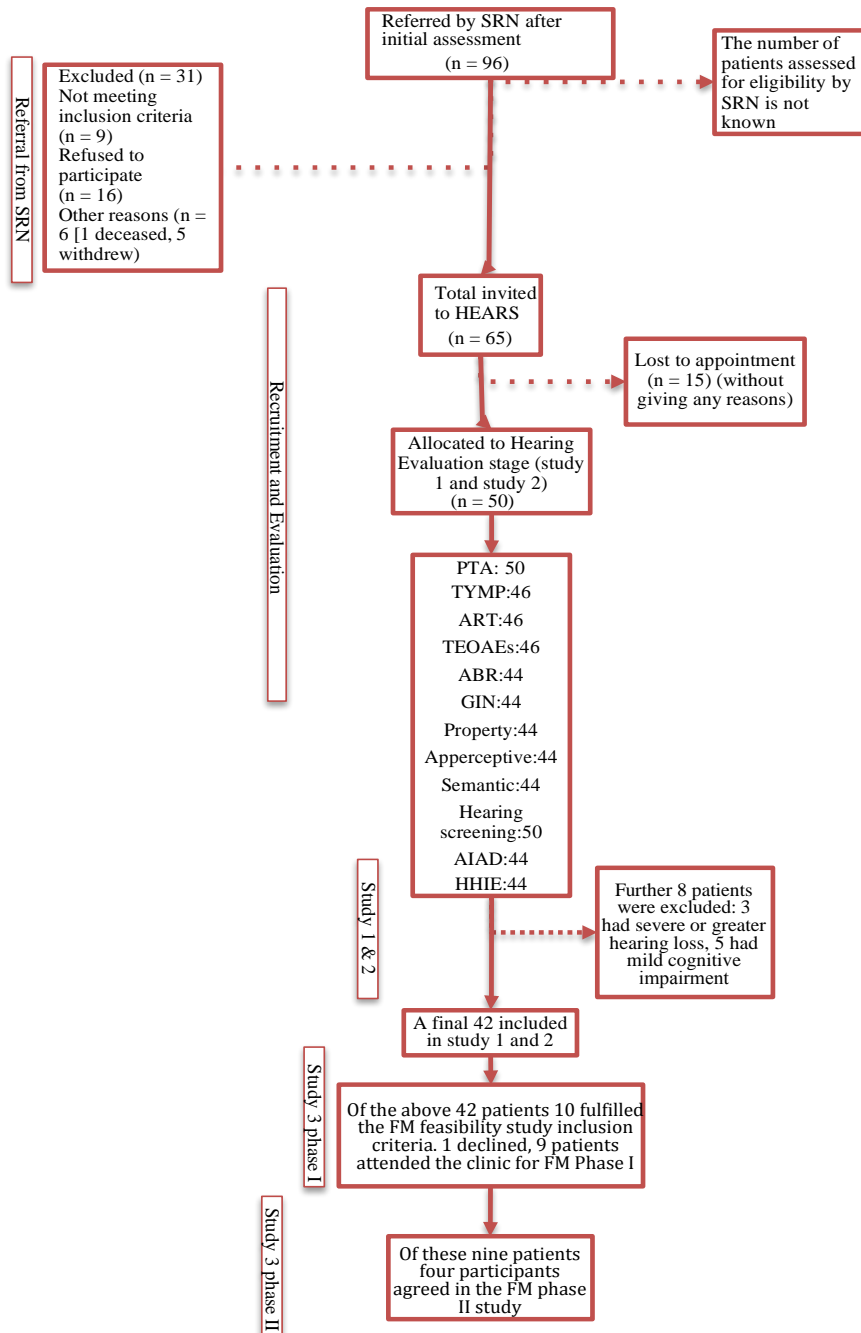


Figure 2-1: Histograms showing the distribution of age in a) control group, and b) stroke group

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Figure 2-2: the CONSORT diagram showing the flow of participants through each stage of the HEARS study. KEYS: SRN, stroke research network; PTA, pure-tone audiometry; TYMP, tympanometry; ART, acoustic reflex thresholds; TEOAEs, transient otoacoustic emissions; ABR, auditory-evoked brainstem responses; GIN, gaps-in-noise; AIAD, Amsterdam inventory for auditory disability; HHIE, hearing handicap inventory for elderly



2.5 Materials

The equipment used for the MRIs was:

- 1.5 Tesla GE Signa scanner (General Electric, Milwaukee, WI)

The equipment used for audiological assessment consisted of:

- Otoscopy
 - Welch Allen Otoscope (Guymark UK Limited, UK)
- Tympanometry and Acoustic Reflexed thresholds
 - GSI 33 Middle Ear Analyzer (Grason-Stadler Inc., Milford, New Hampshire)
- Audiometry
 - GSI 61 audiometer with TDH-39 headphones
- Transient Evoked Otoacoustic Emissions
 - the ILO v6 (dual channel)
- Auditory-evoked Brainstem Responses
 - Nicolet Spirit 4 channel equipment (Nicolet, Madison, Wisconsin)
- Auditory processing tests
 - Sony CD Player (passed through a GSI 61 diagnostic audiometer to TDH-39 matched earphones)
- Auditory cognition and speech-in-babble tests
 - Matlab-based signal-synthesis algorithm (version. 2012b) over Sennheiser (Wedemark, Germany) HD 600 supra-aural headphones

The Equipment used for the Hearing Screening was:

- ROTO (frequency range 250-6000 Hz intensity range 20 - 70 dB HL, Otovation) warble-tone screening device
- SL-4010 LUTRON Digital Sound Level Meter

The Hearing Questionnaires used were:

- The (modified) Amsterdam Inventory for Auditory Disability and Handicap (AIAD) (Meijer et al., 2003)

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- Hearing Handicap Inventory for Elderly (HHIE) (Weinstein et al., 1986)

The equipment used for the evaluation of speech in noise recognition in the auditory rehabilitation study was:

- AB-York Crescent of Sound (Kitterick et al., 2011)

The device used for the auditory rehabilitation was:

- iSense Micro receiver
- ZoomLink+ transmitter

The questionnaires used for the inclusion criteria for the auditory rehabilitation study were:

- Western Aphasia battery (with a cut-off of 93.8) (Kertesz, 1982)
- Montreal cognitive assessment (scores of 25.2-30 were considered indicative of no cognitive impairments) (Nasreddine et al., 2005)

2.6 Methods

The methodology used for each of the studies undertaken will be presented under the following three sections: A) Hearing evaluation and screening process (Studies 1 and 2). B) Auditory rehabilitation process FM study Phase I. C) Auditory rehabilitation process FM study Phase II.

2.6.1 Hearing Evaluation and Screening Stage (Study 1 & 2)

2.6.1.1 Study Design

This observational case-control study incorporated a stroke group and a control group. Both groups were matched for age. They all underwent thorough audiological assessments performed in a single session. The stroke patients had their assessments over a single session, 3 to 12 months after stroke onset. The timing of these tests took into account that auditory deficits can be reversible during the hyper-acute and acute stages of stroke (Rey et al., 2007). Test results were explained to the participants after the testing session. A detailed report with the test results and recommendations

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for further audiological management, to be taken up by the local services, was provided to every participant tested. Please see Figure 2-7 (p. 73) for further details.

2.6.1.2 Background Assessments

Brain Imaging Acquisition

All the participants had a brain MRI performed with a 1.5 Tesla GE Signa scanner (General Electric, Milwaukee, WI) 48 hours after the stroke. The acquisition techniques included diffusion weighted imaging and T1- weighted three-dimensional fast low-angle-shot images for volumetric and morphometric analyses. The scan acquisition parameters for the volumetric T1 weighted imaging were: repetition time = 15 ms; echo time = 5.4 ms; flip angle = 15; inversion time = 650 ms. All scans were reviewed by a consultant stroke neurologist (DW) and a consultant neuro-radiologist (CH) in order to identify and categorise stroke-related structural brain abnormalities.

Cognitive Assessment

The Montreal Cognitive Assessment (MoCA) (Nasreddine et al., 2005) includes sections on visuospatial/executive function (alternating trail-making, cube copy, clock drawing), naming (lion, rhinoceros, camel), attention (forward and backward digit span, tapping to the letter A, subtracting 7s from 100), language (sentence repetition, letter fluency), abstraction (similarities between train and bicycle, watch and ruler), memory (delayed verbal recall of 5 words) and orientation to time and place (6 questions). A qualified neuropsychologist or a stroke specialist nurse (blind to the study) administered the MoCA in the acute stage. If a mild or greater cognitive impairment was detected, the test was re-administrated 3 months after the stroke in the UCLH stroke follow-up clinic, a routine UCLH procedure. The SRN team only referred those with no impairments or with mild cognitive impairments. We reviewed the second MoCA assessment for those with mild cognitive impairment and excluded those showing impairment on the second attempt (scores of 25.2-30 were indicative of no cognitive impairment).

HEARS***2.6.1.3 Routine Audiological Test Battery at the NHNN Neuro-otology Department*****Clinical Examination**

Before the audiological assessment, we conducted a short medical history interview. We collected information about the patients' hearing status. Careful inspection of the ear, including the auricle, the external auditory meatus, and the tympanic membrane, was conducted. Presence of a collapsing external acoustic meatus, obstructing wax, and abnormalities of the tympanic membrane were noted. We removed wax, using syringing or micro-suction, if it were present in the patient's external ear canal.

Pure-Tone Audiometry

Pure-tone audiometry (PTA) was carried out using a calibrated GSI 61 audiometer with TDH-39 headphones (Grason-Stadler Guymark UK Limited, Veronica House, West Midlands, UK). Air-conduction thresholds were measured for each ear at 0.25, 0.5, 1, 2, 3, 4, 6 and 8 kHz following the procedure recommended by the British Society of Audiology (BSA) (2011). Results were averaged in each ear across the frequencies of 0.5, 1, 2, 4, and 8 kHz for the 'PTA average', and at 4, 6, and 8 kHz for the 'high-frequency average' (HFA). Normal hearing thresholds were considered < 20 dB across the above frequency range, as recommended by the BSA (2011). The degree of hearing loss was then classified as mild (20–40 dB HL), moderate (41–70 dB HL), severe (71–95 dB HL), or profound (>95 dB HL) (Figure 2-3, following page, as recommended by the BSA [2011]). In order to be able to characterise the hearing impairments, those with severe or greater hearing loss were later excluded from the study.

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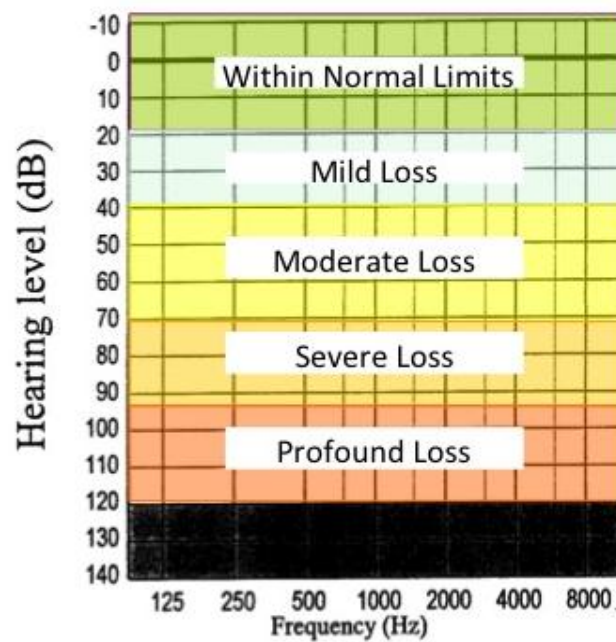


Figure 2-3: An audiogram with areas shaded to demonstrate the degree of hearing loss (BSA, 2011)

Tympanometry

Tympanometry (TYMP) measurement is a technique for obtaining information about the state of the middle ear. The measurements are derived from ear canal pressures. The graph produced is an expression of how the immittance of the ear is altered when the external ear canal is pressurised above and below atmospheric pressure. Aural immittance has an important clinical use in identifying high impedance middle ear abnormalities, i.e. otitis media and otosclerosis, and low-impedance abnormalities such as ossicular interruption. It is an objective, non-invasive and well-tolerated measure.

Tympanograms were obtained with a continuous probe-signal of 226-Hz tone at 85 dB sound pressure level using a GSI 33 Middle Ear Analyzer (Grason-Stadler Inc., Milford, New Hampshire). The tympanogram results (TYMP) were considered normal if the middle ear pressure was -150 mm H₂O or greater and the compliance was greater than 0.3 cm.

HEARS**(Stapedial) Acoustic Reflexes Thresholds**

The stapedial acoustic reflex is an acoustically evoked contraction of the stapedius muscle. Figure 2-4 (p. 59) is a schematic view of the neural pathways of the acoustic reflex arc proposed by Borg (1973). The auditory nerve, the low pons, and the facial nerve must all be intact to provide a normal acoustic reflex.

The ipsilateral and contralateral acoustic reflex thresholds (ART) were measured on a calibrated GSI 33 Middle Ear Analyzer at 0.5, 1, 2, and 4 kHz at levels ranging from 70 dB HL up to a maximum of 120 dB HL, in 5 dB steps, to assess middle-ear, cochlear, VIIIth- nerve, and lower brainstem functions. A consistent change in the compliance of the middle ear $\geq 0.03\text{ml}$ following stimulation was the criterion for the presence of the acoustic reflex. Acoustic reflexes were considered abnormal if they exceeded 105 dB nHL at two or more adjacent frequencies, or if the interaural threshold difference exceeded 10 dB on at least two adjacent frequencies (Cohen and Prasher, 1988). The patterns interpreted as indicating a brainstem lesion were the ‘vertical’ (abnormal ART by stimulation of one ear only), ‘horizontal’ (ART abnormal by contralateral stimulation of both ears), ‘inverted-L’ (combined vertical and horizontal) and ‘full house’ (all ipsilateral and contralateral reflexes abnormal) (Cohen and Prasher, 1988).

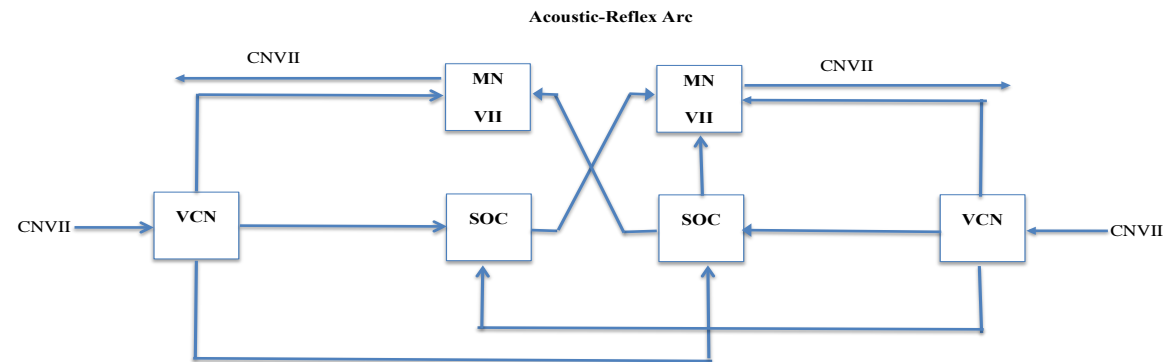


Figure 2-4: A schematic view of the acoustic-reflex based on the rabbit model (Adapted from Borg, 1973). The arc involves input through CNVIII to the ventral cochlear nucleus (VCN), from which there are neural pathways through the two superior olivary complexes (SOC) to the motor nuclei of CNVII (MN VII) and the CNVII that innervates the stapedius muscle.

HEARS**Transient Evoked Otoacoustic Emissions**

Transient evoked otoacoustic emissions (TEOAEs) analyse the function of the outer hair cells (Kemp, 1978). Click stimuli were delivered through a probe in the ear canal. The inner ear responses to the click stimuli were recorded automatically. A dual channel analyser was utilised. A linear click at 80 (± 3) dB SPL intensity, with 260 averages, was used for ipsilateral stimulation. The repetition rate was 50/s, and the post-stimulus recording time was 20 ms. The fast Fourier transform (FFT) spectrum analysis and average waveform calculations were performed automatically by the ILO v6 Otodynamic Analyser system. Normal responses were considered finding overall TEOAEs amplitudes >12 dB or amplitudes of ≥ 6 dB in at least three adjacent frequency bands.

Auditory-evoked Brainstem Responses

The generators of the auditory-evoked brainstem responses (ABR) have been the subject of much research and controversy and are still not entirely agreed upon. The first peak in the sequence, peak I, is the only one for which there is general agreement regarding its generator. This peak is the only one to survive the section of the cochlear nerve central to the internal auditory canal, placing its origin in the cochlea. Peak III is generally agreed to be generated in the brainstem, but there is disagreement about the exact origin. Suggested generators span the lower brainstem between the cochlear nucleus, through the trapezoid body to the superior olivary complex. All evidence points to the generators of the IV-V complex as being in the upper pons, between the superior olivary complex, through the lateral lemniscus, with a possible contribution from the inferior colliculus. The ABR is generally accepted as a tool to study the function of the brainstem auditory nuclei and tracts, is very sensitive to brainstem abnormalities, and is useful in evaluating undetected damage to the auditory system (Hosford-Dunn, 1985; Chiappa, 1997; Pillion et al., 2008; Jiang et al., 2010).

The ABR were recorded with the Nicolet Spirit 4 channel equipment (Nicolet, Madison, Wisconsin). Electrodes were placed on the forehead (A) and on each mastoid (A1 and A2); the A electrode was used as the ground. Monaural alternating click stimuli of 100 microseconds were presented at a rate of 11.1/second via

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headphones. Electrode impedance was less than 5 kOhms. The electrical activity was amplified and filtered (range, 100-3000 Hz). A total of 1000 stimuli were given, with a mean window of 10 milliseconds. A standard minimum intensity of 90 dB was used, provided that clear waveforms with waves I, III, and V were observed; 100 dB nHL was used for those with hearing loss. Analysis of the ABR was restricted to waves I, III, and V. Waveform morphology, peak latency, and interwave latency were compared with normative departmental data. Peak I broadly corresponds to the distal portion of the VIIIth nerve, peak III to the superior olivary complex, and wave V to the termination of the lateral lemniscus axons at the inferior colliculus (Möller, 1998). Subjects were categorised as normal if no deficits in either ear were detected or if the absolute latencies were delayed with normal interwave intervals when an audiometric hearing loss was present (Musiek et al., 1996). Otherwise, they were classified as abnormal. The ABR were recorded only in subjects with up to moderate hearing loss (at 2 and 4KHz frequencies). The departmental normative data are presented in Table 2-1.

Table 2-1: ABR normative data from the Queen Square neuro-otology department: KEY: I, wave 1; III, wave 3; V, wave 5; ms, millisecond.

I	III	V	I-III	III-V	I-V	IAD-V	IAD I-V
1.31-1.83 ms	3.40-4.08 ms	5.18-6.01 ms	1.83-2.52 ms	1.49-2.19 ms	3.54-4.48 ms	<0.22 ms	<0.36 ms

2.6.1.4 Non-verbal Auditory Processing Test Battery

Cognitive and language impairments are common after stroke (Tatemichi et al., 1994; Sinanovic et al., 2011), and the presence of such conditions may potentially affect the behavioural auditory processing test battery (Gates et al., 2010). Auditory processing tests in general should include both non-verbal and verbal stimuli to examine different aspects of auditory processing (AAA, 2010; BSA, 2011). However, performance on speech-based behavioural tests is heavily influenced by linguistic factors and cognition (Loo et al., 2013; Gates et al., 2010). The present study thus opted to utilise a non-verbal auditory processing test battery that would place minimal demands upon language, working memory and attention of the stroke patients. Temporal resolution is important to speech perception, and its assessment provides insight into the neural integrity of the central auditory nervous system

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(CANS) (Gordon-Salant and Fitzgibbons, 1993; Walton et al., 1997). Gaps-in-noise (GIN) is a test of temporal resolution that has a known high sensitivity and specificity to the central auditory nervous system (Musiek et al., 2005). The GIN employs non-verbal stimuli and a non-verbal response mode.

Goll et al. (2010) proposed that the main processing stages of non-verbal auditory cognition could be conceptualised as the early perceptual, apperceptive and semantic levels, and thus developed the Queen Square Tests of Auditory Cognition (QSTC) auditory processing battery.

The QSTAC comprises individual sound categorisation and sequential comparison tasks that were specifically designed to minimise cognitive and linguistic demands on the patient. This battery has been utilised in patients with cognitive disorders (Goll et al., 2010). This test battery probes spectral property processing, apperceptive processing, which refers to the perceptual representation of whole ‘auditory objects’ (Nelken & Bar-Yosef, 2008), and semantic auditory processing, which refers to the association of stored knowledge (i.e. semantic memory) with the perceptual (apperceptive) object representations (Goll et al., 2010).

Gaps-in-Noise (GIN)

GIN is a test of temporal resolution that provides an estimate of threshold (shortest gap identified), a total percentage correct responses score, and an estimate of attention levels (% accuracy at different gap duration levels). The sensitivity of the GIN with respect to cortical lesions is 67%, and the specificity is 94% (Musiek et al., 2005). All participants in this study were tested in a sound-treated booth. The GIN stimuli, which were previously recorded on a compact disk, were played on a Sony CD Player and passed through a GSI 61 diagnostic audiometer to TDH-39 matched earphones. Regarding the presence of peripheral hearing loss, while some studies have reported a hearing loss effect on GIN performance (Leigh-Paffenroth & Elangovan, 2011; John et al., 2012), others have demonstrated that the GIN threshold is affected only when the stimuli is presented below 35 dB SL (Weihsing et al., 2007). In the present study, the stimuli were consistently presented at 50 dB sensation level re: PTA to each ear independently (Musiek et al., 2005). The GIN is composed of a series of 6-sec segments of broadband noise containing 0-3 silent

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intervals, or gaps, per noise segment. The inter-stimulus interval between successive noise tokens (segments) is 5 seconds, and the gap durations presented are 2, 3, 4, 5, 6, 8, 10, 12, 15, and 20 msec. Both gap duration and the location of gaps within the noise segments are pseudorandomised in regard to their occurrence. In addition, the number of gaps per noise segment is varied. These variances in the number, duration, and placement of the gaps were incorporated as a test feature in the GIN to decrease both the probability of guessing correctly and the number of trials needed to obtain statistically significant information. Five practice items precede the administration of the test items (Musiek et al., 2005). The departmental normative data at NHNN are correct responses of 50% or more at a minimum threshold of 6 msec.

OSTAC- Property Processing

Auditory perceptual property processing includes the representation of individual properties like frequency, pitch and timbre, but not whole sound objects. Sounds were digitally generated using a Matlab-based signal-synthesis algorithm (Warren et al., 2005), which enabled the generation of harmonic series with specified spectral shape. Different ‘trapezoidal’ spectral shapes were created in the frequency domain by varying the gradient of the ‘ascending’ slope of the frequency trapezoid. Frequency bandwidth, sound duration and temporal envelope were held constant. The fundamental frequency and average intensity (Root Mean Square level) values were varied across the stimulus set to reduce any tendency for subjects to use the absolute intensity level in a particular frequency band to perform the test. 32 sound pairs were created. There were 16 ‘same’ pairs comprising identical sounds, and 16 different pairs comprising sounds that differed only in spectral shape. The sounds in each pair were presented sequentially (inter-stimulus interval: 1 second). All experimental auditory cognition tests (property, apperceptive, and semantic processing) were run under Matlab 2012b® (www.mathworks.com) on a desktop computer. Sounds were delivered using a high-fidelity external soundcard (Edirol® UA-4FX) and linear headphones (Sennheiser® HD265) at a comfortable listening level (50 dB SL re: PTA). Subject responses were entered directly by the experimenter (NK), and saved for offline analysis. For all auditory cognition tests, performance on each test item was probed using a simple question with two alternative responses. Answers could be given verbally, or in the case of speech

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output difficulty, by pointing to a prompt sheet displaying the two responses. Each test was prefaced with a brief example phase of 6 items to ensure subjects understood the test. The raw scores were compared with the normative data obtained by Goll et al. (2010).

OSTAC- Apperceptive Processing

The term apperceptive processing refers to mechanisms that enable the perceptual representation of whole objects prior to the attribution of meaning. The key experimental manipulation here was spectral inversion (SI) (Blessner, 1972). The SI procedure flips the frequencies of the energies present in a broadband sound (i.e. it exchanges the energy present between higher and lower frequencies) about a user-specified frequency value to create a frequency structure that is ‘impossible’ in a natural sound. Goll et al. (2010) selected 20 animal and human vocalisations from online sound databases (e.g., www.sonomic.com; www.soundrangers.co.uk). Individual items were chosen to vary the ease with which they were identified by normal subjects (Goll et al., 2010). Each natural sound was modified using SI to create an additional set of 20 novel sounds.

For the auditory apperceptive test, the 40 sounds (20 non-SI, 20 SI) were presented individually in a fixed balanced order; conditions were randomly distributed throughout the test sequence. For each sound, the subject was asked: ‘Is it a real thing or not a real thing?’. The raw scores were compared with the normative data obtained from Goll et al. (2010).

OSTAC- Semantic Processing

Assessments were designed to examine the association of conceptual meaning with environmental sound objects. Thirty-two individual sounds representing a range of human and animal sounds and environmental noises were chosen and arranged to constitute 32 pairs of sequentially presented sounds. In the experimental test, sounds were paired such that the individual sounds in a pair had dissimilar acoustic characteristics in order to reduce the availability of perceptual matching cues. In the ‘same’ pairs, sounds were produced by the same source (e.g. horse neighing, horse galloping). In the ‘different’ pairs, sounds were produced by different sources (e.g.,

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horse neighing, human coughing). All 32 sounds appeared once in the ‘same’ and once in the ‘different’ condition to control for item-specific effects. For the auditory apperceptive test, the 40 sounds (20 non-SI, 20 SI) were presented individually in a fixed balanced order. Conditions were randomly distributed throughout the test sequence. For each sound, the subject was asked, ‘Is it a real thing or not a real thing?’

2.6.1.5 Hearing Screening Tools

Handheld Hearing Screener as a Screening Tool

We screened hearing using the protocol recommended by ASHA (1997), presenting pure-tones at 25 dB HL at the frequencies of 1000, 2000, and 4000 Hz. The objective was to present a 25 dB HL warble tone at the above-mentioned frequencies through an earphone to each ear separately and to record a positive or negative response. A handheld screener, the ROTO warble-tone screening device (frequency range 250-6000 Hz, intensity range 20 - 70 dB HL, Otovation), was used (Figure 2-5, below). The device and earpiece were calibrated on a yearly basis with either the IEC 60645-1 (2001) or the American National Standards Institute (ANSI) S3.6 and ISO 389-1 (1998) standards, according to locale. More details are in Chapter 4.



Figure 2-5: demonstrates the hearing screening device, ROTO. Image from: <http://aimtechnologies.ca/products/audiometersscreening-2>

HEARS**Sound Level Meter**

Ambience noise levels were continuously checked with a calibrated sound level meter (Figure 2.6). Signal was presented to the patient only when noise levels were ≤ 39 dB SPL. The acceptable background noise level was calculated according to British Society of Audiology (BSA) standard on pure-tone air-conduction and bone-conduction threshold audiometry with and without masking (2011). The noise levels are set to provide accurate air-conduction threshold of ≥ 0 dB HL. In this research, the hearing-screening device was able to detect hearing thresholds ≥ 25 dB HL. Therefore, we added 25 dB to every value presented in the guideline. The noise level (read from the sound level meter) was calculated according to the recommendations of the International Electrotechnical Commission [IEC], IEC 61672-1. A commercial handheld sound level meter, which shows the average sound level from all frequencies, was used. The averaging technique, called A-weighting, was used. A-weighting takes into account the fact that the human ear does not perceive sounds of different frequencies with equal loudness. As a result, the sound level measure weights the sounds from different frequency accordingly. Table 2-2 shows the acceptable background noise level recommended by BSA.

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Table 2-2: The acceptable background noise level recommended by BSA: KEY: Hz, hertz; dB, decibel; HL, hearing level; SPL, sound pressure level; IEC, International Electrotechnical Commission

	Acceptable noise level recommended by BSA for testing hearing level of 0dB HL (dB SPL)	Acceptable noise level recommended by BSA for testing hearing level of 25dBHL (dB SPL)	Frequency A-weighting by sound pressure level meter by IEC (dB)	Acceptable noise level measured by sound pressure level (dB SPL)
500Hz	18	18+25=43	-3.2	43-3.2= 39.8
1000Hz	23	23+25=48	0	48+0= 48
2000Hz	30	30+25=55	+1.2	55+1.2= 56.2
3000Hz	33	30+25=55	+1.2	55+1.2=56.2
4000Hz	36	26+25=41	+1	41+1= 42

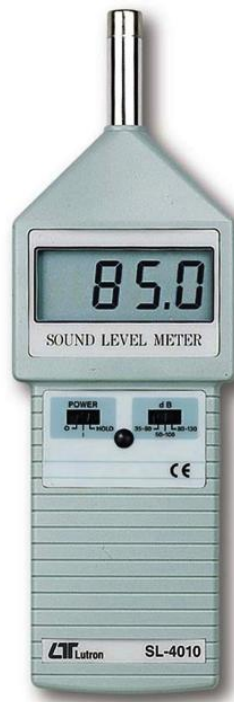


Figure 2-6: Sound Level Meter (SLM)

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From the table above (Table 2-2), we calculated the acceptable background noise levels read by the sound level meter. For our research, the levels needed to be below 39.8 dB SPL. During audiological screening, the sound level meter was monitored at all times. When ambient sound levels exceeded this calculated reference, the testing condition was considered ‘non-appropriate’. The test was interrupted and peripheral noise was minimised (e.g. by closing the door, window, etc.).

2.6.1.6 Hearing Questionnaires for Patient-reported Auditory Characterization and as a Hearing Screening Tool

The (modified) Amsterdam Inventory for Auditory Disability and Handicap (AIAD)

The (modified) Amsterdam Inventory for Auditory Disability and Handicap ([m]AIAD) by Meijer et al. (2003) was used. 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 (modified by Meijer, 2003) has 28. It assesses auditory disability in five key domains (discussed later in this paragraph). We chose the modified AIAD questionnaire for our study, as Neijenhuis and colleagues (2003) had administered it to patients with suspected auditory processing disorders and for whom the scores for speech intelligibility and localisation items on (m)AIAD were worse in comparison to those of controls. The inventory was designed to identify factors related to hearing disability that affected the individual in daily life and to assess the impact the disability had on quality of life. Normative data had 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 (m)AIAD is a self-assessment hearing questionnaire. Its 28 items cover all the factors relevant for everyday hearing ability. It assesses five domains: intelligibility of speech in noise; intelligibility of speech in quiet; auditory localisation; recognition of sound; detection of sound. The response scale consists of ‘almost always’ (3 points),

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‘frequently’ (2 point), ‘occasionally’ (1 point), and ‘almost never’ (0 point). A lower score indicates a greater disability; a score of 84 corresponds to no hearing disability at all. Meijer (2003) demonstrated that the (m)AIAD is a promising and reliable tool for the assessment of hearing impairment in daily life. For the purpose of this thesis, (m)AIAD will be referred to as AIAD throughout the thesis.

Hearing Handicap Inventory for the Elderly (HHIE)

While audiological assessments provide a quantitative measure of hearing loss, they do not reflect the impact of such a loss on an individual’s life. Hearing handicap is used to denote a change in hearing that interferes with performing the activities of daily living (Weinstein et al., 1986). The Hearing Handicap Inventory is a widely used clinical measure of communicative function. It contains a series of questions that attempt to quantify the social and emotional impact of hearing loss on daily communication and functioning.

Weinstein et al. (1986) supported the use of the Hearing Handicap Inventory for the Elderly (HHIE) as a reliable index of self-perceived hearing handicap. The HHIE is a self-assessment questionnaire of hearing handicap comprising 25 items. Of them, 13 deal with emotional aspects (E), and 12 deal with social and situational aspects (S). For each item or situation, subjects are asked to give one of the following responses: ‘yes’ (4 points); ‘sometimes’ (2 points), or ‘no’ (0 points). Scores for the total scale range from 0, suggesting no perceived handicap, to 100, indicating significant perceived handicap.

2.6.1.7 Procedure – Study 1

The author performed all the testing. Consecutive acute care admissions to the stroke service were reviewed by the research stroke nurse specialist (SRN) from the UK Stroke Research Network (UKSRN) to determine eligibility for the project, and patients meeting the inclusion criteria were asked to participate in the HEARS study. Later, we invited those patients referred by the SRN to the Neuro-otology department at the National Hospital for Neurology and Neurosurgery for auditory assessment (refer to Figure 2.7). All patients were tested during a single session; the average time required to complete the entire test battery (baseline audiological assessments

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and auditory processing) was two hours. A twenty-minute break was provided between the assessments. On arrival to the NHNN neuro-otology department, the participants underwent a structured medical interview and the thorough audiological assessment.

2.6.1.8 Patient Grouping

Age Groups

Defining a 'significant' level of hearing impairment as at least 25 dB HL averaged over the frequencies 0.5, 1, 2, 4 kHz, 16% of the adult population (between 17 and 80 years of age) have a bilateral, and about one in four a unilateral or bilateral, hearing impairment (Davis, 1989). The increase in prevalence of hearing loss is particularly steep after the age of 61 and older. Sixty percent of adults age 61-80 years old in England have hearing impairment of 25 dB HL or greater, whilst the prevalence of hearing impairment in adults aged 18-60 years is only 10% (Davis, 1989). Thus, to minimise the confounding factor of age, we divided the patients into two groups, younger (18-60 years old), and older (61-80 years old).

Audiological Assessment Outcomes

For the purpose of this thesis, according to the outcomes of the audiological assessment, each patient was placed into one of four groups (ASHA, 2015): 1) Normal; 2) Peripheral hearing loss (cochlea to auditory nerve); 3) Central auditory processing disorder (brainstem to cortex and beyond) (ASHA, 2015; BSA, 2011); 4) Combination (peripheral hearing loss and central auditory processing disorder). Below we describe the definition and diagnostic criteria for each category.

Definition of Peripheral Hearing Impairment and Diagnostic Criteria

Threshold assessments were made at 250, 500, 1000, 2000, 3000, 4000, 6000 and 8000 Hz and a pure-tone average was calculated. The severity of any hearing loss was determined using the British Society of Audiology (BSA) audiometric descriptors (BSA, 2011). Also, high-frequency hearing loss was defined as the air conduction average of the frequencies 4, 6, and 8 kHz exceeding 20 dB HL. Mild

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hearing loss was defined as PTA >20 dB HL and ≤ 40 dB HL, moderate (41–70 dB HL), severe (71–95 dB HL), and profound (>95 dB HL).

Peripheral hearing loss (attributed to pathology in the middle ear, or to the cochlea and/or the distal portion of auditory nerve) was defined as: a) ‘cochlear type’ hearing loss: abnormal PTA average, reduced or absent TEOAEs, present and normal acoustic reflexes, and normal ABR or normal interwave interval ABR (Musiek et al., 1996); b) ‘neural type’ hearing loss, i.e. consistent with VIII nerve damage (Starr et al., 1996): normal or raised PTA average, normal TEOAEs, or delayed I–III or I–V interwave intervals or absent wave I (showing damage to the distal portion of the auditory nerve) (Musiek et al., 1996) and/or abnormal ART with an inverted or vertical pattern (Cohen & Prasher, 1988).

Definition of Central Auditory Processing Deficits and Diagnostic Criteria

According to the technical report of the American Speech-Language-Hearing Association (ASHA) Working Group (2005), deficits in the perceptual processing of auditory information in the Central Nervous System (CNS) and the neurobiological activity that underlies that processing and gives rise to electro-physiological auditory potentials constitute a central auditory processing disorder (CAPD). This was the definition adopted by this study.

A CAPD diagnosis was based on the presence of at least two central auditory nervous system test abnormalities i.e. ABR, ART, GIN, and QSTAC (spectral property and apperceptive tests) in at least one ear, with at least one test abnormality being in a behavioural AP test, and with the following additional considerations:

- i. the electrophysiological test abnormality was not attributable to the presence of hearing loss (see ABR and ART criteria);
- ii. a semantic processing abnormality (QSTAC) when found in isolation was not accepted as evidence of disordered auditory processing.

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Definition of Combination Hearing Impairment (Peripheral and Central) and Diagnostic Criteria

For the purpose of this thesis, if central auditory processing deficits and/or isolated brainstem type ABR and ART test abnormality were detected in the presence of peripheral hearing loss, we defined the pattern as a combination (peripheral and central) type auditory impairment.

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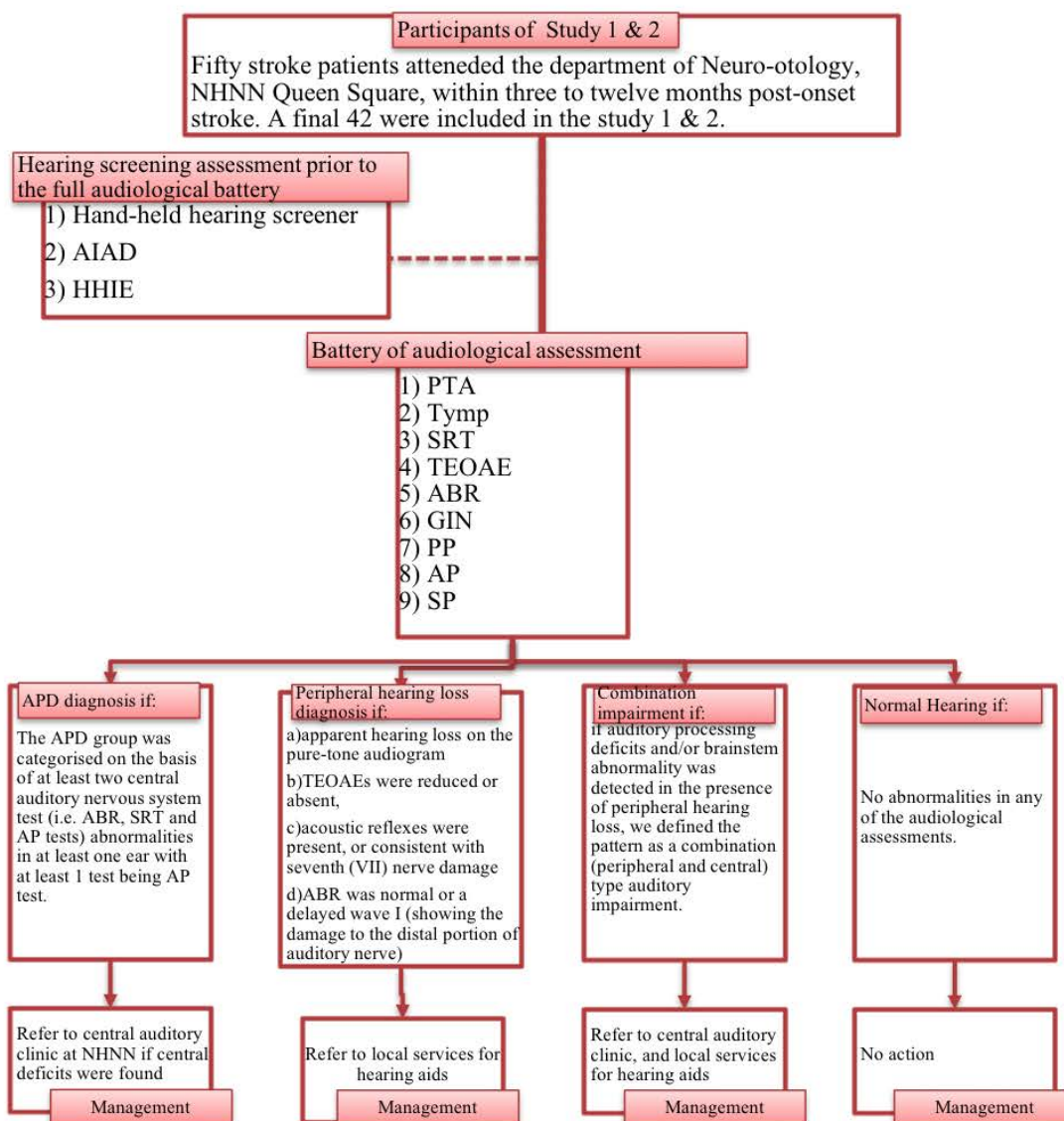


Figure 2-7: Flowchart of study 1 & 2 procedure and the diagnosis criteria

HEARS**2.6.1.9 Procedure - Study 2**

The following screening tools were utilised in study 2:

1. Handheld hearing screener
2. AIAD
3. HHIE

The hearing-screening test was performed at the department of neuro-otology, in a quiet test room that although not soundproof was free of visual and auditory distractions. This room was very similar to the room that was situated in the NHNN/UCLH stroke follow-up clinic, with the same level of ambient noise level that did not exceed 50dBA. The level of ambient noise present in the room, measured with a sound level meter (Figure 2-6), was most commonly around 41-42 dBA. All the screening tests were completed for each subject in a randomised order during a single visit before the administration of the full audiological assessment. For the latter, the participants were asked to respond according to the British Society of Audiology (BSA) recommended procedure for pure-tone audiometry. Following procedure instructions and placement of the headphone, the researcher (NK) started testing the better hearing ear first, with a maximum three presentations of sound for each frequency at the frequencies of 1, 2, and 4 kHz (ASHA, 1997). The pass criterion was two out of three correct identifications of sound for each frequency. The inter-stimulus intervals were at least 1 to 2 seconds, and rhythm in presentation pattern was avoided. The second ear was then tested in the same way. If the patient responded to all frequencies, 'pass' was indicated on the screening form.

The (m)AIAD and HHIE questionnaires were administered to the stroke patients at least three months after the onset of stroke before the audiological testing. Pass/Fail criteria and the criteria for gold standard diagnoses are described in detail in Chapter

2.6.2 Hearing Rehabilitation, Stage Study 3, Phase I

2.6.2.1 Study Design & Participants

All 42 stroke patients from studies 1 and 2 were screened for all FM study inclusion and exclusion criteria. The inclusion criteria were: (a) patient experiencing hearing-in-noise difficulty as reported on the speech-in-noise subscale of the Amsterdam Inventory for Auditory Disability (AIAD) per the departmental normative data (based on Spyridakou's MD thesis, 2014), (b) abnormal performance in the speech-in-babble test² (additional verbal auditory processing test only for the participants of study 3) and in at least one non-speech AP test, and (c) pure-tone audiogram average (from 500 to 8000 Hz at octave levels) better than 25dBHL. Exclusion criteria were severe aphasia (cut-off of 93.8 on the complete Western Aphasia Battery test). Ten patients fulfilled the inclusion and exclusion criteria and were invited to participate in the FM feasibility study. One declined due to involvement in other research. Nine patients attended the clinic on a second occasion to complete the feasibility study test protocol. All nine stroke patients were fitted with personal FM systems binaurally and were tested with and without the FM systems with a speech (sentence) perception test in a crescent of sound. 'Crescent of sound' is defined in section 2.6.2.3., below.

2.6.2.2 Personal FM Systems (Receiver and Transmitter)

The Phonak iSense personal FM systems are designed for individuals with normal or near-normal hearing. It consists of the iSense Micro (Figure 2-8 a, p. 77) receiver and the ZoomLink+ (Figure 2-8 b) transmitter. This device has dynamic FM, which features a proprietary component referred to as the Dynamic Speech Extractor (DSE). The DSE adaptively varies the gain of the FM receiver depending on the level of noise at the microphone of the FM transmitter. In quiet and in noisy environments, when speech is not present at the input of the FM microphone of the

² The speech-in-babble (SiB) test was administered via a custom Matlab software system (2012b) over Sennheiser (Wedemark, Germany) HD 600 supra-aural headphones in a sound-attenuated room. The target stimuli were monosyllabic phonetically balanced meaningful words spoken by an adult female British English talker. Each word is delivered with 500 milliseconds of 20-talker babble, and the speech volume is varied adaptively. The listener repeats the words heard, and a threshold value is obtained, calculated by the software as the mean SNR of 70.7% correct performance criteria in each ear (Spyridakou et al., 2012).

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Phonak iSense Dynamic FM transmitter, the receiver is muted in an attempt to optimise sound quality. This feature may reduce the audibility of unwanted noise that may be present in the form of ‘static noise’ or a ‘rushing noise’ that accompanies the primary FM signal. When speech is presented to the FM microphone and the ambient noise is less than 57 dB SPL, the default gain of the Dynamic FM receiver is set to +10. When the ambient noise levels exceed 57 dB SPL, the gain of the FM receiver is increased by an amount that is proportional to the noise level. The maximum gain of the FM receiver is +24 at a noise-input level of approximately 75 dB SPL (Wolfe et al., 2009).

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Figure 1a: FM receiver is a lightweight hearing receiver that is worn as one of a pair.



Figure 1b: The Microphone settings of Dynamic FM Transmitter

Microphone Settings	
SuperZoom	The SuperZoom microphone picks up speech from the front and suppresses noise from all other directions.
Zoom	Wide-angle sound pick up. It is the universal setting for medium noise level.
Omni	Omni is a 360° setting that picks up sound from all around the transmitter.

FM technology picks up the voice of the speaker via a body-worn transmitter microphone. It then uses harmless radio waves to send this signal wirelessly to the listener, who wear a hearing receiver.

Figure 2-8: FM receiver and transmitter: a) FM receiver is a lightweight hearing receiver that is worn as one of a pair. b) The Microphone settings of the Dynamic FM Transmitter.

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2.6.2.3 Outcome Measures Tools and Testing Methods

AB-York Crescent of Sound

The AB-York Crescent of Sound is a sound attenuated booth with nine audio and seven visual stands, an equipment cabinet, and a testing station for the assessment of spatial-listening skills (Kitterick et al., 2011). The stands are arranged in a semi-circular arc (Figure 2-9) with a radius of 1.45 m. Seven stands are separated at 30° intervals, and two additional stands are placed 15° on either side of 0°, where 0° is straight ahead of the listening position. The testing station controls the apparatus, including administering listening tests and recording and analysing the responses of participants.

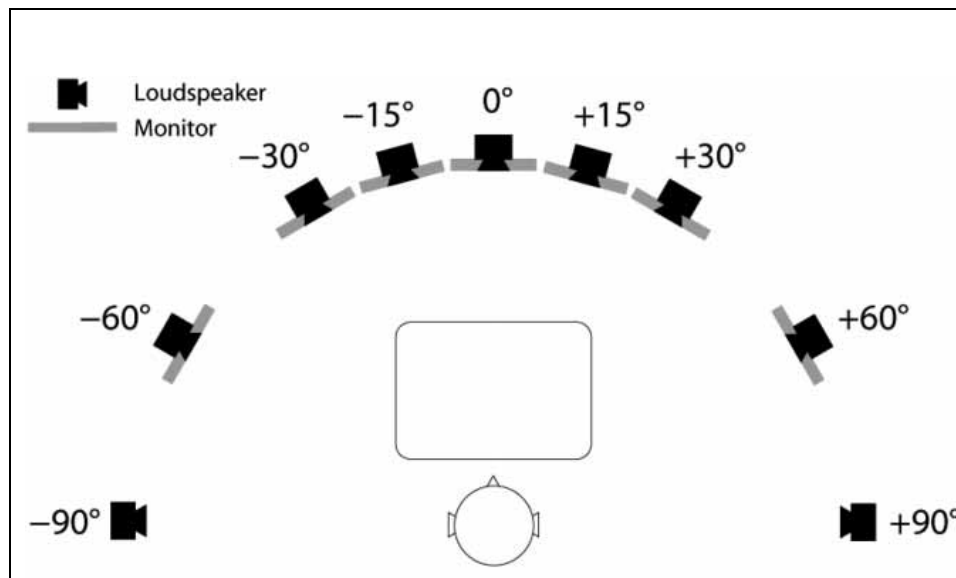


Figure 2-9: The schematic view of the setup for the sentences in noise. Reprinted from Kitterick et al., 2011.

Speech Stimuli: Sentences in Noise

In this test, sentences are presented from straight ahead (0°) while noise is coming from 90° to the left or right of the participant, who is asked to repeat the sentence. The number of keywords successfully repeated is recorded. The repetition of at least three keywords per sentence is required to judge correct performance. The level of the sentences and the background noise are adaptively varied to estimate the signal-to-noise ratio (SNR) for 50% correct performance.

HEARS**Speech in Noise Test with and without FM systems in the Crescent of Sound**

The sentences were presented from a loudspeaker positioned at 0° azimuth located 1 m from the participant. The microphone of the FM transmitter was placed on a stand 12 cm from the 0° azimuth loudspeaker. All testing was conducted utilizing a directional microphone.

The advantage for speech intelligibility is typically observed when the interfering sounds are spatially separated from the target. We carried out a condition when speech and noise simultaneously came from the front (0°) to calculate the signal-to-noise ratio benefit for speech.

The test was conducted with the participant using the FM system (the aided condition) or not using the FM system (the unaided condition). Testing for each of the three locations was repeated twice. Each participant thus completed twelve runs of the Sentences in Noise test (6 aided and 6 unaided), conducted as follows:

1) Aided condition: The FM transmitter microphone was positioned on a stand 12 cm in front from the 0° azimuth loudspeaker, and the participant was asked to wear the personal FM systems in his or her ears. Two runs of the test were conducted for the babble noise coming from each of the three locations: straight-ahead (0° azimuth), left (-90°), and right (+90°) loudspeaker.

2) Unaided condition: The same protocol as per the aided condition, with the babble noise coming from each of the three locations x 2 runs, but with the participant not wearing the binaural FM systems.

The order of the tests was done randomly across participants, and a different sentence list was used in each test run in order to avoid potential learning effects.

The **outcome measures** for this test were:

The speech reception threshold (SRT) obtained for speech and noise presented from 0° (S0° N0°), speech presented at 0° and noise 90° to the left (S0° N-90°) and speech presented at 0° and noise 90° to the right (S0° N+90°).

The signal-to-noise ratio benefit for speech (the SNR benefit) was calculated as the difference in dB between the speech reception threshold (SRT) obtained for speech and noise presented from 0° (S 0°, N 0°) versus speech at 0° and noise at 90° to the

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left (S 0°, N -90°) or speech at 0° and noise at 90° to the right (S 0°, N +90°), per the formula:

- **Right SNR benefit** = $SRT(S0^\circ N+90^\circ) - SRT(S0^\circ N0^\circ)$
- **Left SNR benefit** = $SRT(S0^\circ N-90^\circ) - SRT(S0^\circ N0^\circ)$

2.6.3 Hearing Rehabilitation Stage Study 3: Phase II

2.6.3.1 Study Design and Participants

This was a ‘non-randomised controlled clinical trial’ study. The participants of the phase I FM feasibility study were asked whether they would be willing to use the FM systems at home for ten weeks for the present study. Those who agreed to use the FM (N=4) formed a) the intervention group, while those who did not wish to use the FM but were willing to come back for a re-assessment ten weeks later formed b) the ‘standard care’ group (N=5).

2.6.3.2 Intervention

At visit 1, all four ‘intervention’ subjects were provided with Phonak iSense personal FM systems that consisted of the iSense Micro receiver and the ZoomLink+ Transmitter. At visit 1, all control subjects (‘standard care group’) were given an oral explanation of their listening difficulties and a standard listening strategies advice handout (see Appendix F). They were retested at visit 2, ten weeks later than visit 1.

2.6.3.3 Wearing Schedule and Monitoring

‘Intervention’ subjects were advised to use the FM systems regularly, both at home with family members and with multiple media devices such as music players, radio, television, and computer, and at social situations such as restaurants, meetings, etc. They were asked to do this for seven days a week and about six hours daily over the following ten weeks. Batteries were provided, and the subjects were asked to change them every two weeks to ensure use of a fresh battery at all times. Use of the FM systems was monitored via patients’ reports during the follow-up visit for the re-assessment.

HEARS**2.6.3.4 Fitting**

The FM receivers were set to the default manufacturer settings. Listening checks prior to and during the fitting process were completed to ensure sound quality and equipment function. Patients were instructed on how to check the function of the system and ensure communication between the transmitter and receiver. Formal written instruction was provided regarding the best use of the FM system, troubleshooting tips, and the details of Phonak customer service together with standard advice regarding listening strategies (see Appendix F).

2.6.3.5 Data Collection Schedule

Speech perception in noise (signal-to-noise ratio) in the ‘crescent of sound’, baseline audiological and auditory processing assessments, the AIAD, and the HHIE were measured prior to fitting the FM system during the first visit (see Phase I Method). The speech-perception measure in the ‘crescent of sound’ was repeated on the second visit approximately ten weeks after the first visit in both the case and control groups.

2.6.3.6 Re-assessment

The order of the runs was counterbalanced across participants, and all runs were administered in a single session. No sentence was repeated in order to prevent potential learning effects. The test procedures used in Phase I were repeated for both the ‘intervention’ and ‘standard care’ groups.

The **outcome measures** for this stage were identical to those of Phase I.

2.7 Statistical Analysis

Microsoft Excel for Mac 2010 and 2013 and the statistical package for the social sciences (SPSS) versions 17, 19 and 22 were used for the statistical analyses. More details are given in Chapters 3 to 6.

3 Chapter 3: Study 1– Hearing Characteristics of Stroke Patients

3.1 Introduction

The majority of stroke survivors need rehabilitation (MacDonald et al., 2000), requiring them to be adequately informed of the nature, prognosis, and proposed treatment of their illness. Hearing-impaired stroke survivors have an increased risk of physical decline (odds ratio: 1.83) after discharge to the community (Landi et al., 2006). This may be attributed to restricted participation in post-acute rehabilitation programs due to the hearing impairment (Landi et al., 2006). In addition, it is well known that uncorrected hearing loss may lead to isolation, reduced social activity, and reduced quality of life for the hearing impaired and their families (Arlinger, 2003). Stroke can affect all levels of the auditory system (from the inner ear to the central tracts), and may result in various types of auditory dysfunctions, such as peripheral hearing loss (cochlea to auditory nerve), disordered auditory processing (brainstem to cortex), and cortical deafness. Some of these presentations, such as cortical deafness, are rare but quite dramatic and would not go undetected. Other presentations, however, may be subtler and can only be detected by detailed questioning of the patient and by precise psychoacoustic and electrophysiological testing. Yet they may still have a significant impact on listening, linguistic skills, and overall communication of the affected patient (Hausler and Levine, 2000; Bamiou et al., 2012; Onoue et al., 2014).

Sensorineural hearing loss (SNHL) is highly prevalent in stroke survivors (Formby et al., 1987; Edwards et al., 2006; O'Halloran et al., 2009). Such peripheral type hearing loss may be due to pathology of the inner ear (Lee, 2012), the auditory nerve, or even the early part of the cochlear nuclei, i.e. the part of the central auditory pathway before the crossing of the auditory fibres at the superior olivary complex brainstem level (Luxon, 1980). Furthermore, stroke-related risk factors, such as cigarette smoking and atherosclerosis, which have been associated with a more insidious onset of hearing impairment with advancing age (Yamasoba et al., 2013), may directly affect the peripheral hearing organs, or the stroke event itself may damage the auditory pathway up to and including the low brainstem (Lee et al.,

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2009), thus giving rise to the observed SNHL. Formby et al. (1987) assessed hearing in stroke patients between two weeks and one-month post-onset of stroke. They reported hearing loss in 61.7% of these patients. Two subsequent longitudinal population-based Australian studies indicated that a past history of stroke increased the likelihood of having hearing loss. Kiely et al. (2012) studied 3,526 adults aged 50 years or older and found that a previous history of stroke predicted hearing thresholds, while Gopinath et al. (2012) reported that the odds of reporting stroke were significantly higher for those with moderate-to-severe hearing loss. The observed association between hearing loss and stroke could be attributed to age-related changes of the inner ear or of the auditory nerve (Jacquin et al., 2012), as the risk of both hearing loss and cardiovascular accidents (CVA) increases with age (Hung et al., 2011).

Altogether, the findings from the aforementioned studies suggest that the prevalence of hearing impairment in stroke survivors could be higher than that of the hearing impairment that would be expected in the general population. However, none of the few previous studies sought to systematically characterise the auditory function of stroke patients in detail to establish the different types of hearing impairments in this cohort of patients. It is well established that if the stroke involves the central auditory pathway in the brain, from the brainstem and beyond, patients may also suffer from auditory processing deficits that are not reflected by their pure-tone hearing thresholds (Bamiou et al., 2006, 2012). Whilst there are a few studies looking at the auditory processing of highly selected stroke cohorts (e.g. Bamiou et al., 2006; Rey et al., 2007; Bamiou et al., 2012), to date no study has sought to establish the prevalence of auditory processing deficits in the broader stroke population in the presence or absence of peripheral hearing impairment. Such information would be clinically useful for understanding and addressing the hearing needs of stroke survivors, so that appropriate management can be given to these patients in order to improve their quality of life.

The present study examined hearing in detail and characterised the different types of hearing impairment in stroke patients in a systematic observational case-control study with the ultimate aim of informing a better taxonomy of hearing impairment in stroke patients.

3.2 Purpose

The aim of the present study was:

1. To assess hearing impairment in detail in stroke patients who are in the post-stroke subacute stage by means of a detailed baseline auditory battery (pure-tone audiometry, acoustic immittance tests, auditory-evoked brainstem responses, and transient evoked otoacoustic emissions), and a detailed non-verbal auditory processing battery (gaps-in-noise [GIN], i.e. a sensitive test of auditory temporal resolution) (Musiek et al., 2005), and by perceptual spectral property processing, apperceptive processing, and semantic processing tests (Goll et al., 2010), and to compare the results with those of individuals without stroke.
2. To characterise the different types of hearing impairment (peripheral, i.e. cochlear and/or neural, or central, i.e. due to pathology beyond the nerve, or a combination of peripheral and central) in the stroke group in order to identify the prevalence of all types of hearing impairment in this cohort.
3. To examine the prevalence and correlates of different hearing impairments in stroke patients in comparison to those of age-matched controls. On the basis of previous research, it was expected that the type of hearing impairment would be different in the stroke group compared to individuals without stroke.

3.3 Methods

3.3.1 Participants

Fifty stroke patients were tested at the department of Neuro-otology, NHNN Queen Square, within three to twelve months post-onset stroke. After excluding those with severe or greater hearing loss and those with cognitive impairments (Chapter 2, Section 2.4.1), a final 42 patients were included in the Study 1. For comparison, forty control subjects were also recruited from the hospital staff, colleagues, hospital visitors and friends.

3.3.2 Overview of Test Battery

All the research participants underwent the following battery of tests that have been described thoroughly in Chapter 2 of the research thesis. The audiological tests were conducted in a sound-proof room.

Baseline audiological assessment

- Pure-tone Audiometry (PTA) (250–8000 Hz)
- Tympanometry (TYMP)
- Stapedial Acoustic Reflex Thresholds (ART)
- Transient Evoked Otoacoustic Emissions (TEOAEs)
- Auditory-evoked Brainstem Responses (ABR)

Central Auditory Tests

- Gaps-in-noise (GIN)
- Perceptual Property Processing (PP)
- Apperceptive Processing (AP)
- Semantic Processing (SP)

3.4 Statistical Analysis

Data were initially analysed using the Statistical Package for the Social Sciences SPSS 22.0 for descriptive analyses. Univariate analyses (Chi-squared and Fisher's exact tests) were carried out to examine whether there was any association between the results of a particular hearing test and the stroke status of the participants (with and without age group classification). Prior to conducting the chi-squared analysis, the assumption of adequate cell size was assessed. The assumption requires all cells to have expected values greater than zero, and 80% of the cells to have expected values of at least five. If the assumptions were not met, Fisher's exact test was used.

Logistic regression models were fitted to the data to assess the association between the binary hearing test results and age (as a dichotomous variable) and stroke status.

Multinomial logistic regression models were fitted to the data with the categorical variable 'type of hearing' as the dependent variable. Type of hearing could be either 'CAPD,' 'normal', 'peripheral', or both 'peripheral and CAPD'. Group (Stroke / Control) and age (as a dichotomous variable) were the included explanatory variables.

Multinomial regression

Multinomial response regressions were performed. The regressions looked at the conditional distribution of the types of hearing given age (dichotomous; ≤ 60 / ≥ 61) and health status (stroke patient / healthy control). They also estimated a set of coefficients, b^1 , b^2 , b^3 , b^4 , corresponding to each response outcome. X represents the covariate (age and study group) in the following formulae.

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$$\Pr(\text{Type of hearing} = \text{CAPD}) = \frac{e^{Xb^1}}{e^{Xb^1} + e^{Xb^2} + e^{Xb^3} + e^{Xb^4}}$$

$$\Pr(\text{Type of hearing} = \text{Normal}) = \frac{e^{Xb^2}}{e^{Xb^1} + e^{Xb^2} + e^{Xb^3} + e^{Xb^4}}$$

$$\Pr(\text{Type of hearing} = \text{Peripheral}) = \frac{e^{Xb^3}}{e^{Xb^1} + e^{Xb^2} + e^{Xb^3} + e^{Xb^4}}$$

$$\Pr(\text{Type of hearing} = \text{Peripheral and CAPD}) = \frac{e^{Xb^4}}{e^{Xb^1} + e^{Xb^2} + e^{Xb^3} + e^{Xb^4}}$$

3.5 Results

3.5.1 Descriptive

The total number of participants in our study, from 2012 to 2015, was 90 (50 stroke and 40 controls). Three patients were unable to complete the CAPD test battery due to a hearing loss greater than a moderate degree, and five had cognitive impairment. These patients were excluded, and a final 42 out of 50 were selected to determine the difference in abnormality distribution in the different audiological tests and the prevalence of the different types of hearing impairment in the stroke cohort.

In the final 42 selected stroke patients with complete audiological testing, the age ranged from 23 to 80 years old, with an average of 58.19 years old ($SD = 15.06$). To eliminate the confounding factor of age (Davis, 1989), we also divided the age into two subgroups; age group 1 (18-60 years), and age group 2 (61-80 years). The most frequently observed category of age was those in the older group ($n = 22$, 54%), whose mean age was 70 ($SD = 5.4$), while the average age of the younger group was 45.4 ($SD = 10.6$). The most frequently observed category of sex in the stroke group was male, ($n = 33$, 78%). The demographic data on these patients are presented in Table 3-1 (p. 90). The age of the control group ranged from 22 to 80 years old, with an average of 53.08 years old ($SD = 15.33$). The most frequently observed category of sex in the control group was female, ($n = 26$, 65%). Age was not normally distributed in either the stroke or control groups. A Kruskal-Wallis rank sum test was

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conducted to examine whether there was a significant difference between the mean rank of age in the stroke group and the mean rank of age in the control group. The results of the Kruskal-Wallis rank sum test were not significant, $H= 511.5$, 1 d.f., $p = .172$. This indicates that the age differences between stroke patients and controls are explainable by random variation. The results of the Kruskal-Wallis test also did not show a significant difference between the age of the younger stroke and control groups, $H= 0.34$, 1 d.f., $p = .560$, as well as of the older stroke and control groups, $H= 0.37$, 1 d.f., $p = .545$. Figure 3-1 (p. 89) refers.

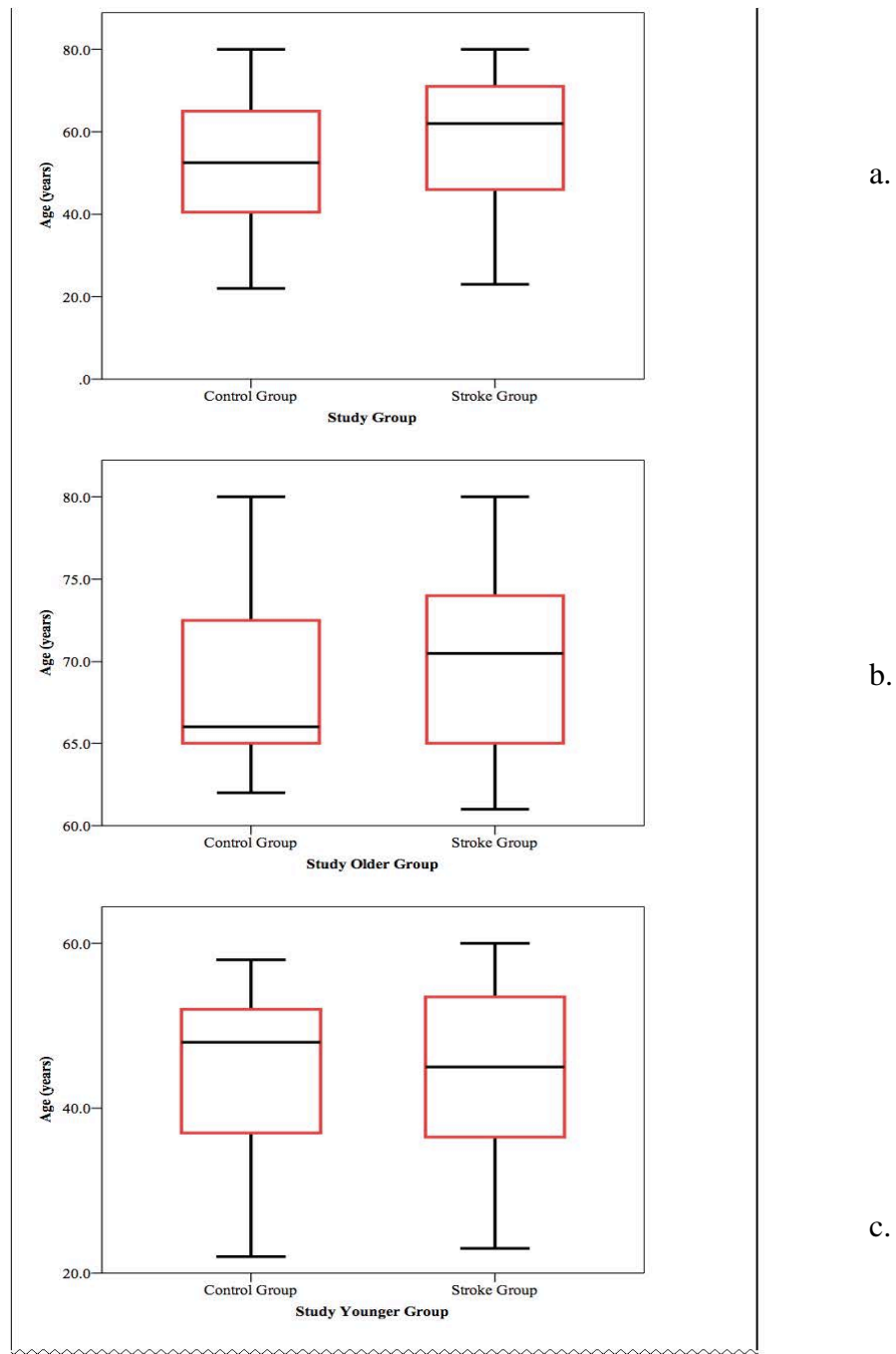


Figure 3-1: Box Plot of age in a. total stroke and control groups, b. younger stroke and control groups, and c. older stroke and control groups.

HEARS**Table 3-1: Frequencies and percentages for age-groups, auditory vs. non-auditory (site of lesion), sex and side of lesion in the stroke group.**

Variable	n	%
Age group		
Younger	20	42
Older	22	58
Auditory vs. Non-auditory		
Non-auditory	18	43
Auditory	14	33
Auditory & Non-auditory	10	24
Sex		
Male	33	78
Female	9	22
Side		
Right	22	52
Left	18	43
Bilateral	2	5

3.5.2 Pure-Tone Audiometry, ART, TEOAE, ABR and CAPD

Figure 3-2 (p.91) provides the mean hearing thresholds across frequency categories in the stroke group versus the control group. Although the overall mean thresholds for the stroke group were more elevated compared to normal control, there was no statistically significant difference between the two groups.

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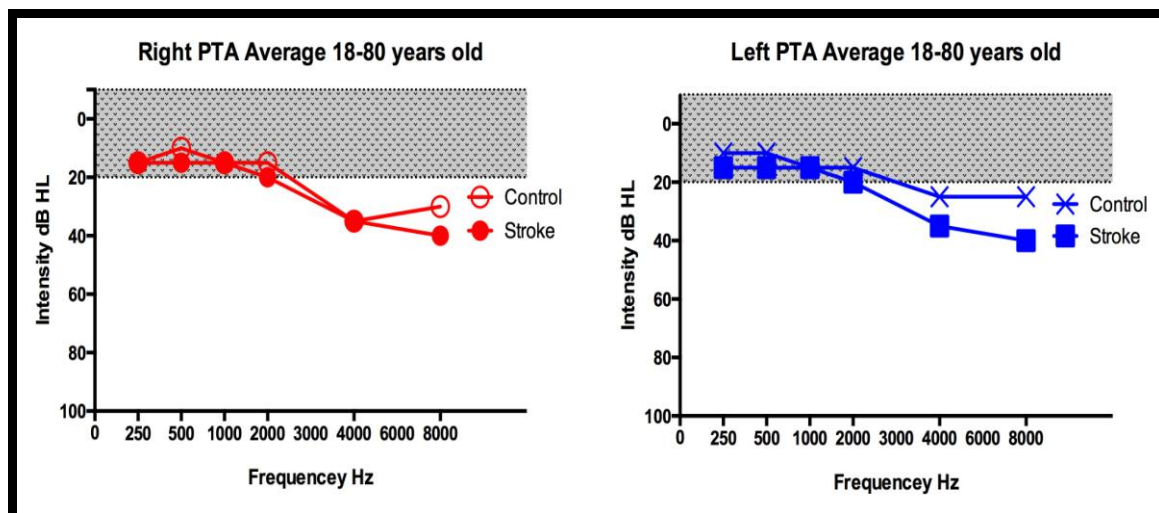


Figure 3-2: Hearing thresholds in 42 stroke patients and 40 controls. Results for right and left air conduction are plotted against frequency. KEYS: PTA, pure-tone audiometry; dB, decibel; HL, hearing level. Colour code: red, right ear; blue, left ear; shaded area, PTA normal limits.

The differences in the abnormality distribution in different audiological tests between the stroke and control groups were analysed using non-parametric tests including chi-squared test for categorical data, with χ^2 or Fisher's exact test used where appropriate. The null hypothesis, that there was no significant difference in distribution across the two groups, was rejected when the level of significance of $p < 0.05$ was reached. There were two levels in the groups: stroke group and control group. There were two levels in each of the audiological tests: abnormal and normal. Table 3-2 (pp. 92-93) shows the distribution of individuals with and without impairment in both stroke and control group.

3.5.3 Summary of Auditory Impairment Diagnosis

The type of hearing impairment was determined using the criteria described in the Materials and Methods chapter. Summary of the lesion description and hearing impairment diagnosis are shown in Table 3-3 (pp. 94-96).

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Table 3-2: Distribution of individuals with and without audiological test abnormalities in the stroke and control groups. KEYS: PTA, pure-tone audiometry; ART, acoustic reflex threshold; TEOAE, transient evoked otoacoustic emissions; ABR, auditory brainstem responses; GIN, gaps in noise; PP, perceptual property processing; AP, apperceptive processing; SP, semantic processing. (Continues on following page.)

	STROKE	CONTROLS	P-VALUE
PTA			
Total			
Normal	15	26	0.02
Abnormal	27	14	
Younger			
Normal	14	22	0.69
Abnormal	6	4	
Older			
Normal	1	4	0.06
Abnormal	21	10	
ART			
Total			
Normal	34	35	0.25
Abnormal	8	5	
Younger			
Normal	16	25	0.15
Abnormal	4	1	
Older			
Normal	18	10	0.69
Abnormal	4	4	
TEOAE			
Total			
Normal	29	33	0.2
Abnormal	13	7	
Younger			
Normal	17	25	0.30
Abnormal	3	1	
Older			
Normal	12	8	0.87
Abnormal	10	6	
ABR			
Total			
Normal	34	39	0.02
Abnormal	8	1	
Younger			
Normal	20	26	0.2
Abnormal	2	0	
Older			
Normal	14	13	0.2
Abnormal	6	1	
GIN			
Total			
Normal	11	38	0.000
Abnormal	31	2	
Younger			
Normal	8	25	0.000
Abnormal	12	1	
Older			
Normal	3	13	0.000
Abnormal	19	1	

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PP			
Total			
Normal	22	37	0.000
Abnormal	20	3	
Younger			
Normal	12	23	0.02
Abnormal	8	3	
Older			
Normal	10	14	
Abnormal	12	0	0.001
AP			
Total			
Normal	25	40	0.000
Abnormal	17	0	
Younger			
Normal	14	26	0.004
Abnormal	6	0	
Older			
Normal	11	14	0.002
Abnormal	11	0	
SP			
Total			
Normal	37	40	0.06
Abnormal	5	0	
Younger			
Normal	19	26	0.43
Abnormal	1	0	
Older			
Normal	18	14	0.14
Abnormal	4	0	

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Table 3-3: Age, sex, lesion description, side of lesion and type of hearing impairment in the stroke group. KEYS: M, male; F, female; Rt, right; Lt, left; CAPD, central auditory processing disorders; PTA, pure-tone audiometry; ART, acoustic reflex threshold, TEOAE, transient evoked otoacoustic emissions; ABR, auditory-evoked brainstem responses; CAP, central auditory processing assessment. + signifies an impairment. Table continues on following two pages.

Patient	Age	Sex	Lesion description	SIDE	Hearing impairment	PTA/ART/TEOAE/ABR/CAP
1	43	M	diffusion in the right putamen, extending into the corona radiata in keeping with an acute ischaemic infarct	RIGHT	CAPD	-/-/-/+
2	23	M	large left MCA territory infarct and severe left supraclinoid ICA stenosis, the left insula, frontal and temporal lobes	LEFT	CAPD	-/-/-/+
3	76	M	Acute pontine infarct	LEFT	Peripheral	+/-/+/-
4	68	M	diffusion involving the right caudate and lentiform nuclei, and anterior internal capsule, acute right striato-capsular infarct	RIGHT	Peripheral	+/-/-/-
5	76	M	Supramarginal gyrus, angular gyrus, Postcentral gyrus	RIGHT	Peripheral and CAPD	+/-/+/+
6	63	M	Rt MCA territory infarction, the right insula, inferior frontal gyrus and antero-lateral temporal lobe, with involvement of the basal ganglia	RIGHT	Peripheral and CAPD	+/-/-/+
7	53	F	Rt MCA, Ischaemic stroke. corona radiata bilaterally	LEFT	Normal	-/-/-/-
8	32	M	Spontaneous intracerebral bleed, brainstem. pontine haemorrhage.	BILATERAL	Normal	-/-/-/-
9	66	M	Rt MCA, Ischaemic stroke	RIGHT	Peripheral	+/-/-/-
10	31	M	involving the right temporal lobe including temporal operculum, with further smaller infarcts in the posterior right temporal lobe	RIGHT	CAPD	-/-/-/+
11	72	F	basal ganglia haemorrhages, mature foci of encephalomalacia centred on the globi pallidi and putamina on the left and more extensively on the right at this is seen to also involve the head and anterior body of the right caudate nucleus Small vessel disease	BILATERAL	Peripheral	+/-/-/-
12	60	M	the left occipital infarct	LEFT	Normal	-/-/-/-
13	73	M	Posterior circulation infarct, pontine stroke	RIGHT	Peripheral and CAPD	+/-/+/+
14	59	M	the right thalamus/corona radiata may represent an acute/subacute infarct. Old lacunar infarct in the right corona radiata is seen ventral and cranial to this.	RIGHT	Peripheral	+/-/+/-
15	44	M	left MCA opercular territory infarct, the left supramarginal and suncentral gyri and posterior insular cortex with foci of high linear and curvilinear high density noted in addition in this region,	LEFT	CAPD	-/-/-/+
16	67	M	Acute infarction in the territory of the left middle cerebral artery with an abrupt calibre change and poor distal opacification in	LEFT	Peripheral and CAPD	+/-/+/+

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			the left M1 segment, indicating intravascular thrombus			
17	57	M	Left MCA territory infarction, several foci of restricted diffusion the left insula and corona radiata in keeping with acute infarct	LEFT	CAPD	-/+/-/+
18	75	F	left inferior parietal lobule infarct	LEFT	Peripheral	+/+/-/-
19	80	F	infarct in the territory of the right middle cerebral artery, Small acute/subacute thromboembolic infarct in right hemisphere	RIGHT	Peripheral	+/-/-/-
20	54	F	multiple right supratentorial acute infarcts, a few infarcts in the right middle cerebral artery territory	RIGHT	Peripheral and CAPD	+/+/-/+
21	53	M	Primary intracerebral haemorrhage. L cerebral hemisphere. well-defined hyperdensity in the left parietal lobe here may be a third lesion in the peripheral aspect of the right temporal	LEFT	Peripheral	+/-/-/-
22	77	M	left occipital infarct, mild small vessel disease with bilateral supratentorial white matter lesions	RIGHT	Peripheral and CAPD	+/+/-/+
23	63	M	Diffusion within the medial right thalamus	RIGHT	Peripheral	+/-/-/-
24	46	M	Right PCA, MCA and BG infarct and small vessel disease	RIGHT	CAPD	-/-/-/+
25	71	M	right middle cerebral peduncle and the right frontal white matter and at the level of the left precentral gyrus, critical mid basilar stenosis	RIGHT	Peripheral and CAPD	+/+/-/+
26	52	M	medial left temporal lobe, the superior right cerebellar hemisphere and the left lateral medulla. These correlate with left PCA, right MCA and left PICA/vertebral artery territories.	LEFT	Peripheral	+/+/-/-
27	63	F	Lt MCA, Insular cortex at its anterior portion and the left frontal operculum	LEFT	Peripheral and CAPD	+/-/+/+
28	74	M	Left pontine acute infarct	LEFT	Normal	-/-/-/-
29	74	M	small vessel ischaemic change involving the frontoparietal white matter, deep grey structures and pons	RIGHT	Peripheral and CAPD	+/+/-/+
30	70	M	Left parietal lobe infarct. Small adherent thrombus within the distal left CCA	LEFT	Peripheral and CAPD	+/-/-/+
31	65	M	Rt MCA, R caudate infarct, infarcts are also noted in the right thalamus, bilateral basal ganglia as well as the right inferior frontal gyrus	RIGHT	Peripheral and CAPD	+/-/-/+
32	74	M	left parietal lobe at the level of the corona radiata consistent with an area of subacute infarction. A further focus of subacute infarction is noted in the inferior aspect of the left insular cortex.	LEFT	Peripheral and CAPD	+/-/-/+
33	65	M	Right basal ganglia haemorrhage	RIGHT	Peripheral and CAPD	+/-/-/+
34	70	M	infarction in the right insular cortex, corona radiata and inferior frontal gyrus	RIGHT	Peripheral	+/-/-/-
35	48	M	Patchy left frontal infarction,	LEFT	Normal	-/-/-/-

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36	43	F	Pontine cavernoma bleed	RIGHT	CAPD	
37	44	M	Right MCA, Right Middle and inferior frontal gyri	RIGHT	Peripheral and CAPD	-/+/-/+
38	61	M	Left MCA ischaemic stroke	LEFT	Peripheral and CAPD	+/-/+
39	36	M	Left MCA ischaemic stroke secondary to left ICA dissection	LEFT	CAPD	-/-/-/+
40	32	M	Right MCA involving the inferior parietal lobule, temporal operculum, angular gyrus and posterior insular.	RIGHT	CAPD	-/-/-/+
41	54	F	Pontine and left cerebellar haemorrhage	LEFT	Peripheral and CAPD	+/-/-/+
42	37	F	Acute MCA territory infarct affecting the right inferior frontal gurus, superiro temporal gyrus, insular, right putamen and caudate	RIGHT	Normal	-/-/-/-

3.5.4 Types of Hearing Impairment

The most common type of hearing loss in stroke patients was the combination ('peripheral hearing loss and CAPD') in the 61-80-year-old subgroup, and 'CAPD' in the 18-60-year-olds. Table 3-4 (p. 98) summarises the types of hearing impairment in stroke and controls in both age subgroups. Regardless of type, the percentage of hearing impairment (of any types) was significantly higher in the 18-60-year-old stroke group than in the controls.

Types of hearing impairment as a function of age group and the side of stroke are shown in Figures 3-3 and 3-4 (p. 97), respectively.

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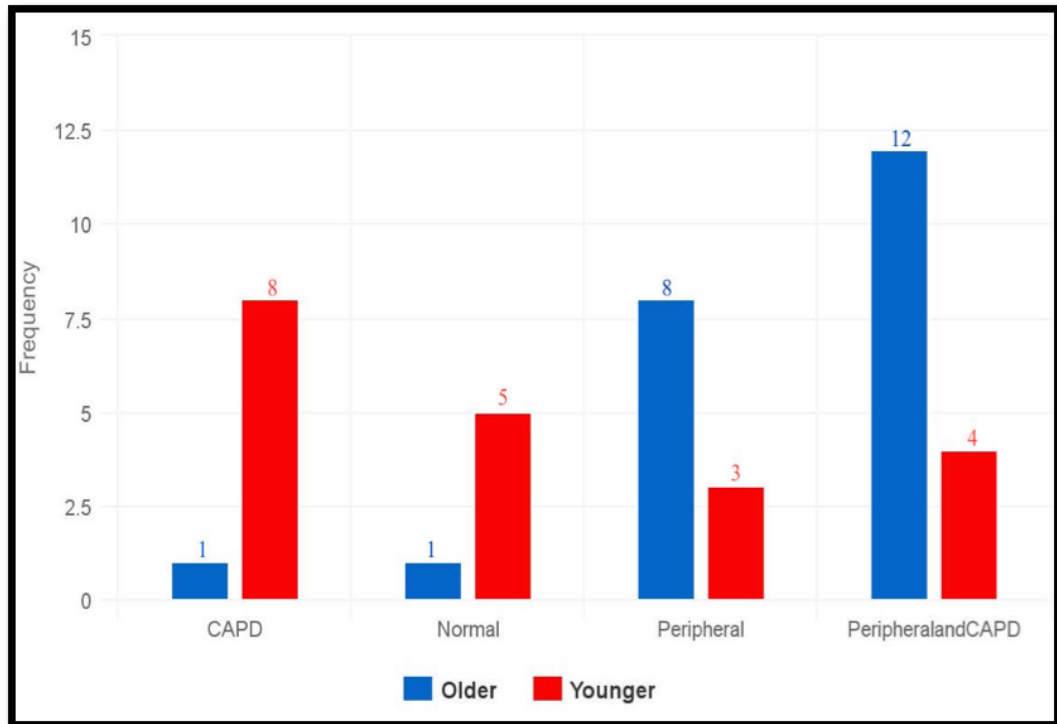


Figure 3-3: Types of hearing impairment as a function of age group. KEY: CAPD, central auditory processing disorders

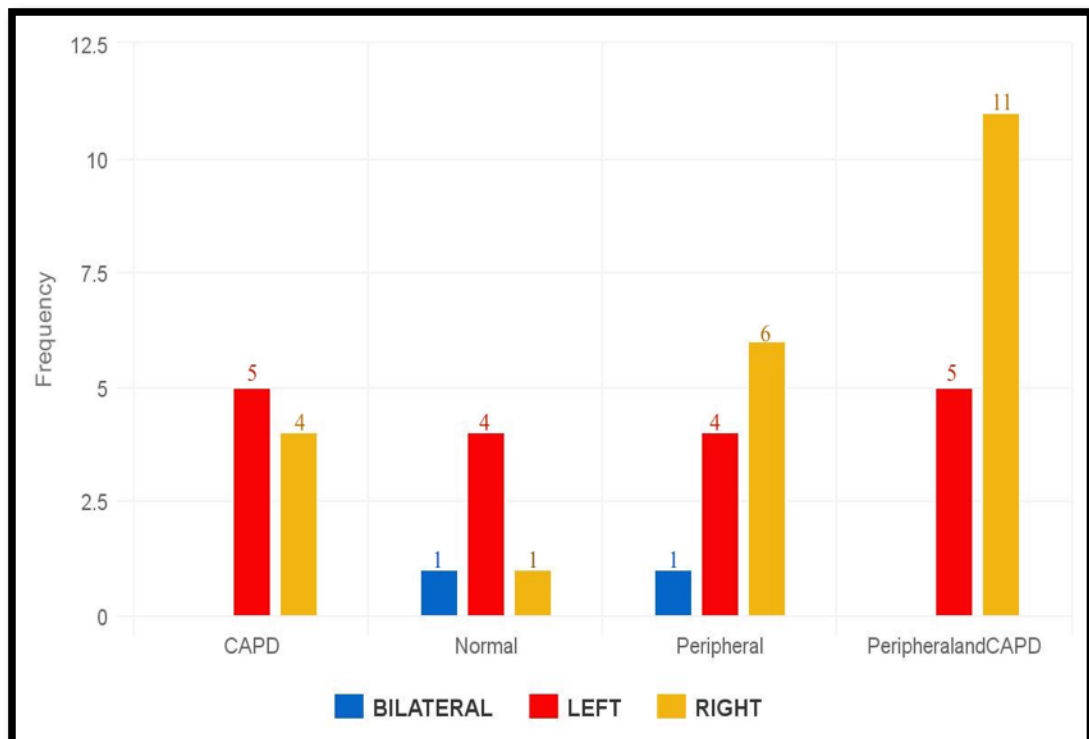


Figure 3-4: Types of hearing impairment as a function of side of lesion. KEY: CAPD, central auditory processing disorders

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Table 3-4: Types of hearing impairment in stroke and controls. Number of patients with different types of hearing impairment. KEY: CAPD, central auditory processing disorders

Age group	Type of hearing in control subjects				Total
	CAPD	Normal	Peripheral	Peripheral and CAPD	
< 61 years old	1 (4%)	21 (81%)	4 (15%)	0 (0%)	26 (65%)
≥ 61 years old	0 (0%)	4 (29%)	9 (64%)	1 (7%)	14 (35%)
Total	1 (2%)	25 (62%)	13 (32%)	1 (2%)	40

Age group	Type of hearing in stroke patients				Total
	CAPD	Normal	Peripheral	Peripheral and CAPD	
< 61 years old	8 (40%)	5 (25%)	3 (15%)	4 (20%)	20 (48%)
≥ 61 years old	1 (4%)	1 (4%)	8 (36%)	12 (56%)	22 (52%)
Total	9 (21%)	6 (14%)	11 (26%)	16 (38%)	42

A multinomial logistic regression is appropriate when the outcome is a polytomous variable. Thus, this model was fitted to the data to model the effect of study group and age group on the probabilities of having ‘normal’ hearing, ‘CAPD’, ‘peripheral’, or ‘peripheral and CAPD’ impairments. The response (dependent variable) is the type of hearing, which takes the values ‘normal’, ‘CAPD’, ‘peripheral’, and ‘peripheral and CAPD’. There are two study groups; stroke patients and healthy control subjects. The participants are classified into two age groups, a younger group (< 61 years old) and an older group (≥ 61 years old). Study group and age group are dichotomous variables.

One model was calculated where ‘peripheral’ type of hearing was the reference categories for the outcome, while healthy group and younger age group (<61 years old) were the reference categories for the independent variables.

Table 3-5: Estimates of the coefficients of the multinomial logistic regression model fitted to the data with Type of hearing as the dependent variable and group and age Group as independent variables.

Type of hearing	Coef.	Std. Error	95% Conf. Interval		P-value
			lower	upper	
CAPD					
group (stroke patients)	2.394	1.206	0.031	4.757	0.047
ageGroup (\geq 61 years old)	-3.106	1.186	-5.431	-0.781	0.009
(Intercept)	-1.450	1.101	-3.608	0.708	0.188
Normal					
group (stroke patients)	-1.233	0.716	-2.636	0.169	0.085
ageGroup (\geq 61 years old)	-2.523	0.686	-3.867	-1.179	<0.001
(Intercept)	1.696	0.511	0.694	2.698	0.001
Peripheral	(Base outcome)				
Peripheral and CAPD					
group (stroke patients)	2.937	1.110	0.762	5.112	0.008
ageGroup (\geq 61 years old)	0.268	0.799	-1.299	1.834	0.738
(Intercept)	-2.760	1.198	-5.108	-0.412	0.021

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Table 3-6: Estimated relative risk ratios given by the multinomial logistic regression model that was fitted to the data with type of hearing as the dependent variable and group and age group as independent variables. RRR: Relative Risk Ratio

Type of hearing	RRR	Std. Error	95% Conf. Interval		P-value
			lower	upper	
CAPD					
group (stroke patients)	10.960	13.215	1.032	116.450	0.047
ageGroup (≥ 61 y.o.)	0.045	0.053	0.004	0.458	0.009
(Intercept)	0.235	0.258	0.027	2.030	0.188
Normal					
group (stroke patients)	0.291	0.209	0.072	1.185	0.085
ageGroup (≥ 61 y.o.)	0.080	0.055	0.021	0.308	<0.001
(Intercept)	5.452	2.787	2.002	14.847	0.001
Peripheral	(Base outcome)				
Peripheral and CAPD					
group (stroke patients)	18.861	20.930	2.143	166.012	0.008
ageGroup (≥ 61 y.o.)	1.307	1.044	0.273	6.259	0.738
(Intercept)	0.063	0.076	0.006	0.662	0.021

Table 3-7: Probabilities of falling in each category of the outcome (type of hearing), calculated using the fitted multinomial logistic regression model given above.

	Normal		CAPD		Peripheral		Peripheral+CAPD	
	Stroke	Healthy	Stroke	Healthy	Stroke	Healthy	Stroke	Healthy
< 61 y.o.	0.250	0.808	0.405	0.035	0.157	0.148	0.188	0.009
≥ 61 y.o.	0.045	0.286	0.041	0.007	0.357	0.653	0.556	0.054

Stroke is associated with an increase in the relative probability of having ‘CAPD’, and ‘peripheral and CAPD’ (combination) rather than ‘peripheral’ hearing impairment. Older stroke patients were more likely to have a combination (peripheral and central) hearing impairment rather than peripheral hearing loss (respective probabilities: 0.556 and 0.357). The older control group was more likely to have peripheral hearing loss (probability of peripheral given age group ≥ 61 and healthy study group = 0.653). The probability of having a ‘CAPD’ impairment is on average 22% higher for stroke patients than for healthy controls in

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the same age group. The probability of having ‘peripheral and CAPD’ hearing impairment is on average 21% higher for older participants than for younger participants in the stroke group.

3.6 Discussion

3.6.1 Audiometric Characteristics in Stroke Patients

To our knowledge, this is the first study to examine types of hearing impairment, using detailed audiological assessments, in stroke patients. Although overall mean thresholds (PTA average and HF average) for the stroke group were more elevated compared to those of the healthy controls, there was no statistically significant difference between the control and stroke groups in the overall groups and when divided into two age subgroups (18-60 and 61-80-year-olds). In all frequencies, there was no significant difference in pure-tone thresholds between the age subgroup of subjects in the stroke patients and controls. We found that 67% of our older group had a pure-tone average of more than 25 dB HL, very similar to the results of Formby’s study (1987). The proportion of our stroke samples with a hearing loss greater than 25 dB HL was also very similar to that in Davis’s UK population study (1989), who found that 61.5% of 61-80-year-olds had a hearing loss of 25 dB or more (mean PTA thresholds). These initial results suggest that the abnormality rate in PTA average in the UK stroke units is similar and comparable to that found among elderly persons in nursing homes (Schow et al., 1980), stroke units in Australia (O’Halloran et al., 2009), and in the general population in the USA (Formby et al., 1987).

Auditory brainstem lesions often damage one or both of the crossed reflex pathways (Jerger and Jerger, 1974), and auditory impairment due to brainstem stroke is well documented in the literature (Jerger and Jerger, 1974; Luxon et al., 1980; Musiek and Pinheiro, 1987; Aharonson et al., 1998; Lee et al., 2002). Abnormal ART is reported in lesions of the auditory nerve, cochlear nuclei and superior olivary complex (Hausler and Levine, 2000; Lee et al., 2002). Only two stroke patients with abnormal ART (patient numbers 17 and 26) had abnormalities on the brainstem auditory pathways (ART patterns were consistent with intra-axial brainstem pathologies).

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Overall, the percentage of pathological acoustic reflexes in our cohort did not significantly exceed that of the age- matched control subjects.

The origin of hearing loss was further investigated by recording TEOAEs. There was no statistically significant difference between the TEOAE results of stroke patients and the age- -matched controls in both the older and younger groups. Since we used transient evoked otoacoustic emissions rather than distortion product otoacoustic emissions, it is possible that subtle cochlear deficits may have been missed.

Hearing abnormalities in isolated stroke lesions of the auditory brainstem are well documented in the literature (Johnson, 1977; Starr et al., 1996; Hausler and Levine, 2000; Lee et al., 2002; Lee et al., 2008; Pennings et al., 2011), and abnormal ABR results have been found in lesions affecting the eighth nerve, medulla (cochlear nuclei), pons (superior olivary complex, trapezoid body, lateral lemniscus) and midbrain (inferior colliculus). Sinanović (2008) analysed ABR abnormalities in patients with brainstem stroke and reported that 83% of their patients had abnormal ABR results. In the present study, we found that 8 (19%) of all our patients had abnormal ABR latencies as compared to 2% of the control subjects. Four of these patients with abnormal ABR had a brainstem stroke, out of a total of five brainstem stroke patients in our sample, i.e. 80% of the brainstem stroke patients had abnormal ABR, similar to Sinanović's (2008) findings. The remaining brainstem stroke patient with the normal ABR had an upper brainstem stroke lesion in the ventral lateral medulla, which would not be expected to affect the ABR. Four patients with abnormal ABR had cortical lesions, with the abnormality in ABR possibly reflecting effects of microvascular ischemia (Mills and Ryals 1985). The difference in normal vs. abnormal ABR in stroke patients vs. controls was significant. However, there was no statistically significant difference when the older and younger stroke groups were compared to the same groups in control subjects.

There was a statistically significant difference between the GIN results of the stroke patients and the age-matched controls in both the older and younger groups. We found that 74% of our cohort had abnormal unilateral or bilateral GIN. The MRI showed abnormalities in the central auditory pathways in 48% of these stroke patients but in the remaining 26% non-auditory areas were affected, while two of these (stroke patients with the involvement of non-auditory areas) had severe small

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vessel disease. A GIN abnormality could be attributable to specific isolated brain lesions, small vessel disease, or could simply be the result of advancing age (Bamiou et al., 2000; Bamiou et al., 2006; John et al., 2012). Strouse et al. (1998) found that there are age-related differences in temporal processing. Older listeners without SNHL were found to have higher gap detection thresholds (GDTs), which would appear to be an indication of an aging effect in the central auditory system. A recent study by John et al. (2012) provides evidence of significant deleterious effects of advancing age on GIN test performance. Since our study is a cross-sectional study, and we included patients with up to a moderate hearing loss, it is not possible to identify precisely the cause of the abnormalities in the GIN test performance.

This is the first study to explore the prevalence of auditory cognition deficits using detailed auditory cognition assessments in stroke patients. Deficits of property processing and apperceptive processing, as compared to semantic processing, were more common in stroke patients. We found a statistically significant difference between the perceptual property and apperceptive processing results of stroke patients and the age-matched controls in both the older and younger groups. However, the difference in semantic processing was not significant in either group.

3.6.2 Types of Hearing Impairment and Disordered Auditory Processing in Stroke Patients

Aging is accompanied by a decline in hearing sensitivity due to sensory changes in the ear. Other changes in the central auditory nervous system may contribute to the difficulty older adults experience understanding speech in background noise. Pathological conditions such as stroke can further compromise auditory function. There are many factors that should be considered for the management of stroke patients with peripheral and central auditory dysfunction. Thus it is essential to differentiate peripheral and central deficits for the evaluation and rehabilitation of stroke patients. Furthermore, auditory processing disorders and perceptual deficits in stroke patients are less well studied and possibly underdocumented (Polster and Rose, 1998). Patients will not necessarily report such deficits in their less severe forms unless they are explicitly questioned (Blaettner et al., 1989; Bamiou et al., 2012). Thus the prevalence of auditory processing deficit among the wider stroke

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population is not established. To our knowledge, this is the first study to investigate the prevalence of non-verbal auditory processing deficits in the stroke population on the basis of a non-verbal auditory psychoacoustic battery (GIN, PP, AP, SP), an electrophysiological test that is sensitive to temporal processing, brainstem abnormalities (ABR), and an electroacoustic test that is sensitive to low brainstem lesions (ART), and to investigate the type of hearing loss in the stroke population. Although the proportion of people with peripheral hearing loss did not significantly differ from the healthy control group, our results indicate that the most common type of hearing impairment in our stroke patients was the combination of peripheral and central hearing impairment in the 61-80-year-olds subgroup (55%), and disordered auditory processing in the 18-60-year-olds (40%). Both were significantly higher than the controls. This is of particular significance as none of the younger group with AP deficits were referred for audiological assessments after the onset of stroke. They did not complain of any ‘hearing problems,’ which were only identified with the hearing questionnaires that were particularly looking into difficulty hearing speech in background noise and localizing sounds. (The results of the hearing questionnaires in this patient group will be discussed in Chapter 4). Temporal and perceptual property processing are important to speech perception (Gordon–Salant and Fitzgibbons, 1993; Walton et al., 1997), in keeping with a high number of self-reported hearing symptoms among the stroke patients on the Amsterdam inventory for auditory disability questionnaire (AIAD) (Bamiou et al., 2012). Identification of GIN or other central-type deficits in stroke patients would thus require appropriate management in order to help stroke survivors cope with the challenges they face during and after the recovery period and to help them participate as fully as possible in intellectual, social, and family activities.

3.6.3 Implications for Practice

Our study demonstrates that hearing impairment of any type was present in the majority of stroke patients (86%), none of whom had been previously referred for a hearing assessment. This would suggest that hearing impairment remains a ‘hidden’ disability in this population, one that may be overlooked by the neurologists and other healthcare professionals. The current National Institute for Health and Care Excellence (NICE) guidelines (2013) on stroke rehabilitation provide advice on

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cognitive functions, sensory functions (vision), digestive system function, movement-related functions, communication (speech), mobility, and domestic life. Strategies for identification and management of auditory dysfunction, however, receive significantly less attention, with auditory rehabilitation post-stroke arguably being the ‘lost dimension’ of stroke rehabilitation. Our study findings would suggest that current guidance would benefit from the addition of a hearing assessment, or increasing awareness of possible hearing impairment in stroke patients, as such impairment may affect the patients’ post-stroke physical outcome and may impact patient communication in everyday life in the chronic stage of stroke (Bamiou et al., 2012). Conventional hearing aids may be a suitable option for those with peripheral hearing loss, while counselling, directional microphone hearing aids with built-in FM, and educating the patients and caregivers may be an appropriate rehabilitation plan to meet the needs of older stroke patients with mixed peripheral and central hearing losses.

Hearing loss is associated with cognitive decline and dementia in older adults (Lin and Yaffe, 2013), and the presence of peripheral hearing loss may lead to an unjustified diagnosis of cognitive impairment (Jorgensen, 2012). There is evidence to suggest that evaluation of peripheral and central auditory function may be important in cases of suspected dementia or other cognitive disorders in older adults (e.g. Gates et al., 1996, 2002, 2008, 2011; Jorgensen, 2012). Because the presence of sensory or perceptual deficit can result in ‘upstream’ effects on memory and related cognitive abilities due to insufficient processing resources (Pichora-Fuller et al., 1995; McCoy et al., 2005), it is critical that audiologists be a part of the multidisciplinary team together with neuro-psychologists, speech therapists, neurologists, and other professionals in the evaluation of stroke patients, in an effort to disentangle the relative effects of peripheral and central auditory dysfunction from higher-level cognitive, language, and other deficits.

Finally, the level of background noise in acute or rehabilitation stroke units is worth noting. Difficulty hearing speech in noise is a common disability experienced by stroke patients with hearing impairment (Bamiou et al., 2012). Therefore, it would seem imperative to minimise the level of background noise in hospitals and rehabilitation units in which many patients have hearing impairment.

3.6.4 Limitations and Future Research

This was a cross-sectional study, and it is challenging to identify precisely the cause of hearing impairment in this population. Also, this study has the limitations of differences in demographic factors between groups, small male numbers in the control group, small numbers in the older control group, the exclusion of patients with more than one stroke, those with a greater than moderate hearing loss, and those over 80 years old, and the fact that there was no retesting of the changes in hearing thresholds and auditory processing deficits after 12 months. Taking these caveats into account, the evidence presented here should motivate future work in larger patient and control cohorts and the retesting of patients after 12 months to monitor any auditory changes. Furthermore, the differences in the hearing thresholds might have reached statistical significance with a larger sample size. Finally, structural and functional neuroimaging will be required to be performed at least 24 hours prior to the audiological assessments to correlate AP deficits with patterns of network-specific infarction in stroke patients.

Offering a comprehensive audiological assessment to all stroke patients would be a costly and time-consuming process. Therefore, a preliminary screening program for such patients needs to be identified, e.g. by means of a questionnaire, so that the full audiological assessment could be reserved for those who fail the initial hearing screening.



4 Chapter 4: Study 2. Validating an Auditory Screening Protocol for the Stroke Patients and Patient Reported Hearing Difficulty in Stroke Patients

4.1 Introduction

4.1.1 Effects of Early Identification of Hearing Impairment and Intervention in Stroke Patients

Some stroke patients appear to be uncooperative, inattentive, or cognitively impaired, when in fact they may have a significant hearing impairment that is causing them to respond inappropriately (Loiselle, 1991). This can, in the worst case, lead to misdiagnosis when diagnosis depends on behavioural assessments. In addition, hearing impairments may impact rehabilitation, since one common setting for a stroke patient undergoing rehabilitation is a large room for physical and occupational therapy in which there is a significant amount of background noise. For a patient with a hearing sensitivity loss or auditory processing disorder, this can be a very difficult environment in which to follow instructions, as the patient might not understand the tasks required.

Clinical diagnosis of hearing impairment is predominantly based on routine audiological testing. However, routine assessments may not always include complex tests of auditory processing despite the presence of significant auditory complaints (Kumar et al., 2007). In order to assist the stroke patients in their communication abilities, it is important for clinicians to be also aware of the potential interference of central auditory dysfunction in such patients. Rey et al. (2007) conducted a range of auditory processing (AP) assessments, including sound recognition, localisation and sound motion perception, on 24 patients who sustained focal hemispheric lesions in acute/sub-acute post-stroke and retested them in the chronic stages. They concluded that in the acute and sub-acute stages, a widespread and non-specific dysfunction occurs in the auditory network beyond the penumbra, causing transient deficits even in domains whose specialised networks are spared by the stroke. From the early chronic stage on, the presence of deficits is associated with damage to the specialised

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network, and the likelihood of recovery is variable. In a study by Blaettner (1989), patient reports of difficulties on potential auditory or speech perceptual problems in demanding everyday hearing circumstances revealed a high incidence of reported problems. Blaettner and colleagues (1989) administered a hearing questionnaire to 45 patients with unilateral telencephalic hearing disorder prior to baseline audiological testing and auditory processing assessments. They reported that 49% of such patients stated perceptual problems, most commonly in situations with several simultaneous speakers. Interestingly, the results did not correlate with the pure-tone audiometry results, but strongly correlated with the administered auditory processing tests. The results of the hearing questionnaire revealed that these patients did not experience a hearing problem, but rather discomfort or overload, leading to poorer understanding of speech in social situations demanding high auditory selectivity. Bamiou et al. (2012) conducted a study on 21 patients with strokes affecting the auditory brain and with relatively spared audiometric thresholds for whom the Amsterdam Inventory for Auditory Disability (AIAD) had been administered. All participants also underwent a detailed auditory processing assessment. None of the inventory subscales correlated with the pure-tone audiometry results, but sound recognition and localization strongly correlated with dichotic digits and pattern tests. The authors highlighted the need of administering a hearing questionnaire to such patients in order to identify those who may require more extensive assessment.

Undetected and untreated hearing impairment may affect the delivery of medical and psychological services after stroke. Therefore, it is necessary to identify hearing deficits (peripheral and/or central) in stroke survivors, as the presence of hearing impairment may affect the patients' post-stroke physical outcome. The national clinical guidelines for stroke patients, recommended by the UK Royal College of Physicians (2012), state that stroke patients should be assessed in the acute stage of stroke for their 'ability to hear and need of hearing aids', while a broad recommendation is made that 'any person who appears to have perceptual difficulties should have a formal perceptual assessment, followed by intervention'. However, offering a comprehensive audiological assessment to all stroke patients would be a costly and time-consuming process. Therefore, a preliminary screening test for such

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patients is required so that the full audiological assessment could be reserved for those who fail the initial hearing screening.

The American Speech-Language-Hearing Association's (ASHA) adult hearing screening recommendations suggest four screening procedures: case history, visual inspection and otoscopy, pure-tone screening, and self-reported hearing disability (ASHA, 1997). The World Health Organization (WHO) defines a screening test as follows:

‘The presumptive identification of unrecognised disease or defect by the application of tests, examinations or other procedures which can be applied rapidly’ (WHO).

Thus the hearing-screening test for stroke patients should be a brief test that can rapidly identify hearing difficulties among stroke survivors in a stroke unit.

The main purpose of a screening test is to identify patients with a possible disorder or disease for further investigations. Therefore, an ideal screening test should be able to detect as many patients with the disorder or disease as possible. This leads to the need for developing a screening test with high sensitivity (Lalkhen, 2008). On the other hand, in order to identify every potential case, we may accidentally include the normal population (normal hearing) in this cohort. Such cases will later be excluded with a comprehensive standard test. Therefore, a slight compromise in the specificity level of the test in order to keep the high sensitivity of the screening test is acceptable (Musiek, 2015). Still, too low specificity can lead to increased workload in the process of providing full ‘gold standard’ testing.

4.1.2 Accuracy of a Hearing-Screening Program

An effective screening program should, as accurately as possible, separate individuals into two categories: pass (negative) and refer/fail (positive). Screening accuracy is examined using a 2x2 contingency table (Table 4-1) that is compared with the results of diagnostic testing. This contingency table contains four possible outcomes: hit (true-positive), false alarm (false-positive), miss (false-negative), and correct rejection (true-negative). Frequent indicators of efficacy are sensitivity and specificity.

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Table 4-1: Contingency matrix

		Present (+)	Absent (-)
Screening Results	Positive (+) (Fail/Refer)	Hit (True positive) A	False Alarm (False positive) B
	Negative (-) (Pass)	Miss (False negative) C	Correct rejection (True negative) D

Table 4-2: Column Data (in reference to the disorder)

Measure of Accuracy	Formula	Probability that ...
Sensitivity	$A/(A+C)$	Someone with the disorder has a positive screening result
Specificity	$D/(B+D)$	Someone without the disorder will have a negative screening result
False Negative rate	$C/(A+C)$	Someone with the disorder will have a negative screening result
False Positive rate	$B/(B+D)$	Someone without the disorder will have a positive screening result

4.1.3 Handheld Hearing Screener

Handheld hearing screeners are not intended to determine hearing thresholds but rather to identify the possibility of an individual presenting with hearing loss (ASHA, 1997). Hearing screening tests must have a high sensitivity to be useful to clinicians, because otherwise, negative results may be false-negatives (Fletcher, 1996). False-negatives should be the main concern for the screening. Handheld audiometers typically have a sensitivity of 92% and a specificity of 94% in detecting sensorineural hearing loss (Frank et al., 1987). A study by Cardoso et al. (2014) showed that hearing screening devices can be effective in screening for hearing loss in adults and older adult persons, but when only using the proper methodology. When hearing loss goes undetected, individuals are not referred for assessment and diagnosis, which consequently prevents treatment from being initiated. Evidence shows hearing aids improve social functioning and quality of life even for mild hearing losses, and long-term outcomes are better when they are obtained early (Marlow, 1990; Chisolm, 2001). Thus, the cut-off or criterion used must prioritise maximum sensitivity (Fletcher 1996; ASHA, 1997; Goulart, 2007) even for a mild hearing loss. Therefore, the protocol employed in a hearing screening program should have enough sensitivity to identify minimal hearing loss.

4.1.4 Questionnaires as Screening Tools

Pure-tone thresholds are considered the 'gold standard' for identifying the degree of hearing loss. Subsequently, comprehensive audiological tests are required to diagnose the nature of hearing impairment and to assess patients' ability to hear sounds and speech. To perform these diagnostic tasks, one should have well-calibrated equipment, acoustically treated testing rooms, and qualified audiologists. But these requirements are not always available. Hence as an alternative, the self-assessment of hearing difficulty has been widely used because it is an easy procedure and involves no special set-up, especially in cases where expenses and time restrictions are concerns (Gates & Mill, 2005). Lately, self-report measurements have become valuable tools in the field of audiology that can be used from screening to intervention. Self-reported inventories are standardised questionnaires that are used to characterise a complex clinical picture. Use of a questionnaire to identify hearing

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loss has been an attractive option because no costly equipment is needed and the training demands to administer the questionnaire are minimal (Newton et al., 2001).

A good standardised questionnaire should have good reliability and validity, short administration time, ease of scoring, and detection of specific functional, emotional, and physical problems (Newman et al., 1990).

The standardised questionnaires should be easily understood by lay people, easy to score, and should not take time to be completed. The questionnaires should include a variety of items in order to identify and measure the difficulties encountered by each individual in their life environment and the impact those difficulties have on their quality of life.

An additional consideration is the readability of the questionnaires. Atcherson and colleagues (2013) assessed the readability of various screening questionnaires that are being used to assess hearing difficulties in children who are suspected of having CAPD and decide the need for referral to a specialist clinic. They stated that poor literacy skills might negatively influence questionnaires' outcome. The authors proposed that the reading grade level of the questionnaire should be written as low as possible, using plain language and clear writing and with careful consideration given to word choice and word syllable length. They also proposed that the design and layout of the questionnaire should be one that facilitates comprehension, is easy to use, and enhances the likelihood of obtaining reliable and valid responses. This is particularly important in our cohort, as some stroke patients may have subtle cognitive and linguistic deficits that make them unable to answer inquiries at the level of complexity necessary to tap the relevant issues.

Questionnaires are invaluable tools for clinicians when they are used properly and when respondents can provide valid and reliable data. Another consideration is the mode of administration. Self-administrated measures tend to be less resource intensive than interview-administrated measures. However, physical difficulties that limit the ability to complete a questionnaire, or cognitive or linguistic problems that affect concentration or understanding, may render self-completion an arduous, if not impossible, task for some people. Interviewer-administrated questionnaires may also be problematic to apply, because some stroke patients will be unable to respond in an interview setting owing to speech problems. Thus, given the range of impairments

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often experienced after stroke, it is important to establish whether a questionnaire can be both self- and interviewer-administrated (Segal & Schall, 1994; Dorman et al., 1997; Wild & Sargeant, 1997).

As well as appropriateness and comprehensiveness, reliability and validity are vital with any outcome measures, to ensure confidence in their scientific robustness. Reliability is the extent to which measurements for the same individual on same occasions or by different observers produce similar results (Streiner & Norman, 1992). Validity is the extent to which an instrument measures what it is meant to measure (Fitzpatrick et al., 1998).

4.1.5 Use of Hearing Questionnaires in Adult Population with CAPD

Approx. 4% of working age adults (Hind et al., 2011) and up to 10% of all adults (Kumar et al., 2007) who present to audiology departments with complaints of significant listening difficulties have normal pure-tone thresholds. A proportion of these patients give abnormal performance on complex psychoacoustic tests, and their listening difficulties are attributed to functional deficits in sound processing within the extended central auditory nervous system (Moore et al., 2013). Application of auditory questionnaires to the patients with AP deficits may help identify patients with auditory disability and inform the individualised management and intervention approach by defining the nature and severity of the auditory processing deficits (Bamiou et al., 2006).

Neijenhuis et al. (2003) published a study of 24 adults with suspected CAPD (based on reported hearing difficulties) on whom a Dutch CAPD test battery was validated. Adults with suspected CAPD scored significantly worse in all aspects of Amsterdam Inventory for Auditory Disability (AIAD), particularly in understanding speech in noise and in auditory localisation, compared to normal controls. Bamiou et al. (2012) gave the AIAD questionnaire to 21 adult patients with stroke of the auditory brain 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 questionnaire scores correlated significantly with tests of auditory processing but not with hearing thresholds. It was proposed

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

4.1.6 Hearing Questionnaires as Screening for Hearing Loss

Some epidemiological studies have used self-report methods to estimate the prevalence of hearing loss (Rosenhall et al., 1987; Skinner, 1995). In a population of 60- to 85-year-old women in Iowa (Clark et al., 1991), self-reported hearing loss had a sensitivity of 84% and a specificity of 75% if the measured hearing loss were at least 40 dB HL (pure-tone thresholds average of 1, 2, 3, and 4 kHz). A study by Lutman (1990) showed that self-reported disability was under-rated by older subjects with mild impairment, and there was only a low correlation between self-reported hearing loss and the results of behavioural tests, such as words in quiet and sentences in noise. Another study by Salonen and colleagues (2011) showed that the Hearing Handicap Inventory for the Elderly (HHIE) is a sensitive and specific tool for identifying moderate to severe hearing loss, and suggested that although mild hearing loss was difficult to identify reliably with the HHIE, this questionnaire can be used to evaluate the need for audiological rehabilitation in an elderly population.

4.1.7 Patient-reported Auditory Symptoms in Stroke Population

Audiological assessments generally do not reflect the communication difficulties that the patients encounter within their everyday dynamic acoustic environments (Gatehouse and Noble, 2004). Hearing questionnaires thus may be used to identify and quantify patients' specific symptoms in real life. There are only a few hearing questionnaire studies of stroke patients (Blaettner et al., 1989; Bamiou et al., 2012) that suggest stroke patients may report sound localisation and speech in noise difficulties (Blaettner et al., 1989) or severe functional limitations with sound recognition (Bamiou et al., 2012). However, their results may not be directly extrapolated to all stroke patients with all types of hearing impairment. The aforementioned hearing questionnaire studies in stroke patients only included patients with relatively normal audiograms and did not attempt to assess the patient-reported auditory symptoms in those with peripheral hearing loss and/or peripheral and CAPD impairment. Those with a variety of CAPD presentations report

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complaints comparable to those in hearing-impaired adults, for example, difficulties with in speech-in-noise perception, or localization of sounds (Meijer et al., 2003; Noble and Gatehouse, 2006; Bamiou et al., 2012; Spyridakou et al., 2012). Application of these questionnaires to the stroke population with all types of hearing impairment may help identify patients' symptoms in a more structured and validated manner and expand on the symptoms reported spontaneously by the patient during clinical assessment and history taking.

This study aimed to evaluate and characterise listening difficulties and their associated handicap measured through two questionnaires, the HHIE and the AIAD, in the subacute stage stroke patients with all types of hearing impairments and to compare their questionnaires with those of patients with normal hearing.

4.2 Purpose

The primary purpose of this study was to determine whether a handheld hearing screener and the AIAD and HHIE questionnaires could be used as a hearing screening tool to facilitate early identification and appropriate referral of hearing impaired stroke patients in the subacute stage.

The secondary aim was to explore auditory symptom differences among stroke patients with normal hearing, peripheral hearing loss, combination hearing impairments (peripheral and CAPD), and CAPD.

4.3 Methods

4.3.1 Participants and Settings

Fifty stroke patients were tested at the department of Neuro-otology, NHNN Queen Square, within three to twelve months post-onset stroke. After excluding those with severe or greater hearing loss and those with cognitive impairments (Chapter 2, Section 4.2.1), a final 42 patients were included in the study 2. The full demographic data were presented in Chapter 3. All the screening tests were completed for each subject in a randomised order during a single visit, before the administration of the full audiological assessment.

4.3.2 Screening Tools

Three screening tools (fully described in Chapter 2) for the identification of hearing impairment were evaluated in this research study:

- Handheld hearing screener
- AAID questionnaire
- HHIE questionnaire

4.3.3 Criteria for ‘gold standard’

For the handheld hearing screener, the pure-tone audiogram was established as the ‘gold standard’. The hearing loss was determined per the BSA recommended protocol for pure-tone audiometry (2011).

For the hearing questionnaires, information from different audiological tests was combined to construct the ‘reference standard outcome’³. All patients received the same set of audiological tests that were described in Chapter 2. They were classified as having normal hearing, peripheral hearing loss, combination (peripheral and CAPD) impairment, or CAPD hearing impairment. To calculate the sensitivity and specificity of the hearing questionnaires, the scores of the HHIE and the AIAD were compared against the hearing types (reference standard outcome) i.e. normal hearing, peripheral hearing loss, combination and CAPD.

4.3.4 Pass and Fail Criteria for Hearing Screening Tools

- Handheld hearing screener: Fail at least one frequency across both ears (Fail), or pass all frequencies in both ears (Pass).
- HHIE questionnaire: Hearing impairment was defined by the criteria of Ventry and Weinstein (1982). If the total score ≤ 16 , then no hearing impairment was identified; if the total score was ≥ 17 , the subject was considered to have a hearing impairment.

³ The reference standard is the test, combination of tests, or procedure that is considered the best available method of categorising participants in a study of diagnostic test accuracy as having or not having a target condition.

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- AIAD questionnaire: AIAD has been validated in both patients with hearing loss (Meijer et al., 2003) and with those with CAPD (MD thesis, Chrysa Spyridakou, 2015). Hearing impairment was defined by the criteria of Meijer et al. (2003) for peripheral hearing loss: pass was defined as AIAD scores ranging from 64-84 (no disability), and fail was defined as a total score of < 64 .
- Combined handheld hearing screener and AIAD questionnaire for identifying CAPD: For those with CAPD, auditory disability was defined by the criteria of Spyridakou's thesis (2015): Fail if the total score of the AIAD was ≤ 58 , or if the total score of the AIAD was > 58 but the localisation subscore was ≤ 10 and/or the speech in noise subscore was ≤ 7 .

4.4 Statistical Analysis

4.4.1 Accuracy of the Hearing Screening Tools

To evaluate the accuracy of the screening tools for the diagnosis of hearing impairment, calculations of sensitivity, specificity, positive predictive value, and negative predictive value were performed using the 'gold standard' described in Methods. Sensitivities were calculated as the proportions of persons with hearing impairment correctly identified by the tests, while specificities were calculated as the proportions of persons without hearing impairment correctly identified by the tests.

4.4.2 Exploring the Auditory Symptoms of Stroke Patients

The Kruskal-Wallis test is a nonparametric test, and is used when the assumptions of ANOVA are not met. The tests assess for significant differences on a continuous dependent variable by a grouping independent variable (with three or more groups). In the ANOVA, we assume that the distribution of each group is normally distributed and there is approximately equal variance in the scores for each group. However, in the Kruskal-Wallis Test, these assumptions are omitted. Since data did not meet the criteria of normality, a Mann-Whitney two-sample rank-sum test was conducted to examine whether there were significant differences in the hearing questionnaire

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scores among the levels of the hearing type groups. The Mann-Whitney two-sample rank-sum test is a non-parametric alternative to the independent samples t-test and does not share the independent samples t-test's distributional assumptions.

4.5 Results

Data from 42 stroke patients were obtained for all screening protocols (for the handheld hearing screener, n = 84 ears).

4.5.1 Validation of Hearing Screening Tools

4.5.1.1 Accuracy of Handheld Hearing Screener

To analyse the use of the portable hearing screening equipment regarding sensitivity and specificity in terms of detecting hearing loss, the results of the diagnostic audiometry (BSA, 2011) was defined as the 'gold standard'. Data were analysed for both ears.

According to the results presented in Table 4-4 (next page), it was found that the hearing screening device had a high sensitivity for detecting a hearing loss using the ASHA protocol, reaching a value of 92.59%. Of the 54 ears identified as having a hearing loss, 4 passed the screening. Specificity, in turn, was 100% (i.e., of the 50 ears classified as having normal hearing, all passed the screening). Positive predictive value (PPV) is the probability that subjects with a positive screening test truly have the disease, and negative predictive value (NPV) is the probability that subjects with a negative screening test truly do not have the disease. Among those who had a positive screening test, the probability of having a hearing loss was 100%, and among those who had a negative screening test, the probability of having normal hearing was 88.24%.

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Table 4-3: Pass/Fail results for handheld hearing screener, ASHA protocol

		PTA result		Total
		Normal	Abnormal	
Hearing screening per ASHA Protocol	Pass	30	4	34
	Fail	0	50	50
Total		30	54	84

Table 4-4: Analysis of responses to hearing screening in both ears, considering the interpretation according to ASHA protocol

	Estimate (%)	95% confidence interval (exact)	
		Lower limit (%)	Upper limit (%)
Sensitivity	92.59	75.71	99.09
Specificity	100.00	78.20	100.00 (*)
Positive Predictive Value	100.00	86.28	100.00 (*)
Negative Predictive Value	88.24	63.56	98.54

* one-sided confidence interval

4.5.1.2 Accuracy of HHIE Questionnaire

To analyse the accuracy of the HHIE questionnaire in terms of identifying hearing impairments, the result of the reference standard outcome (see Section 4.3.3) was defined as the ‘gold standard’.

According to the results presented in Table 4-6, it was found that the HHIE questionnaire had a sensitivity of 44.44% for detecting hearing impairments using the published cut-off point of ≥ 17 in hearing impaired people (Ventry and Weinstein, 1982). Specificity, in turn, was 100% (Table 4.6). Among those who had a positive screening test, the probability of having a hearing impairment was 100% (positive predictive value), and among those who had a negative screening test, the probability of having normal hearing was 23.08%.

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Table 4-5: Pass/Fail results for HHIE

		Type of hearing		Total
		Normal	Abnormal	
HHIE	Normal (≤ 16)	6	20	26
total score	Abnormal	0	16	16
Total		6	36	42

Table 4-6: Sensitivity, specificity, positive predictive value and negative predictive value of HHIE

	Estimate (%)	95% confidence interval (exact)	
		Lower limit (%)	Upper limit (%)
Sensitivity	44.44	27.94	61.90
Specificity	100.00	54.07	100.00 (*)
Positive Predictive Value	100.00	79.41	100.00 (*)
Negative Predictive Value	23.08	8.97	43.65

*one-sided confidence interval

4.5.1.3 Accuracy of AIAD Questionnaire

According to the results presented in Table 4-8, it was found that the AIAD questionnaire had a sensitivity of 36.11% for detecting hearing impairments using the published cut-off point of < 64 in hearing-impaired patients (Meijer et al., 2003). Specificity, in turn, was 100% (Table 4-8). Among those who had a positive screening test, the probability of having a hearing impairment of any types was 100% (positive predictive value), and among those who had a negative screening test, the probability of having normal hearing was 20.69%.

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Table 4-7: Pass/Fail results for AIAD

		Type of hearing		Total
		Normal	Abnormal	
AIAD total score	Normal (> 64)	6	23	29
	Abnormal	0	13	13
Total		6	36	42

Table 4-8: Sensitivity, specificity, positive predictive value and negative predictive value of AIAD

	Estimate (%)	95% confidence interval (exact)	
		Lower limit (%)	Upper limit (%)
Sensitivity	36.11	20.82	53.78
Specificity	100.00	54.07	100.00 (*)
Positive Predictive Value	100.00	75.29	100.00 (*)
Negative Predictive Value	20.69	7.99	39.72

*one-sided confidence interval

4.5.1.4 Combining the Handheld Hearing Screener and AIAD Questionnaire for Identifying CAPD

The greatest test accuracy in identifying a CAPD type hearing impairment in stroke patients was found when the handheld hearing screener and the AIAD questionnaire were combined. According to the results presented in Table 4-10, it was found that the AIAD questionnaire had a sensitivity of 50% for detecting CAPD using the previously reported cut-off point of ≤ 58 , or an AIAD > 58 but with the AIAD localisation subscore ≤ 10 and/or the AIAD speech in noise subscore ≤ 7 in CAPD patients (Sprydakou, 2015) and when the hearing screening test indicated a pass. Specificity, in turn, was 88.89% (Table 4-10). Among those who had a positive screening test, the probability of having a CAPD was 80% (positive predictive

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value), and among those who had a negative screening test, the probability of having normal hearing was 66.67%.

Persons should be considered in need of referral if they pass the handheld hearing screening tool but have an AIAD total score of ≤ 58 , or an AIAD score > 58 but with the AIAD localisation subscore ≤ 10 and/or with the AIAD speech in noise subscore ≤ 7 .

Table 4-9: Pass/Fail results for combining handheld hearing screener and AIAD

		Type of hearing		Total
		Not CAPD	CAPD	
Combined AIAD and screener	Not CAPD	8	4	12
	CAPD	1	4	5
Total		9	8	17

Table 4-10: Sensitivity, specificity, positive predictive value and negative predictive value of combined handheld hearing screener and AIAD

	Estimate (%)	95% confidence interval (exact)	
		Lower limit (%)	Upper limit (%)
Sensitivity	50.00	15.70	84.30
Specificity	88.89	51.75	99.72
Positive Predictive Value	80.00	28.36	99.49
Negative Predictive Value	66.67	34.89	90.08

4.5.2 Exploring the Questionnaires' Data: Self-reported Auditory Symptoms in Stroke Patients

4.5.2.1 Hearing Handicap Inventory for Elderly (HHIE)

A boxplot of distributions of the total score of the HHIE questionnaires as well as the emotional and situational subscores for the different hearing impairment groups are shown in Figure 4-1. The data are skewed and not normally distributed.

Figure 4-1: Boxplots showing the distributions of the total and 2 subscores in HHIE questionnaire for the different hearing impairment groups

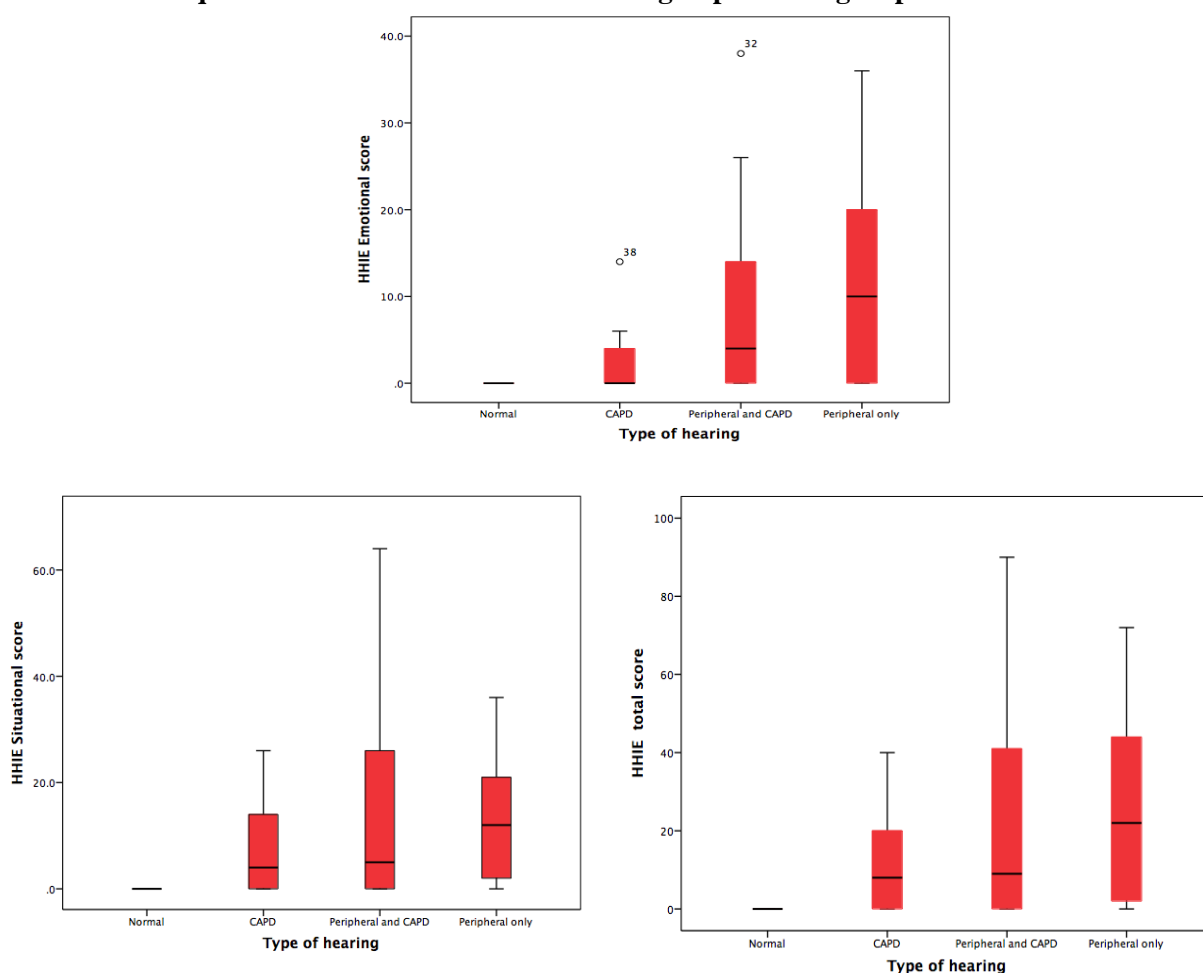


Table 4-11 (p. 124) shows the overall values of the mean, median and standard deviation of the total scores of the HHIE questionnaires for the four groups: normal, CAPD, peripheral and CAPD, and peripheral only.

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Table 4-11: Overall mean, standard deviation median and range for each dimension of the HHIE questionnaire in stroke patients

Score	Mean	Standard deviation	Median	Range
HHIE emotional	6.81	10.47	0	0 to 38
HHIE situational	9.95	13.80	4	0 to 64
HHIE total	16.76	23.24	6	0 to 90

Kruskal–Wallis testing confirmed a highly significant difference among the four groups for the total scores and for the emotional and situational subscores of the HHIE questionnaire (Table 4-12).

Table 4-12: Kruskal-Wallis non-parametric statistical analysis for four groups (Normal, CAPD, Peripheral and CAPD, peripheral) for all aspects of the HHIE questionnaire

	χ^2 (d.f.)	probability	χ^2 with ties (d.f.)	probability
HHIE emotional score	6.239 (3)	0.1005	7.302 (3)	0.0629
HHIE situational score	8.428 (3)	0.0380	9.043 (3)	0.0287
HHIE total score	9.219 (3)	0.0265	9.883 (3)	0.0196

Table 4-13: Kruskal-Wallis non-parametric statistical analysis for three groups (CAPD, Peripheral and CAPD, peripheral) for all aspects of the HHIE questionnaire

	χ^2 (d.f.)	probability	χ^2 with ties (d.f.)	probability
HHIE emotional score	1.810 (2)	0.4046	1.990 (2)	0.3697
HHIE situational score	1.183 (2)	0.5534	1.222 (2)	0.5429
HHIE total score	2.132 (2)	0.3444	2.198 (2)	0.3332

Subsequently, a Mann-Whitney non-parametric test was performed to check for any statistically significant differences among the participants with CAPD and participants with normal hearing; ‘peripheral and CAPD’ and ‘normal’; ‘peripheral only’, and ‘normal’. Table 4-14 records the results of the Mann–Whitney non-parametric test for the HHIE questionnaire (overall and by aspect) among the four groups.

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Table 4-14: Mann-Whitney non-parametric test between the four groups.

	HHIE emotional score	HHIE situational score	HHIE total score
CAPD vs Normal	0.0691	0.0353	0.0348
CAPD vs CAPD+Peripheral	0.3498	0.5612	0.4332
CAPD vs Peripheral	0.1630	0.2322	0.1141
CAPD+Peripheral vs Normal	0.0253	0.0092	0.0093
CAPD+Peripheral vs Peripheral	0.5394	0.6180	0.4854
Peripheral vs Normal	0.0180	0.0041	0.0041

Significance levels <0.05

4.5.2.2 Amsterdam Inventory for Auditory Disability (AIAD)

A boxplot of distributions of the total score of the AIAD questionnaire as well as the five subscores for the different hearing impairment groups are shown in Figure 4-2 (p. 126). The data are skewed and not normally distributed.

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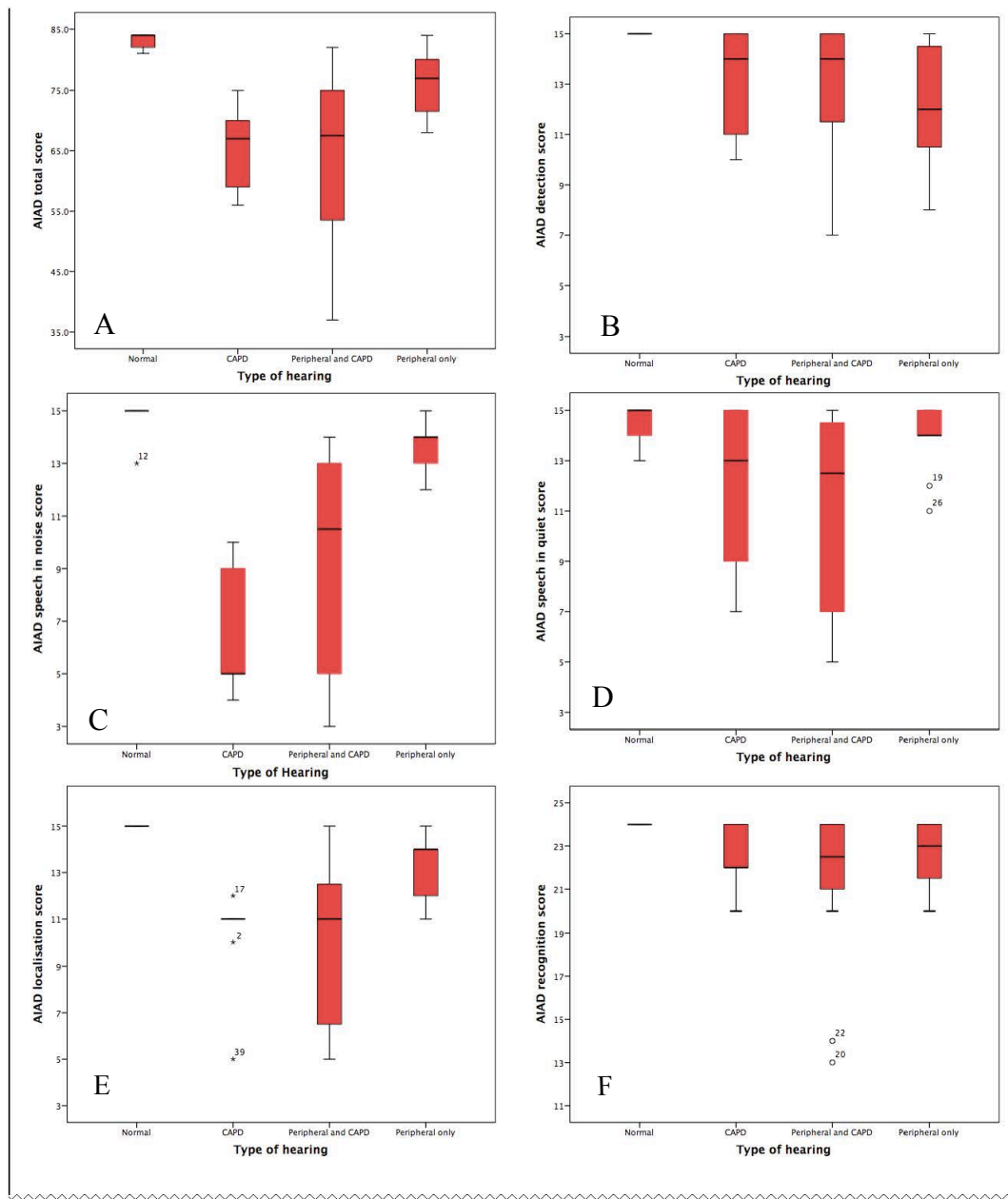


Figure 4-2: Boxplots showing the distributions of the total (A) and 5 subscores (B-F) in AIAD questionnaire for the different hearing impairment groups

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Table 4-15 shows the values of the overall mean, standard deviation, median and range of scores of the AIAD questionnaires for the four groups: ‘normal’, ‘CAPD’, ‘peripheral and CAPD’, and ‘peripheral only’.

Table 4-15: Overall mean, standard deviation, median and range for each dimension of the Amsterdam Inventory for Auditory Disability for the four groups (AIAD)

Score	Mean	Standard deviation	Median	Range
Speech in noise	10.05	4.58	10.5	3 to 15
Speech in quiet	12.48	3.19	14	5 to 15
Auditory localisation	12.29	3.35	13.5	5 to 15
Recognition of sound	22.48	2.46	24	13 to 24
Detection of sound	13.21	2.25	14	7 to 15
AIAD total	70.5	12.53	71	37 to 84

Kruskal-Wallis testing confirmed a highly significant difference among the four groups for the total AIAD score (Table 4-16) and for the speech in noise, speech in quiet, and localisation aspects of the AIAD questionnaire. Table 4-17 (next page) shows the Kruskal–Wallis non-parametric statistical analysis for three groups (all except the normals) for all aspects of the AD questionnaire.

Table 4-16: Kruskal-Wallis non-parametric statistical analysis for four groups (normal, CAPD, peripheral and CAPD, peripheral) for all aspects of the AIAD questionnaire

	χ^2 (d.f.)	probability	χ^2 w/ ties (d.f.)	probability
Speech in noise	9.351 (3)	0.0250	9.660 (3)	0.0217
Speech in quiet	7.627 (3)	0.0544	8.226 (3)	0.0416
Auditory localisation	7.815 (3)	0.0500	8.518 (3)	0.0364
Recognition of sound	4.917 (3)	0.1780	5.918 (3)	0.1157
Detection of sound	7.003 (3)	0.0718	7.798 (3)	0.0504
AIAD total	9.412 (3)	0.0243	9.553 (3)	0.0228

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Table 4-17: Kruskal-Wallis non-parametric statistical analysis for three groups (CAPD, peripheral and CAPD, peripheral) for all aspects of the AIAD questionnaire

	χ^2 (d.f.)	probability	χ^2 with ties (d.f.)	probability
Speech in noise	1.551 (2)	0.4606	1.582 (2)	0.4533
Speech in quiet	5.116 (2)	0.0775	5.408 (2)	0.0669
Auditory localisation	1.425 (2)	0.4904	1.489 (2)	0.4749
Recognition of sound	0.837 (2)	0.6580	0.944 (2)	0.6238
Detection of sound	0.932 (2)	0.6276	0.993 (2)	0.6086
AIAD total	0.709 (2)	0.7015	0.714 (2)	0.6999

Subsequently, a Mann-Whitney non-parametric test was performed to check for any statistical significant differences between the participants with ‘CAPD’ and participants with ‘normal’ hearing; ‘peripheral and CAPD’ and ‘normal’; ‘peripheral only’ and ‘normal’. Table 4.18 records the results of the Mann-Whitney non-parametric tests for the AIAD questionnaire (overall, and its aspects) between the four groups.

Table 4-18: Mann-Whitney non-parametric test between four groups. KEYS: SiN: (a) speech in noise (b) SiQ: speech in quiet, (c) LOC: localisation, (d) REC: recognition of sound and (e) DIS: sound detection; CAPD, central auditory processing disorders

	SiN	SiQ	Loc	Rec	Det	Total
CAPD vs Normal	0.0049	0.1053	0.0161	0.0679	0.0348	0.0058
CAPD vs CAPD+Peripheral	0.1873	0.4376	0.5634	0.3501	0.7679	0.9321
CAPD vs Peripheral	0.4897	0.1185	0.5565	0.7440	0.3684	0.3808
CAPD+Peripheral vs Normal	0.0143	0.0337	0.0092	0.0250	0.0153	0.0069
CAPD+Peripheral vs Peripheral	0.7086	0.0269	0.2363	0.5498	0.4321	0.5355
Peripheral vs Normal	0.0142	0.6099	0.0180	0.0340	0.0089	0.0157

Significance levels ≤ 0.05

4.6 Discussion

4.6.1 Handheld Hearing Screener, AIAD and HHIE Questionnaires as Screening Tools

Hearing loss is not routinely assessed after stroke. It can remain undetected, yet it may have important implications for rehabilitation. However, conducting a complete audiological assessment of all stroke patients would not be practical. Therefore, a preliminary screening program for such patients is required so that the full audiological assessment could be reserved for those who fail the initial hearing screening. Several studies have highlighted screening as an important hearing care activity, because it enables early diagnosis and intervention in adults and of older adults in particular (Scudder et al., 2003; Yueh et al., 2003; Davis, 2007; Yueh et al., 2007). However, to our knowledge, no studies have evaluated the efficacy of a hearing screening program in the stroke population. The aim of our study was to explore the efficacy of a handheld hearing screener and validated hearing questionnaires (HHIE & AIAD) as screening tools to identify stroke patients with hearing impairment who may require referral for possible targeted intervention, or for making recommendations regarding ways acute stroke units and/or stroke rehabilitation units can optimise a hearing screening program.

4.6.1.1 Handheld Hearing Screener

Hearing screening protocols should be effective, efficient, and accurate in identifying patients needing comprehensive audiological assessments with minimum investment of time and effort, and the usefulness of a screening should be evaluated against an independent standard; in audiology, the ‘gold standard’ is pure-tone audiometry. We calculated the sensitivity, specificity, positive predictive value, and negative predictive value of a handheld hearing screener in stroke individuals using the ASHA protocol and compared the results to the pure-tone audiometry results (the ‘gold standard’). The results obtained show that by analysing the responses to the hearing screening using the ASHA protocol, there was a high sensitivity (93%) as well as a high specificity (100%) in detecting a mild or greater hearing loss in stroke patients,

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similar to previous studies (Lichtenstein et al., 1988; Jupiter, 2009). The probability of the stroke patients indicating hearing loss with genuine underlying hearing loss (PPV) was 100%, and the probability of stroke patients indicated no hearing loss and having normal hearing (NPV) was 88%.

Our concern was that the higher ambient noise levels in the follow-up stroke clinics would interfere with the perception of the tonal signals, thus predicting a possible low sensitivity in this population. However, our results indicate that the handheld hearing screener is a valid, reliable and sensitive instrument for detecting a mild or greater hearing loss in stroke patients when it is performed in a clinical setting.

Screening using a handheld hearing screener does not require expertise in audiology and takes approximately three minutes (Yueh et al., 2010). It was found to be a useful tool even for detecting mild hearing loss in stroke patients.

4.6.1.2 HHIE and AIAD Questionnaires as Screener Tools

One of the aims of the present study was to assess the efficacy and validation of the HHIE questionnaire for screening hearing impairment of any types in the stroke population by calculating its sensitivity and specificity in stroke patients using a published cut-off score (Ventry and Weinstein, 1982). The Blue Mountain study conducted in 2001 demonstrated that the HHIE is sufficiently sensitive and specific to provide reasonable estimates of the prevalence of hearing loss. In our study, when using a cut-off value of greater than 16, the test yielded a low sensitivity (44%) but high specificity (100%) scores. The probability of the stroke patients indicating hearing impairment with genuine underlying hearing impairment (PPV) was 100%, and the probability that stroke patients indicated no hearing impairment and having normal hearing (NPV) was 23%. This means that although the stroke patients had a hearing impairment (any type), they failed to report it. However, our results were not too dissimilar from the results of the Blue Mountain study and of the Nondahl et al. (1998) study. In the Blue Mountain Hearing Study, the HHIE yielded a sensitivity of 58%, specificity of 85%, PPV of 71%, and NPV of 76% when a measured hearing loss of >25 dB was considered (Sindhusake et al., 2001). They also reported that the HHIE questionnaire is better for detecting moderate hearing impairment. Evidence from numerous research studies show that the HHIE questionnaire is an effective

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tool for identifying moderate to severe hearing loss (Weinstein et al., 1986; Nondahl et al., 1998; Deepthi et al., 2012; Tomioka et al., 2013) rather than for identifying a mild hearing loss (Blue Mountain, Nondahl et al., 1998). The low sensitivity yielded in our study may partly reflect the inclusion of those with mild hearing loss and/or CAPD in our cohort. In a study reported by Jupiter and Palagonia (2001), only 10% reported a hearing loss using the HHIE questionnaire compared to the 81% who actually had hearing loss at the 25 dB HL level as detected with pure-tone audiometry (Jupiter & Palagonia, 2001). Comparable to our findings, in Nondahl's study in the United States, the HHIE demonstrated a sensitivity of 34%, specificity of 95%, PPV of 83%, and NPV of 63% when any level of hearing impairment was considered (Nondahl et al., 1998). However, in their study, the HHIE yielded better results when the pure-tone audiometry cut-off value was increased to 40 dB HL, giving it a sensitivity of 56.8% and specificity of 92.4%. A further increase in the cut-off values to 55 dB HL gave sensitivity of 76.2% and specificity of 87.7%. Ventry and Weinstein (1982) pointed out that the relationship between hearing handicap and hearing loss is an imperfect one, with less than 50% of the variability in handicap scores being explained by pure-tone thresholds. Nevertheless, the HHIE has been evaluated for its utility in identifying hearing loss in several studies (Newman et al., 1991; Smith et al., 1992; McBride et al., 1994). In general, these studies report higher sensitivity than does the present study, although comparisons are of limited value due to widely differing definitions of hearing loss, onset of hearing loss, and study sample characteristics. The poor performance in terms of sensitivity in our study could be attributed to the fact that the HHIE is a hearing handicap inventory and not a hearing impairment inventory. Also, it has been reported that older adults tend to wait approximately 10 years from the onset of hearing loss before seeking audiological assessment (Weinstein, 1989). This may reflect the popular belief among individuals that hearing loss is a normal part of aging and not a health problem that deserves special attention. This also may explain in part why the sensitivity and negative predictive value were poor in our cohort.

There is a need for validated questionnaires that can be used as screening tools in order to characterise individuals who will need further tailored assessment. The AIAD involves different hearing situations related to different aspects of hearing, such as spatial hearing, sound source, speech discrimination in quiet and noise, and

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sound discrimination, all of which should be explored when determining if a hearing disability exists. It should also be noted that individuals with normal hearing thresholds may still encounter some hearing difficulties, such as those suffering from auditory processing disorder. The AIAD questionnaire has been validated in individuals with hearing loss (Meijer et al., 2003) and in those with AP deficits (Neijenhuis et al., 2003). However, neither of the aforementioned studies, or in fact no studies to date, have attempted to calculate the sensitivity and specificity of the AIAD questionnaire in individuals with hearing loss or in those with CAPD. An additional primary aim of this research was to explore whether the AIAD questionnaire could be used as a screening tool to identify any hearing impairments in the stroke population. We found that when using a cut-off value of greater than 64 (Meijer et al., 2003), the test yielded low sensitivity (36%) but high specificity (100%) scores. The probability of the stroke patients indicating hearing impairment with genuine underlying hearing impairment (PPV) was 100%, and the probability that stroke patients indicated no hearing impairment and actually having normal hearing (NPV) was 21%. We then combined the handheld hearing screener results and the AIAD scores to find out the sensitivity, specificity, PPV, and NPV of this combined tool. The combination tool (handheld hearing screener and AIAD), when using a cut-off value of 58 or greater for the total score and/or AIAD total score > 58 but AIAD localisation subscore ≤ 10 and/or AIAD speech in noise subscore ≤ 7 (Spyridakou., 2015), yielded a sensitivity of 50% and a high specificity of 89%. The probability of the stroke patients indicating hearing impairment with genuine underlying hearing impairment (PPV) was 80%, and the probability that stroke patients indicated no hearing impairment and actually having normal hearing (NPV) was 67%. Similar to the HHIE results, the stroke patients with a hearing impairment failed to report it. However, the high specificity showed the ability of the auditory questionnaires to correctly identify those patients without a hearing impairment. It is therefore not anticipated that the low sensitivity (high specificity) of the questionnaires will lead to a huge number of unnecessary referrals if the questionnaires were to be used as screening tools.

Screening tests using the handheld hearing screener yielded information about the presence of hearing loss, while self-report measures may be more strongly linked with taking action following screening (Mick and Pichora-Fuller, 2016).

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Furthermore, whether or not people take action after failing hearing screening seems to depend on their willingness to acknowledge and address hearing difficulties (Laplante-Lévesque et al., 2015). Notably, a recent study showed that increasing age and lower education were associated with subjective under-estimation of the severity of hearing loss compared with audiometric measures (Kamil et al., 2015). Accordingly, as we found in our study, screening audiometry could be a more reasonable way to identify individuals with hearing loss compared with subjective measures, since some individuals could be less likely to be identified if screening relied on self-report questionnaires. The potential benefits of screening will depend on whether or not the subjects are ready to engage in aural rehabilitation to deal with hearing loss, or whether they may think that hearing loss is simply a normal part of aging and/or is not a health problem, unlike other disabilities caused by stroke that deserve special attention. Individuals with unacknowledged and/or unaddressed hearing loss may not be ready to accept aural rehabilitation. Self-report measures, including questionnaires and counselling, may help guide health promotion strategies to accelerate action-taking, especially for those who are revealed by audiometric screening to have unacknowledged and/or unaddressed hearing loss. The potential effectiveness of audiometric screening to identify hearing loss in older adults needs to be evaluated in conjunction with a subjective evaluation of whether or not the individuals being screened have already or are ready to acknowledge and address hearing problems.

4.6.2 Comparison of Self-Reported Auditory Symptoms in Stroke Patients with Normal Hearing, Peripheral Hearing Loss, Combination Hearing Loss, and CAPD

The secondary aim of this study was to characterise auditory symptoms in stroke patients with peripheral hearing loss, CAPD, and combination peripheral loss and CAPD. In order to provide a comprehensive picture, two validated questionnaires were used: (a) the Amsterdam Inventory for Auditory Disability (AIAD) and (b) the Hearing Handicap Inventory for Elderly (HHIE). The AIAD questionnaire provides information about auditory complaints, whereas HHIE offers information with regards to emotional and social situations.

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The questionnaires gave significantly different results in the stroke patients with hearing impairments vs. the stroke patients with normal hearing. Participants with CAPD, peripheral hearing loss, and combination hearing impairment scored significantly lower in all aspects of the Amsterdam Disability questionnaire, including speech in noise, speech in quiet, sound recognition, localisation, and detection of sound. The present study is consistent with the results of Neijenhuis et al. (2003), who reported that while their case subjects (adults with hearing difficulties and suspected CAPD) reported significantly more complaints in all five AIAD sub-scores than normal controls, they particularly scored significantly worse in the speech-in-noise and sound localisation aspects of the AIAD questionnaire. Our findings are also consistent with the results of a study by Blattner (1989), who reported that stroke patients complained of understanding speech in noisy situations when they were explicitly asked. At first glance, our results do not appear to replicate fully the findings of Bamiou et al. (2012), who reported that patients with stroke involving the central auditory pathways scored worse only in the sound recognition and sound localisation aspects of the AIAD questionnaire. However, the subjects in their study were recruited on the basis of a confirmed stroke in the auditory brain as opposed to a stroke in *any* region of the brain, as was done in this present study, and it would make sense that the patient symptoms would be more auditory specific rather than broader or speech based. Altogether, our findings are broadly in line with the conclusions of Bamiou et al. (2012), confirming that obtaining abnormal results in a hearing questionnaire may help identify patients who require more extensive assessments in order to inform rehabilitation plans.

Another interesting finding is that stroke patients with any type of hearing impairment, including those with normal PTA but AP deficits, scored significantly worse in the HHIE questionnaire in comparison to those stroke patients with normal hearing. There are no published studies in which the HHIE questionnaire has been given to stroke patients to compare findings. However, numerous studies have shown that hearing impairment puts the individual at great psychological risk and is likely to result in emotional, psychological, and social problems (Weinstein and Ventry, 1982; Rutman, 1989; Welsh and Purdy, 2001). People with hearing loss show anxiety and depressive symptoms at four to five times the rate exhibited by people with normal hearing (Thomas et al., 1980). In summary, as well as hearing impairment having a

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direct effect on communication, our findings also suggest that hearing impairment of any type also affects stroke patients in social and emotional situations.

4.6.3 Limitations & Further Research

One limitation of the current study is the lack of reliable information regarding the aphasic and literacy status of the participants. We only depended on the availability and accuracy of patients' records and did not administer a formal battery of tests for the above functions in the majority of our stroke patients. Further research is required to replicate and extend these findings. The sensitivity of any screening test for auditory processing deficits will need validation in randomised clinical trials in a larger scale.

Future studies should combine administration of a questionnaire in addition to psychoacoustic tests that are more specific to the patient-reported difficulties and comparison of questionnaire results (ideally on a question-by-question basis) to imaging data, neurocognitive function, and psychoacoustic results.

Some individuals with hearing impairment complain of fatigue associated with exhaustive levels of concentration or effort required to understand speech in everyday listening situations, and may experience chronic feelings of tiredness and stress (Hetu et al., 1988). The 'white paper' of the British Society of Audiology special interest group for cognition in hearing highlights 'the critical assumptions made by researchers using self-report, behavioural, and physiological techniques to measure listening effort and listening related fatigue' (McGarrigle et al., 2014). Post-stroke fatigue (PSF) is a common yet debilitating symptom for the majority of post-stroke patients (Kuppuswamy et al., 2015; Maaijwee et al., 2015; Mead et al., 2015; Nadarajah et al., 2015). PSF has an adverse effect on the patient's quality of life, recovery, and mortality (Maaijwee et al., 2015). Its impact on physical function and independence requires further investigation. Although the aetiology of PSF in stroke patients is not well known, validated self-reported questionnaires should be used in this population for the development of better management strategies. Thus future studies should combine the administration of self-reported listening efforts and related fatigue questionnaires in the screening process, as therapy sessions such as hearing therapy may help them reduce stress or avoid situations that are fatiguing.

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The findings of study 2 are preliminary and will require corroboration and development in future studies. Although the two validated questionnaires with the handheld audiometer used in study 2 hold promise as robust screening tools for detecting hearing impairments in the stroke population, results derived from our stroke patients require validation in studies involving larger cohorts, and possibly including those with severe aphasia and/or cognitive impairments. Further, such studies would also provide the opportunity to develop standardised hearing screening measures in stroke units. In turn, the availability of such measures in the future would increase the quantity and comparability of large and small studies alike.

For patients who are very unwell or who have significant language and/or cognitive impairments that prevent screening for hearing impairment in any other way, asking the patient's next of kin about the patient's hearing prior to the stroke and the patient's work history may provide staff with some indication of the patient's hearing.



5 Chapter 5: Study 3, Phase I: Rehabilitation of Central Auditory Processing Disorders in Stroke Patients with Personal Frequency-Modulated Systems

5.1 Introduction

The majority of stroke survivors suffer from some type of hearing or auditory processing (AP) impairment (Formby et al., 1987; O'Halloran et al., 2009; Bamiou et al., 2012). Hearing impairment may be pre-existent in the stroke population because age related degeneration of the hearing end organ and nerve is very common with advancing age (Davis, 1991; Arlinger, 2003) and 3/4 of stroke sufferers are >60 years old (Yamasoba et al., 2013). However, stroke may affect all levels of the auditory pathway and lead to hearing reception and/or perception deficits that may manifest as a variety of symptoms and with clinical presentations that start acutely before, during, or shortly after stroke (MacDonald et al., 2000). Hearing and related communication disability is not limited to those with abnormal hearing thresholds. Aphasia after stroke has been studied extensively, and there is evidence for management strategies for these patients (Allen et al., 2012; Bamiou, 2015). However, there are few empirical studies of AP in non-aphasic stroke survivors (Musiek et al., 1990; Musiek et al., 2005; Bamiou et al., 2012). In addition, approximately one in five stroke survivors report severe difficulties when listening to speech-in-noise despite normal pure-tone thresholds that is attributed to abnormal processing of sounds within the brain (Bamiou et al., 2012). These individuals are more likely to experience communication difficulties in poor acoustic environments, such as in noisy hospital settings (O'Halloran et al., 2012). Uncorrected hearing impairment leads to isolation, reduced quality of life (Arlinger, 2003), and increased odds (1.83) of poorer physical recovery after stroke (Landi et al., 2006).

The patient with significant auditory deficits and functional limitations may require a range of rehabilitation and remediation approaches. Nonetheless, the use of conventional hearing aids by a stroke patient who has AP will not improve the AP deficit, since manipulation of the sound volume does not necessarily alleviate the signal-to-noise ratio (SNR). Despite indications that AP deficits are common after

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stroke (Rey et al., 2007; Bamiou et al., 2012), there is a lack of evidence-based treatment for such impairments.

Several studies have conclusively demonstrated substantial improvements in speech recognition in noise when using personal frequency-modulated (FM) systems (Schafer & Thibodeau, 2004; Wolfe & Schafer, 2008). In recent years, personal FM systems have become available for audiometrically normal patients with AP deficits (Lewis et al., 2006; Kuk et al., 2008; Johnston et al., 2009; Hanschmann et al., 2010). In FM systems, a microphone worn by or placed near the speaker's mouth picks up the speech signal. The FM transmitter then converts the speech signal to an electronic waveform and transmits it using FM radio waves to a receiver worn by the listener. The receiver converts the waveform back into acoustic energy and delivers it directly to the listener's ears. These systems help to address the acoustic problem of distance, background noise, and reverberation (Lemos et al., 2009). Moreover, FM systems enhance the signal-to-noise ratio (SNR) and overall speech signal audibility.

Studies of children (Kuk et al., 2008; Johnston et al., 2009; Hanschmann et al., 2010) with disordered AP and adults with auditory neuropathy (Rance et al., 2010) have demonstrated that the use of the FM systems significantly improve speech perception in noise. No studies to date have assessed the efficacy of personal FM systems for stroke patients with disordered AP. Furthermore, strategies for remediating auditory processing dysfunction after stroke receive significantly less attention, with auditory rehabilitation post-stroke arguably the 'lost dimension' of stroke rehabilitation.

5.2 Purpose

We conducted a feasibility study in order to investigate whether stroke survivors with normal pure-tone thresholds but with difficulties hearing speech-in-noise due to disordered AP would benefit from the use of binaural FM systems.

5.3 Methods

5.3.1 Overview of the Test Battery

5.3.1.1 Identification of Participants

All the research participants (Study 3, Phase I) underwent the following battery of tests that have been described thoroughly in Chapters 2 and 3 of the research thesis.

Baseline Audiological Assessment

- Pure-tone Audiometry (250–8000 Hz)
- Tympanometry
- [Stapedial] Acoustic Reflex Threshold
- Transient Evoked Otoacoustic Emissions (TEOAEs)
- Auditory-evoked Brainstem Responses (ABR)

Central Auditory Tests

- Gaps-in-noise (GIN) test
- Perceptual Property Processing (PP)
- Apperceptive Processing (AP)
- Semantic Processing (SP)
- Speech in Babble (SiB)

Questionnaires

- Amsterdam Inventory for Auditory Disability (AIAD)
- Hearing Handicap Inventory for Elderly (HHIE)
- Western Aphasia Battery (WAB)
- Montreal Cognitive Assessment (MoCA)

5.3.1.2 FM Feasibility Study

All nine stroke patients were fitted with personal FM systems binaurally and were tested with and without the FM systems on a speech (sentence) perception test in the ‘crescent of sound’.

5.3.2 Participants

We identified nine out of 42 (21%) stroke patients who would be eligible for this intervention under stringent selection criteria. All nine participants were diagnosed with CAPD according to the CAPD diagnosis criteria described in Chapter 2. These patients attended the clinic on a second occasion to complete the feasibility study test protocol. The mean age for the participants in the rehabilitation phase I stage (age range: 24-78 years old) was 49.2 years (SD=17.08). Demographic data, disease duration, and description of stroke lesion of the nine study participants are shown in Table 5-1 (p. 141).

5.4 Statistical Analysis

A Mann-Whitney test was performed to assess for potential differences between the groups (differences in AIAD and HHIE questionnaire scores in patients compared to normative data; differences in signal-to-noise ratio benefit in stroke patients with right- and left-sided lesions). A repeated ANOVA measures was conducted to determine whether there was a statistically significant difference in spatial speech reception with FM use with the noise coming from different angles.

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Table 5-1: Lesion description in the nine recruited stroke patients.

Participant #	Age (Y)	Sex	Lesion	Disease Duration (Days)
1	64	Male	Paramedial right thalamus and left cerebellar hemisphere infarct	100
2	24	Male	Left frontal, temporal lobes and insula infarct	169
3	44	Male	Right putamen / corona radiata infarct	96
4	52	Male	Left medulla oblongata, right cerebellum, left occipital lobe and hippocampal tail infarct	207
5	53	Female	Right superior parietal lobule infarct	125
6	32	Male	Right temporal lobe infarct	110
7	78	Male	Left Occipito-temporal infarct	265
8	64	Male	Right temporal lobe infarct	179
9	32	Male	Right insula infarct	301

5.5 Results

5.5.1 Auditory Processing Tests and Questionnaires

Auditory processing test performance is summarised in Table 5-2 (p. 143). A cross signifies the presence of a deficit. No participant had a semantic type deficit. Of nine stroke patients in our study, six had bilateral and three had unilateral abnormalities in the GIN. Patient numbers 5, 6, and 9 had infarction in the right superior parietal lobule, right temporal lobe, and right insula respectively, and all had GIN abnormalities in the left ear. SiB were abnormal bilaterally in all patients except for patient number 5, who only had an abnormality in the left ear.

The Mann-Whitney U test was used to assess differences in AIAD and HHIE questionnaire scores in patients compared to normative data and to calculate p values. Patients had significantly worse AIAD questionnaire scores ($p < 0.05$) in the speech in noise and sound localization sub-scores than normal. The results of emotional, situational and total HHIE scores were also significantly worse in the stroke patients ($p < 0.05$) than in normals.

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Table 5-2: Summary of AP Assessment. Cross (+) signifies the presence of a deficit. GIN= Gaps in Noise, SiB= Speech in Babble, Rt= Right, Lt= Left

Participant #	GIN		Perceptual Property	Apperceptive	Semantic	SiB	
	Rt	Lt				Rt	Lt
1	+	+	–	–	–	+	+
2	+	+	+	+	–	+	+
3	+	+	–	+	–	+	+
4	+	+	–	–	–	+	+
5	–	+	+	–	–	–	+
6	–	+	+	–	–	+	+
7	+	+	–	+	–	+	+
8	+	+	+	+	–	+	+
9	–	+	+	–	–	+	+

5.5.2 Sentences in Noise with and without Personal FM Systems

A repeated measures ANOVA was conducted to determine whether there was a statistically significant difference in spatial speech reception with FM use with the noise coming from different angles.

The FM system use x angle of noise interaction was significant, $F(2,8) = 15.765$, $p = 0.002$, indicating that the SNR scores, when the noise came from the different angles, differed when the patients wore the FM systems compared to when they completed the test without the FM systems. When the noise was coming from the right or left loud speakers, the improvement in the SNR scores was significantly more pronounced when the patients used the FM systems by an average of 9.2 SD, 3.4 dB SPL.

The signal-to-noise ratio benefit (SNR benefit) was defined as the difference between SNRs measured with co-located speech and babble ($S0^\circ N0^\circ$) and SNRs measured with spatially separated speech and babble ($S0^\circ +N90^\circ$ or $S0^\circ -N90^\circ$). The SNR benefit was calculated by subtracting the SNR in the $90^\circ+$ or $90^\circ-$ conditions from that in the 0° condition. Table 5-3 shows the mean SNRs for speech recognition in three noise conditions, $S0^\circ N0^\circ$, $S0^\circ N90^\circ+$, and $S0^\circ N90^\circ-$.

The participants completed two runs of the aided condition and two runs of the unaided. There was not a statistically significant interaction between the use of FM systems and the sequence of testing on SNR benefit scores, $F(1,4) = 1.45$, $p < 0.3$, indicating that the changes in the SNR benefit between the first and second sequences were similar in both conditions, that is, with and without FM. Therefore, the two runs were averaged.

A repeated-measures analysis of variance was performed to compare the SNR benefit changes with and without the FM system. The results revealed that there was a significant effect for FM use, indicating that the SNR benefit scores differed in the two different conditions (with vs. without FM). The interaction graph revealed that the FM systems produced a significant increase in SNR benefit when noise was spatially separated from the speech signal by 90° , ($F[1,8] = 117.64$ $p < 0.0000$). There was no significant main effect for right or left SNR benefit without the FM condition ($F[1,8] = 0.56$, $p > 0.05$), and with the FM condition ($F[1,8] = 2.52$,

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$p=0.15$). There was a large effect size, with Cohen’s effect size value of $d = 0.93$. Figure 5-1 shows the mean $90^{\circ+}$ and $90^{\circ-}$ SNR benefit for both the ‘with FM’ and ‘without FM’ conditions.

On average, patients gained 10 dB in SNR benefit when they used the FM system compared to without using the FM system (see Table 5-3).

Table 5-3: Mean, standard deviation and range of SNR (dB) measured in the $S0^{\circ}N0^{\circ}$, $S0^{\circ}N90^{\circ+}$, and $S0^{\circ}N90^{\circ-}$ location, and the calculated SNR benefit for with and without FM conditions.

	$S0^{\circ}N0^{\circ}$	$S0^{\circ}N90^{\circ+}$	$S0^{\circ}N90^{\circ-}$	$SNR90^{\circ+}$	$SNR90^{\circ-}$	$SNR90^{\circ\pm}$
Without FM (dB)						
Mean	1.39	-0.1	-0.77	-1.07	-0.62	-1.06
SD	1.44	2.02	2.84	1.89	3.11	1.73
Range	-1.69 – 3.66	-3.63 – 3.43	-2.35 – 0.91	-3.16 – 2.55	-4.41 – 3.84	-3.11 – 1.65
With FM (dB)						
Mean	0.97	-9.28	-11.04	-10.25	-12	-11.13
SD	0.94	3.02	2.83	3.4	2.86	2.76
Range	-0.44 – 2.69	-5.37 – -14.60	-15.67 – -6.63	-16.29 – -6.46	-16.55 – -7.27	-15.58 – -7.09

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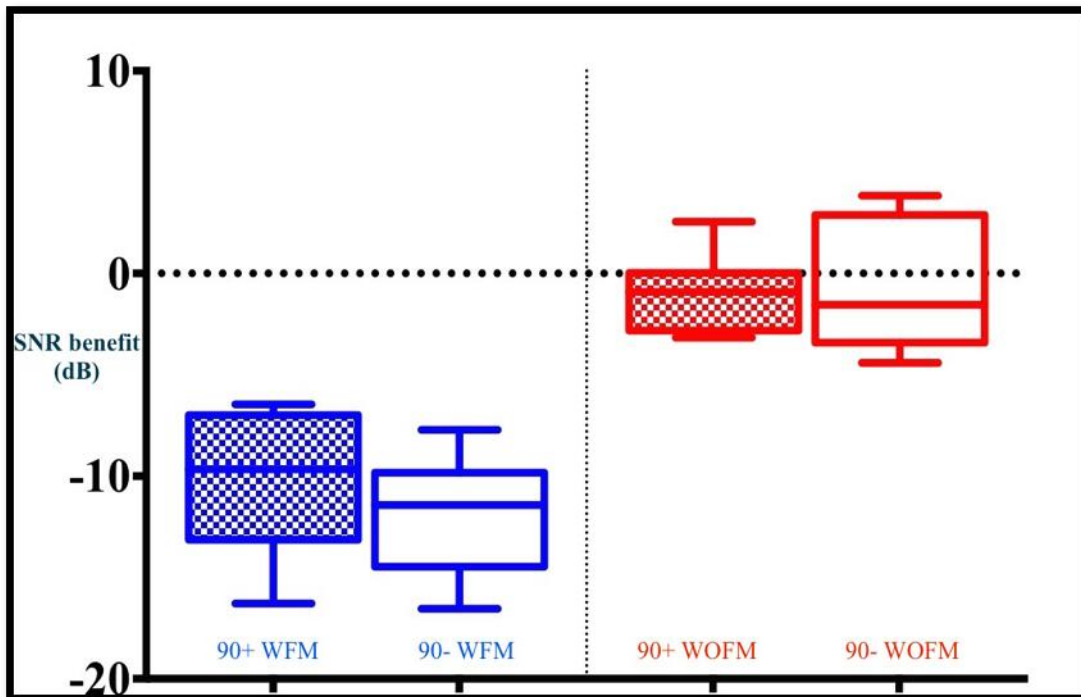


Figure 5-1: Boxplot of the mean $90^\circ \pm$ SNR benefit of patients with and without the FM system conditions. SNR benefit, signal to noise ratio benefit; WF, with FM; WOF, without FM; $+90^\circ$, multi-talker babble from the right loud speaker; -90° , multi-talker babble from the left loud speaker.

A Mann-Whitney U test was conducted to determine whether there was a difference in the SNR benefit scores between the stroke patients with right- and left-sided lesion. Results of that analysis indicated that there was not a significant difference in the right SNR benefit between stroke patients with right and left sided lesion, $z = -.73$, $p < .05$, nor in the left SNR benefit, $z = -1.49$, $p < .05$.

5.6 Discussion

Both ischaemic and haemorrhagic strokes may disturb all levels of the auditory pathway and lead to peripheral and central hearing deficits, which can be identified by baseline audiological assessments, or to AP deficits, which can be identified by complex tests of AP. However, AP deficits after stroke have not been as extensively investigated as other cortical/subcortical deficits, possibly due to the potentially ‘invisible’ nature of this impairment compared to more obvious symptoms (e.g. dysphasia or motor loss). AP deficits attributable to stroke pathology within auditory

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pathways are largely neglected by neurologists, and there is a lack of evidence-based treatment for such deficits for stroke patients with normal hearing thresholds but disordered AP. Our study is novel because it is the first experimental study evaluating the efficacy of FM systems, assessed by speech-in-noise tests in the laboratory, in stroke patients who have difficulty understanding speech in noisy environments due to abnormal auditory processing.

We identified nine out of 42 (21%) stroke patients who would be eligible for this intervention under stringent selection criteria. All of these patients had normal pure-tone thresholds but had deficits in temporal resolution, perceptual and/or appereceptive spectral processing, and in speech-in-noise test performance. Interestingly, our subjects did not have clinically obvious semantic deficits or aphasia. They all reported high levels of auditory disability and auditory-related social and emotional handicap in their everyday lives on questionnaires, but were not eligible for conventional hearing aids or for aphasia-targeted treatment. Their presentations were consistent with auditory processing disorder, in which their listening difficulties are attributed to impaired processing of the sounds at a pre-semantic level (BSA, 2011). At present, there is no proven intervention for this population.

All cases significantly improved speech perception in noise with the FM systems when noise was spatially separated from the speech signal by 10 dB SPL on average, compared to unaided listening. The magnitude of the benefit is considerable, as one dB improvement equals approximately a 10% improvement in speech recognition scores at barely audible (threshold) speech levels (Vorlander, 2011). Our laboratory findings may thus indicate potentially substantial benefits of FM use after stroke for about 21% of this population.

The observed improvement was more marked for the stroke patients in our study as compared to reports assessing the benefit of FM systems in other neurological populations with auditory processing deficits. Only eight out of ten patients with multiple sclerosis (MS) (Lewis et al., 2006) and four out of six adults with an auditory neuropathy due to Friedreich's ataxia (Rance et al., 2010) improved. The common denominator among these three different clinical populations is the presence of impaired temporal processing due to the three different types of neural

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pathology. Friedreich's ataxia is a progressive peripheral de-afferentation type lesion, while MS involves often progressive, widely distributed demyelination in the brain, and it may be that the nature of pathology affects FM outcome. Alternatively, use of more stringent patient selection criteria in our study in terms of severely impaired speech-in-noise test performance, self-reported speech-in-noise difficulties, and non-speech AP deficits may explain why all our patients showed FM-related benefit compared with only 70-80% of patients in the aforementioned studies. Our results need to be replicated in a larger study, preferably a randomised control trial, with longer follow-up that represents real life use of FM devices in these populations in order to more accurately inform clinicians regarding the most appropriate indications for use of these devices.

The observed speech performance improvement in stroke patients may arise from enhanced attention to the speech signal or enhanced neural synchrony and representation of the speech signal in the central auditory nervous system (Song et al., 2008). These influences could be collectively attributed to the improved SNR. Regardless of whether the FM technology assists top-down (cognitively driven) or bottom-up (sensory driven) auditory processing, our study indicates that the benefits gained from the personal FM systems may be a promising intervention to address hearing needs in stroke patients in whom the auditory brain is affected but peripheral hearing is preserved. Furthermore, long-term FM system use is reported to reduce anxiety levels in neurologically normal patients with disordered auditory processing (Johnston et al., 2009). It is noteworthy that our sample consists of adults in the employment-age range. Monzani et al. (2008) conducted a study to investigate the psychological profile and social behaviour of working adults with mild hearing loss. They reported that this group of patients experience more negative emotional reactions and socio-situational limitations than subjects with no hearing problems. Therefore, in view of the high HHIE emotional scores in our patients, the effects of FM systems on the emotional wellbeing and quality of life of stroke patients should be investigated.

There is a strong interaction between hearing and cognition during speech processing in challenging conditions, and cognitive factors such as memory and attentional selection of information play a role in comprehension (Pichora-Fuller, 2003).

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Cognitive impairment is common three months after stroke. It is associated with poor long-term outcomes, including survival and disability, up to four years after stroke (Patel et al., 2002). At the cognitive level, declines in speed of processing, working memory capacity, and the ability to suppress irrelevant information might make it more difficult for the listener to handle multiple streams of information, rapidly switch attention from one talker to another, and comprehend and store information extracted from speech for later recall (Schneider, 2011). Stroke patients with cognitive difficulties may have problems comprehending spoken language, and the cognitive slowing may reduce the ability of stroke patients to manipulate and integrate the on-going flow of information that is received with high-speed rates in challenging noisy listening conditions. One approach to the increase in processing demands is to improve the SNR. On this basis, one would therefore predict that an FM system may even help those with no AP deficits, as it could reduce cognitive load and improve perception. Further research would be useful for exploring the use of FM systems in such patients.

FM systems hold promise for the auditory rehabilitation of stroke patients. Prospective studies should evaluate whether the improvement translates into improved quality of life, while other factors, such as how the system interacts with patient communication demands and auditory lifestyle, should also be considered.

In conclusion, personal FM systems are feasible in stroke patients and may be of benefit for approximately 21% of this population who are not eligible for conventional hearing aids. A clinically significant improvement of more than 10 dB in SNR benefit in laboratory tests and a large effect size ($d=0.93$) indicate that FM systems show promise for the remediation of auditory deficits in a significant proportion of the stroke population.



6 Chapter 6: Study 3, Phase II. Long-term use Benefits of Personal Frequency-Modulated Systems for Speech in Noise Perception in Stroke Patients with Central Auditory Processing Deficits – ‘A Non-Randomised Controlled Trial Study’

6.1 Introduction

Stroke can affect all levels of the auditory pathway (Hausler and Levine, 2000). It can be manifested as pure tone detection deficits on audiometry (Formby et al., 1987; O’Halloran et al., 2009), auditory processing deficits (Rey et al., 2007; Bamiou et al., 2006), and perceptual difficulties in the domains of speech, sound recognition, and localisation (Bamiou et al., 2012). Approximately one in five stroke survivors report severe difficulties with speech recognition in the presence of background noise despite the presence of normal audiometry (Koochi et al., 2016). These deficits are treatable with personal FM (Frequency Modulated) systems, with a robust immediate improvement of 9 decibels (dB) in signal to noise ratio when using the FM systems (Koochi et al., 2016). This is a clinically significant improvement, as 6 dB is the cut-off value for a patient to seek clinical intervention (McShefferty et al., 2016).

Personal FM systems are wireless listening devices that pick up the speaker’s voice and transmit it to a receiver in the listener’s ear, thus reducing the negative effects of noise, distance and reverberation. FM systems are used to improve speech in noise perception in patients with listening difficulties due to disordered auditory processing, such as children with developmental disorders (Johnston et al., 2009; Hornickel et al., 2012) and adults with neurological disorders (Lewis et al., 2006; Rance et al., 2010), including stroke (Koochi et al., 2016) with good immediate benefits. Long-term benefits of FM systems have predominantly been investigated on paediatric populations. Children with disordered auditory processing who used FM systems five months in classrooms showed an improved unaided (i.e. with no FM device) speech in quiet performance by 3.8 dB, suggesting the possibility of bottom up driven auditory neuroplasticity (Johnston et al., 2009). However, due to the lack of controls, maturation effects could not be entirely excluded. Dyslexic children who used FM systems over one year similarly showed improved phonological awareness

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and reduced variability in their subcortical responses to sound (Hornickel et al., 2012).

The potential neuroplastic benefits of prolonged FM system use are of particular interest for stroke survivors with acquired auditory processing deficits. The central auditory nervous system maintains the capacity to be altered in response to auditory stimulation, or in response to deprivation, throughout life (Musiek et al., 2002). Language-based rehabilitation leads to plasticity-type benefits for aphasic stroke subjects (Mattioli et al., 2014), and it would be reasonable to expect similar benefits in less impaired (i.e. non-aphasic) stroke patients with speech reception impairments who receive intervention that promotes better access to speech.

6.2 Purpose

The present study thus aimed to evaluate the potential benefits in speech-perception of personal FM systems when used daily over ten weeks by nonaphasic stroke patients with auditory processing deficits in order to investigate whether plasticity occurs after prolonged use of FM systems.

We hypothesised that improvement in unaided speech in background noise performance, shown in a behavioural task, would occur in stroke patients who used the FM systems for a period of time, but not in a control group of stroke patients who did not use these systems and received standard care.

6.3 Methods

This study was conducted prospectively with a non-randomised case control design. Participants of study 3 - phase I were asked whether they would be willing to use the FM systems at home for ten weeks. Four out of nine (44%) agreed to use the FM (subjects 1, 4, 6, 9; Table 6-1, below). They formed the intervention subjects group, while five out of nine (56%) who did not wish to use the FM but were willing to come back for a re-assessment ten weeks later formed the standard care group (subjects 2, 3, 5, 7, 8; Table 6-1).

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Table 6-1: Lesion description, age, sex, PTA (average in dB HL at 500, 1000, 2000, 4000 Hz) KEY: I = intervention; SC= standard care; M, male; F, female; PTA, pure-tone average; dB, decibel; HL, hearing level)

Participant	Age	Sex	PTA	Lesion
I (1)	64	M	22.5	Paramedial right thalamus
I (9)	32	M	15	Right insula infarct
I (4)	52	M	25	Left medulla oblongata, occipital lobe, hippocampus & right cerebellum infarct
I (6)	32	M	5.5	Right temporal lobe infarct
SC (3)	44	M	8.3	Right putamen / corona radiata infarct
SC (5)	53	F	25	Right superior parietal lobule infarct
SC (2)	24	M	18.3	Left frontotemporal and insula infarct
SC (7)	78	M	25	Left Occipito-temporal infarct
SC (8)	64	M	22.5	Right temporal infarct

6.4 Statistical Analysis

Results were analysed with the statistical package of social sciences (SPSS) version 22 (IBM). Bootstrapping procedures, which facilitate parametric statistical analyses on non-normally distributed datasets, were used to address the limitation of the small sample size. Such procedures estimate statistical parameters based on a large number of random samples (with replacement) from an original dataset. Bootstrapped one-way analysis of covariance (ANCOVA) was conducted to determine a statistically significant difference between the intervention and standard care groups on the speech reception thresholds in noise, at the start of the ten-week intervention while controlling for age and side of lesions, and to examine the differences between the intervention and standard care groups on post-intervention scores while controlling for baseline scores of the same measure.

6.5 Results

The study had no drop outs, and all recruited subjects returned for retesting ten weeks later. All four intervention subjects complied with the daily use of the FMs. According to their own reports, the FM systems were used a minimum of four hours every day.

A bootstrapped one-way analysis of covariance (ANCOVA) was conducted to determine a statistically significant difference between the intervention and standard care groups on the speech reception thresholds in noise at the visit-1-time-point while controlling for age and side of lesions. After assessing for these confounders, there was no difference between groups with regards to the speech reception thresholds in noise when the babble (noise) was presented from either the left or the right, in the aided and unaided conditions (Table 6-2, p. 154). A series of bootstrapped ANCOVAs were calculated to examine the differences between the intervention and comparison groups on visit 2 (post intervention) scores while controlling for the visit 1 (baseline) scores of the same measures. The covariate adjusted analysis, controlled for baseline outcomes, age and side of lesions, showed a statistically significant improvement in SRT in noise when the noise was coming from the left for both the aided and unaided conditions at the visit-2-time-point in the intervention group compared to those who received standard care.

Figure 6-1 (p. 155) shows the SRT individual scores for the intervention and standard care subjects at visit 1 and visit 2 in the aided and unaided conditions.

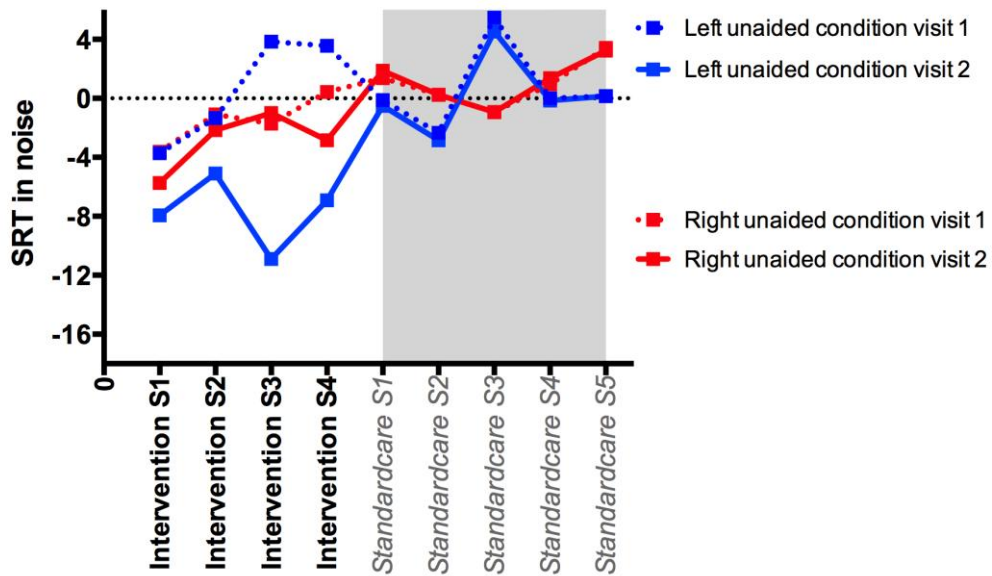
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Table 6-2: Bootstrapped analyses of covariance results for Speech Reception Threshold (in decibel) measured in the S0°N+90°, and S0°N-90° location for aided (with FM) and unaided (without FM) conditions for intervention and standard care subjects at visit 1 (baseline) and visit 2 (post-intervention). KEY: S, speech; N, noise; SD, standard deviation; FM, frequency-modulated.

		Group		p-value
		Intervention	Standard care	
S0N-90 unaided				
	Visit 1, mean (SD)	0.58 (3.7)	0.63(2.9)	0.1
	Visit 2, mean (SD)	-7.7(2.7)	0.23(2.7)	0.04*
	Change from visit 1 to 2	-8.28	0.4	0.04*
S0N+90 unaided				
	Visit 1, mean (SD)	-1.5(1.7)	1.0(1.6)	0.7
	Visit 2, mean (SD)	-3.0(2.0)	1.15(1.6)	0.1
	Change from visit 1 to 2	-1.5	0.15	0.1
S0N-90 aided				
	Visit 1, mean (SD)	-11.0(1.7)	-11.0(3.7)	0.8
	Visit 2, mean (SD)	-19.6(2.8)	-11.4(3.5)	0.04*
	Change from visit 1 to 2	-8.6	-0.4	0.04*
S0N+90 aided				
	Visit 1, mean (SD)	-10.4(3.5)	-8.4(2.7)	0.4
	Visit 2, mean (SD)	-16.1(5.4)	-8.7(2.6)	0.06
	Change from visit 1 to 2	-5.7	-0.3	0.06

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Individual SRT in noise scores [unaided condition]



Individual SRT in noise scores [aided condition]

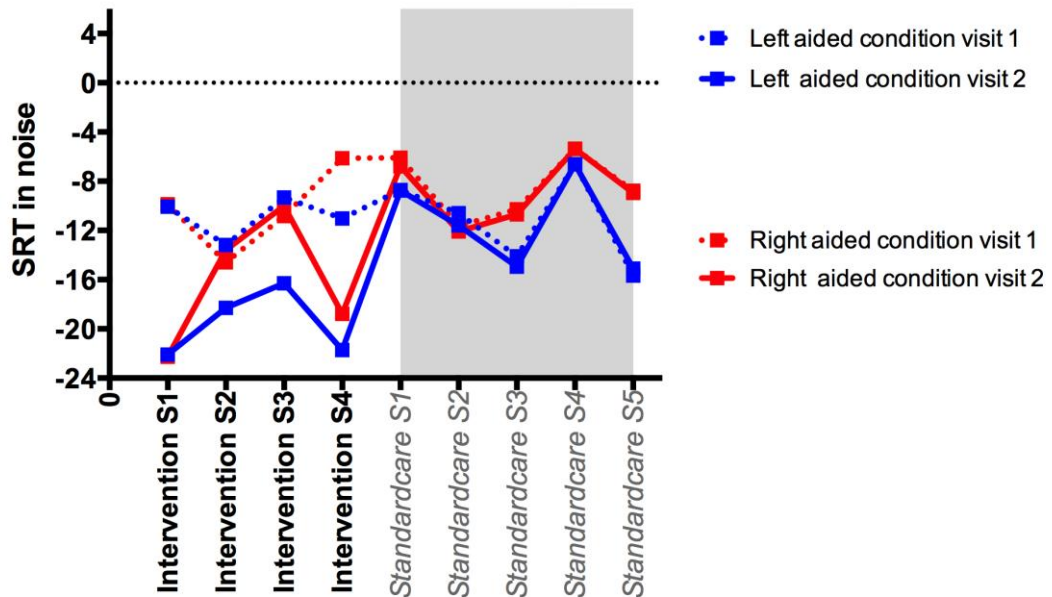


Figure 6-1: the SRT individual scores for intervention and standard care subjects. The standard care subjects are shown in the shaded area. KEY: SRT, speech reception threshold, S, subject

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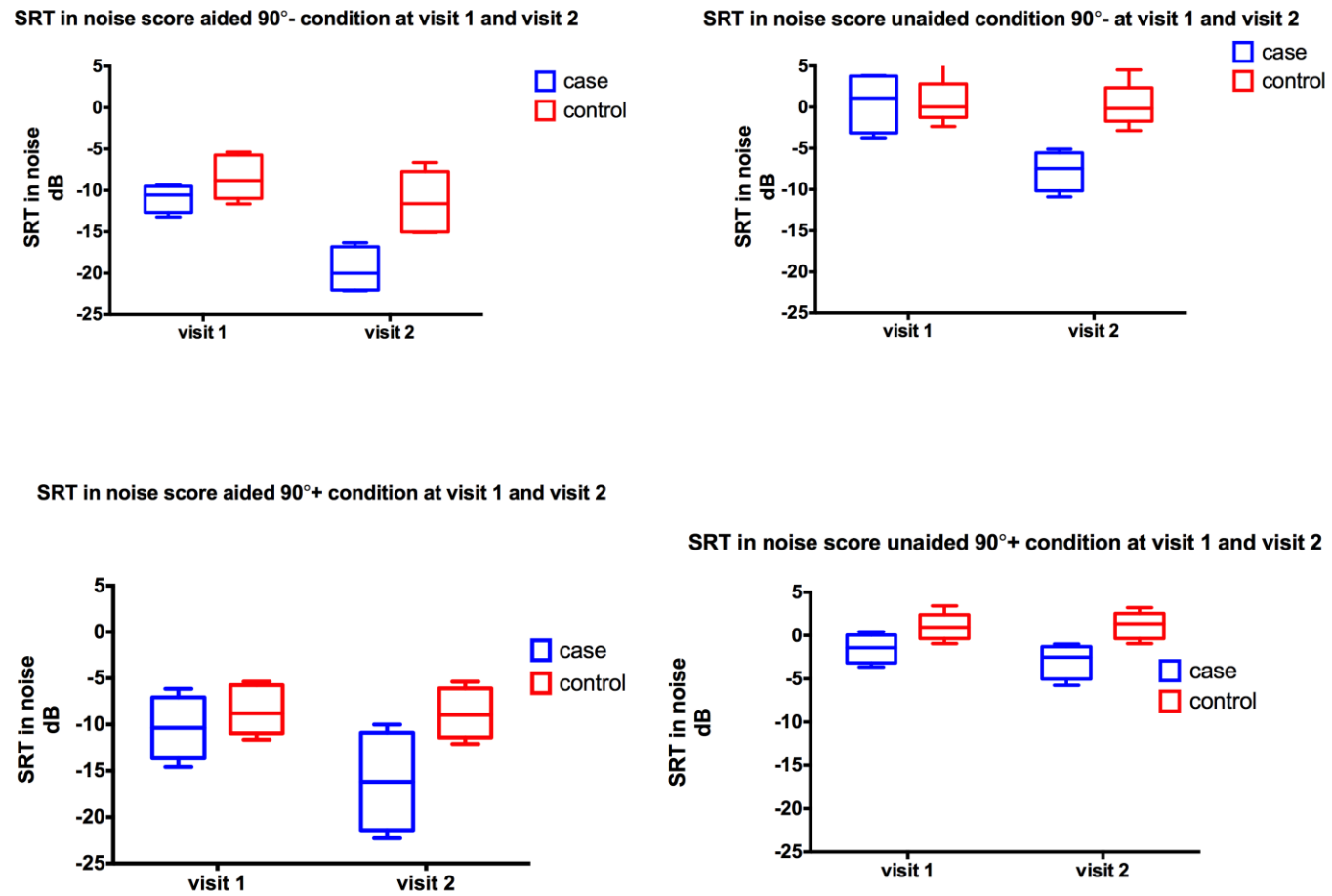


Figure 6-2: the SRT in noise scores for intervention and standard care subjects at visit 1 and visit 2 time point (aided and unaided conditions)

6.6 Discussion

In addition to the immediate benefit in terms of improved speech in noise reception threshold in the aided condition (with the FM system), after a period of ten weeks daily FM use, we found a further substantial benefit for speech in noise test performance even in the unaided condition in the intervention subjects group vs. no benefit in the standard care group. The benefit exceeded 6 dB, which is the cut-off value for patients to clinically seek such intervention when the noise was on their left side, with an effect size exceeding 2.5. Our study's findings have important clinical and other implications. Improved SRTs when using the FM system after prolonged daily FM use could be attributed to acclimatisation effects (i.e. getting used to the device effects), such as improved perception of high frequency phonemes over time (Ellis et al., 2015). However, such benefits – if any – tend to be small (Dawes et al., 2014). The findings of a robust improvement in speech reception thresholds in the unaided condition in the FM system intervention group may thus indicate that a brain plasticity mechanism is involved.

In the presence of normal pure-tone audiometric thresholds and in the absence of aphasia, our stroke subjects had degraded speech encoding, as indicated by their abnormal speech in babble test results, and self-reported difficulties with speech in noise due to their stroke-related auditory processing deficits as evidenced by their abnormal results in other non-speech auditory processing tests. This resulted in impaired identification of lexical items in stored knowledge. Additionally, the increased effort required for speech discrimination because of background noise would be expected to reduce their information processing capacity and thus the short term memory required for speech recall and understanding (Rabbitt, 1991). It has been proposed (Kumar et al., 2011) that each level of the auditory cortical hierarchy attempts to predict the sensory representation of the speech signal of interest at the level below by transmitting a top-down prediction, with prediction error information (i.e. the incoming signal differing from the prediction) transmitted back to the higher level, leading to a recalibration of the higher level representations. This updating of predictions at higher levels is heavily dependent on attention mechanisms that are influenced by the degree of salience of the stimulus and the listening context

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(Feldman and Friston, 2010). It is thus postulated that in our stroke patients, their auditory processing deficits reduced the clarity of incoming speech, and the brain (attention) responded by decreasing the sensory precision or post-synaptic gain. This was to some extent redressed when stroke subjects used the FM system within the crescent of sound, as demonstrated by the immediate improvement in SRTs in the aided vs. the unaided condition in visit 1. It may further be postulated that prolonged use of the FMs over ten weeks, with active listening to salient speech (assuming that cases used the FM system to listen to speech of interest to them) potentially led to attention optimizing the synaptic gain that represents the precision of the bottom up sensory information (prediction error) during the hierarchical inference process within the auditory brain. Candidate brain regions where this effect could take place include the levels of the primary auditory cortex area, or Broca's and inferior frontal gyrus, i.e. the areas showing a relative specialization for phonological encoding (Papoutsis et al., 2009) or subcortical areas, in accordance with the results of Hornickel et al. (2012).

The lower (better) SNR yielded in visit 2, when the noise was coming from the left loudspeaker (as compared to the right) without the FM systems could be explained by the presence of a right ear advantage for linguistic stimuli. The right ear advantage is often explained by the auditory sensory projections being stronger to the contralateral (left) hemisphere, as the ipsilateral pathway are of less consequence at the auditory cortex level, while language perception is lateralised to the left hemisphere (Kimura, 1967). Attention further modulates the right ear advantage (Hugdahl et al., 2000). It should be noted that our patients predominantly had right cortex/subcortex lesions, and would thus be expected to have a stronger right (than left) ear advantage in the ear contralateral to the stroke, demonstrating a deficit in dichotic listening (Bamiou et al., 2006).

Our findings are novel, since this is the first study to investigate auditory plasticity following prolonged use of FM systems in adult patients with acquired stroke brain lesions. Despite robust findings, this study has small case numbers, and its findings ought to be interpreted with caution. Low study numbers affect precision of measurements, and even a nominally statistically significant finding may not reflect a true effect. Furthermore, the study lacked randomization, thus being prone to

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selection bias, while the factors influencing patient preference and thus group allocation were not determined. Taking these caveats into account, the evidence presented here should motivate further work with a larger randomised clinical trial to investigate the mechanism for the observed plasticity.

In conclusion, we found clinically significant improvements in speech in noise perception even when not using the FM system after prolonged use of binaural FM devices by stroke patients with speech in noise deficits due to disordered auditory processing. This improvement may well be due to auditory-driven brain plasticity. Around 21% of the stroke population (Koochi et al., 2016) might benefit by this intervention. Further research is, however, required to replicate the study's results, since this study was small and lacked randomisation. In addition, since the recruited patients had predominantly right hemisphere ischemic stroke with different brain areas affected, the effect of type and extent of brain lesion (left vs right, cortical vs subcortical, auditory vs non auditory, etc.) on the degree of benefit needs to be examined. It is not known to what extent cognitive or linguistic factors, daily use of FM, etc., influenced outcome, what the neural correlates of the observed improved speech in noise perception are, or how this translates into real life benefit. Further research should investigate the degree and mechanisms of this benefit.



7 Chapter 7: Summary and General Discussion

7.1 General Aims, Revisited

The main foci of this thesis were to advance the understanding of different types of hearing impairment in stroke patients in the post-stroke subacute stage to enable recommendations for the development of appropriate guidelines for the assessment and management of hearing impairment and for making recommendations for future research in this field. The primary aims of this thesis were twofold. The first aim was to evaluate hearing function in a population of adults with stroke in two main areas: **a.** to observe the prevalence and determine the type of hearing impairment in stroke patients, and **b.** to evaluate the sensitivity and specificity of a hearing screening protocol. The second aim was to investigate the possibility of auditory rehabilitation in stroke patients with auditory processing disorders within two main areas: **a.** to investigate the immediate benefits of personal frequency-modulated (FM) systems in stroke patients with auditory processing disorders, and **b.** to investigate the long-term effect of FM systems after prolonged use in stroke patients with CAPD.

To provide the reader a review of all the work presented in this thesis, the following sections will summarise each of the studies and discuss the main findings in this concluding chapter.

7.2 Summary and General Discussions of Study 1

Stroke survivors may suffer from a range of hearing impairments that may restrict their participation in their post-acute rehabilitation programs. Hearing impairment may have a significant impact on listening, linguistic skills, and overall communication of the affected stroke patient. However, no studies have sought to systematically characterise auditory function of stroke patients in detail in order to establish the different types of hearing impairments in this cohort of patients. Such information would be clinically useful in understanding and addressing the hearing needs of stroke survivors. Study 1 aimed to characterise and classify their hearing impairments by using a detailed audiological assessment test battery, i.e. routine audiological assessments as well a comprehensive auditory processing evaluation, in

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order to determine the level of clinical need and inform appropriate rehabilitation for this patient population. This was a case-control study incorporating forty-two stroke subjects who were discharged from a stroke unit and 40 control subjects matched for age. All subjects underwent pure-tone audiometry, immittance measurements, including acoustic reflex threshold testing, transient evoked otoacoustic emissions, auditory evoked brainstem response, and a central auditory processing assessment battery, all performed in a single session. Hearing impairments were classified as ‘peripheral’ hearing loss (cochlear and neural type), ‘central auditory processing disorder’ (‘CAPD’), and combination ‘peripheral and CAPD’ hearing loss. Overall mean hearing thresholds were not significantly different between the control and stroke groups. The most common type of hearing impairment in the stroke subjects was the combination type, ‘peripheral and CAPD’ in the 61-80-years-old subgroup (present in 55%), and auditory processing deficits in the 18-60 year olds (present in 40%). Both were both significantly higher than in controls. This was the first study to examine hearing function in detail in stroke patients. Given the importance of hearing for efficient communication, it is essential to identify hearing impairments and differentiate peripheral and central deficits in order to define an appropriate intervention plan.

Damage to the central auditory nervous system may not result in hearing deficits in some individuals, but in others they certainly can and do. When they do, it is important to determine the nature and degree of the deficit so that optimal management can be sought. Our study demonstrated that CAPD was present in just over 40% of younger stroke patients, none of whom had been previously referred for a hearing assessment. This would suggest that hearing impairment, in particular impairment of the CAPD type, remains a ‘hidden’ disability in this population that may be overlooked by neurologists and other healthcare professionals. Hearing impairment in young adults may lead to multiple negative consequences, including effects on employment, poor quality of life, and social isolation, and it interferes with so many of life’s activities. It may also prove to be a major impediment for society’s need to have people remain longer in the workforce as the proportion of ‘working age’ people in developed countries shrinks (Dillon, 2006). Early detection and management of this type of hearing impairment may help younger stroke survivors

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cope with the challenges they will face after the recovery period, as well as to participate as fully as possible in intellectual, social, and family activities.

Our results indicate that the most common type of hearing impairment in stroke patients is the combination of ‘peripheral and CAPD’ hearing impairment in the 61-80-year-old subgroup (55%). The ability to understand speech deteriorates with advancing age. Aging is accompanied by a decline in hearing sensitivity due to sensory changes in the ear. Other changes in the central auditory nervous system or general cognitive decline may also contribute to the difficulty older adults have in understanding speech in background noise. Pathological conditions such as stroke can further compromise auditory function. There are many factors that should be considered for the management of stroke patients with peripheral and central auditory dysfunction. Conventional hearing aids may be a suitable option for those with peripheral hearing loss, but it may not help individuals with additional cognitive and/or auditory processing deficits. Hearing aid technology now offers clinicians considerable flexibility in selecting processing strategies for a ‘best fit’ for older adults with various listening needs and capabilities. Counselling, directional microphone hearing aids with built-in FM (which are of particular relevance, given the results of study 3 [Chapter 5] that are discussed below), and educating patients and care-givers may be an appropriate rehabilitation plan to meet the needs of older stroke patients with a combination type of hearing impairment. A multidisciplinary team is crucial for intervention and management of stroke patients with a diagnosis of AP deficits with the incorporation of both bottom-up and top-down approaches.

Strategies to reduce background noise in acute stroke units, neuro-rehabilitation units, or follow up clinics need to be considered when thinking about hospital design and during everyday care and cleaning routines. Health care professionals need a variety of ways to identify patients who may have a hearing impairment.

In conclusion, study 1 demonstrates that hearing impairment is present in a majority of stroke patients and is often overlooked by the neurologists and other healthcare professionals. This suggests that current guidance would benefit from the addition of hearing assessment, or increasing awareness of possible hearing impairments in the stroke patients, as such impairment may affect the patients’ post-stroke physical

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outcome and may impact patient communication in everyday life in the chronic stage of stroke.

7.2.1 Limitations and Future Research

Study 1 was a cross-sectional study, so it was not possible to identify precisely the cause or causes of the hearing losses. In this study, we were only able to show that the majority of stroke patients presented with hearing impairment.

The evidence presented here should motivate future work in larger patient and control cohorts, as the differences in the hearing thresholds might have reached statistical significance with a larger sample size.

The work carried out in Study I has highlighted a few potential areas for further research. First, Study I was conducted based on the exclusion of aphasic patients, those with severe and greater hearing loss, and those aged above 80 years old. It would be interesting to examine the hearing of those with severe aphasia and or cognitive impairment. Second, the difference in the type of hearing impairment in the stroke patients appeared to be influenced by age. A further study with a larger sample size, especially focusing on the younger group, would be necessary to follow up this finding.

A very important consideration is the time when the patients are still in the acute stage of stroke. We might anticipate that the results of hearing thresholds measured early on, in the acute stage, would be more prone to confounding non-sensory factors, such as general confusion, limited attention span, etc., than would hearing thresholds from patients who are evaluated at later times, i.e. when the sensory deficit recovers or is compensated for rapidly after a cortical event. Hence we designed our study to assess the hearing in this population in the chronic stage of stroke to minimise non-sensory influences. However, it is still important that patients in the acute stroke unit with hearing impairment are identified so that stroke unit staff can support these patients to communicate optimally while they are in hospital. For example, this may involve staff employing a range of different communication strategies, fitting and adjusting patients' hearing aids, and/or providing patients with temporary assistive listening devices. Therefore, further research is also required to better understand the hearing impairment of stroke patients in the acute stroke unit so

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that stroke patients with hearing impairment can communicate with their healthcare providers in optimal ways while they are in the hospital.

Our results indicate that the most common type of hearing impairment in stroke patients was the combination type hearing impairment ('peripheral and CAPD') in the 61-80 years old subgroup, and CAPD in the 18-60-year-old group. However, further research is needed to include cognitive assessments such as memory, attention and executive function tests. The combined auditory processing and cognitive results would give further useful information about the profile of these patients and would help clinicians better understand this clinical presentation.

7.3 Summary and General Discussion of Study 2

Undetected and untreated hearing impairment may affect the delivery of medical and psychological services by interfering with the ability to obtain a valid case history by causing the health care professional to misinterpret the patient as having a cognitive disorder, by compounding medical problems such as depression, and by interfering with therapeutic interventions such as the use of prescription drugs and with diet and health treatment regimens. As shown in our study, stroke patients present a variety of auditory symptoms such as listening difficulties in noisy environments and localising sounds. This population, which could be handicapped by its hearing disability, has difficulties in various situations, and the impairment can have an adverse effect on their emotional wellbeing. Furthermore, persistent failure to understand what is being said can affect psychosocial behaviour and result in frustration and discouragement. However, offering a comprehensive audiological assessment to all stroke patients would be a costly and time-consuming process. Thus a preliminary screening test for such patients is required. We examined the accuracy of a handheld hearing screener, AIAD, and HHIE questionnaires for the diagnosis of any hearing impairment types (i.e., peripheral, central, etc.) in the stroke population, and demonstrated that although the questionnaires alone have low sensitivity, they can reliably identify stroke patients who acknowledge hearing difficulties and need further referral for diagnostic hearing assessment. In our study, the sensitivity of a handheld hearing screener was excellent (97%), as was the specificity of the AIAD and HHIE questionnaires. The low sensitivity yielded in our study may partly reflect the

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inclusion of those with mild hearing loss and/or CAPD in our cohort. However, the highest test accuracy was achieved when the results of the handheld hearing screener and of the hearing questionnaires were combined. Accordingly, as we found in our study, audiometry screening plus hearing questionnaires could be a more reasonable way to identify individuals with hearing loss compared with subjective measures alone, since some individuals could be less likely to be identified if screening relied on just self-report questionnaires. According to our study design, the protocol can be completed in 10 minutes without any discomfort to the patient. In addition, it is simple to operate, cost-effective, and acceptable to health professionals.

For patients who are very unwell or have significant language and/or cognitive impairments that prevent screening for hearing impairment in any other way, asking the patient's next of kin about the patient's hearing prior to the stroke and work history may provide staff with some indication of the patient's hearing.

The findings of study 2 are preliminary and will require corroboration and development in future studies. Results derived from our stroke patients require validation in studies involving larger cohorts, and possibly including those with severe aphasia and/or cognitive impairments. Further such studies would also provide the opportunity to develop standardised hearing screening measures in stroke units; in turn, the availability of such measures in the future would increase the quantity and comparability of large and small studies alike. Future studies should combine the administration of a questionnaire in addition to psychoacoustic tests that are more specific to the patient-reported difficulties and a comparison of questionnaire results (ideally on the basis of each question category in the questionnaire) to imaging data, neurocognitive function, and psychoacoustic results.

7.3.1 Recommendations for Hearing Screening in Stroke Units

A cost-effective auditory screening protocol may gather useful information for the rehabilitation team and may help identify those patients who have high levels of deficits and disability in order to decide on the need for additional investigation and input on a case-by-case basis. Thus, judging from our results, in Figure 7-1, below, we show a schematic representation of a hearing screening protocol for stroke patients in the sub-acute or chronic stage.

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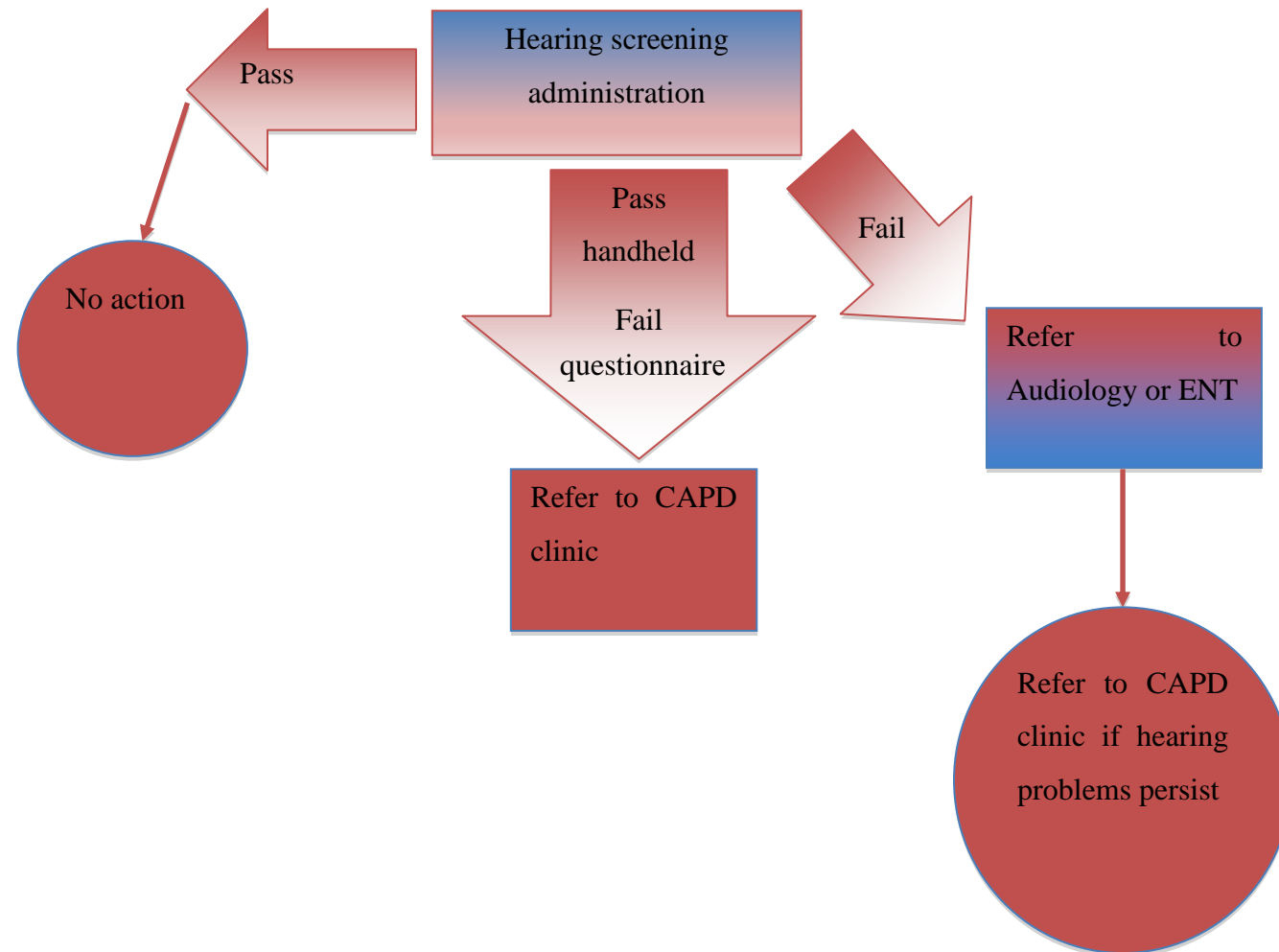


Figure 7-1: A schematic representation of a hearing screening protocol for stroke patients

7.4 Summary and General Discussion of Study 3, Phase I

Auditory disability due to impaired auditory processing (AP) despite normal pure-tone thresholds is common after stroke. It leads to isolation, reduced quality of life, and physical decline. There are currently no proven remedial interventions for AP deficits in stroke patients. This is the first study to investigate the benefits of personal frequency-modulated (FM) systems in normal-hearing stroke patients with disordered AP.

Forty-two stroke patients had baseline audiological assessments and AP tests and completed the Amsterdam Inventory for Auditory Disability and the Hearing Handicap Inventory for the Elderly questionnaires. Nine out of these forty-two patients were diagnosed with disordered AP based on severe deficits in understanding speech in background noise but normal pure-tone thresholds. These nine patients underwent spatial speech-in-noise testing in a sound-attenuating chamber (the ‘crescent of sound’) with and without FM systems.

Signal-to-noise-ratio (SNR) for 50% correct speech recognition performance were measured with speech presented from 0°, and competing babble from either 0° or ±90° azimuths. The signal-to-noise ratio benefit (SNR benefit) was defined as the difference between SNRs measured with co-located speech and babble and SNRs measured with spatially separated speech and babble. The SNR significantly improved when babble was spatially separated from target speech while the patients had the FM systems in their ears compared to without the FM systems.

Personal FM listening devices were successfully fitted to each of the stroke patients in this study. Similar results have been reported in a range of clinical populations (Johnston et al., 2009; Rance et al., 2010; Schafer et al. 2013), but this is the first data to suggest a viable acoustic management option for stroke listeners with severe auditory processing deficit. Additionally, the observed improvement was more marked for the stroke patients in our study compared to reports assessing the benefit of FM systems in other neurological populations with auditory processing deficits.

Personal FM systems may substantially improve speech-in-noise deficits in stroke patients who are not eligible for conventional hearing aids. FM systems are feasible in stroke patients and show promise to address impaired AP after stroke.

7.5 Summary and General Discussion of Study 3- Phase II

Approximately one in five stroke survivors suffer from difficulties with speech reception in noise despite normal audiometry. These deficits are treatable with personal FM systems (Study 3- Phase II). This study aimed to evaluate long term benefits in speech reception in noise after ten weeks of daily use of personal FM systems in non-aphasic stroke patients with auditory processing deficits. This was a prospective non-randomised controlled trial study. Patients were allocated to either an intervention care subjects group or a standard care subjects group according to their willingness to use the intervention. Nine non-aphasic subjects with ischemic stroke, normal pure-tone audiometry, auditory processing deficits, and reported difficulties understanding speech in background noise were recruited in the subacute stroke stage (3-12 months after stroke). Four patients (the intervention care subjects) used the FM systems in their daily lives over the course of ten weeks. Five patients (the standard care subjects) received standard care. All subjects were tested at baseline (visit 1) and ten weeks later (visit 2) on a sentences in noise test with the FM system (aided) and without the FM system (unaided). Speech reception thresholds showed clinically and statistically significant improvements in the intervention subjects but not in standard care subjects after ten weeks in both the aided and the unaided conditions. Our results indicate that ten weeks' use of FM systems by adult stroke patients may lead to benefits in unaided speech in noise perception. Our findings may indicate auditory plasticity type changes; however, this inference requires further investigation in larger studies.

7.5.1 Limitations and Future Research

It has become clear that exposure to auditory enrichment can result in large functional changes in the central auditory nervous system. Even mature sensory systems retain the potential for extensive plasticity (Skoe et al., 2015). Therefore, establishing the efficacy of such treatments should be among the highest research priorities. Future studies should use outcome measures to evaluate treatment outcomes and inform quality improvement efforts.

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Although recording auditory brainstem and cortical potentials are time consuming and relatively complex, they are useful tools to document treatment outcomes. Electrophysiological measures may be more sensitive than behavioural tests and are less influenced by external variables. Thus future research should employ such assessment to monitor the efficacy of auditory interventions such as FM systems and/or auditory training.

Finally, the study has small case numbers; thus its findings ought to be interpreted with caution. Low study numbers affect the precision of measurements, and even a nominally statistically significant finding may not reflect a true effect. Furthermore, the study lacked randomization, and is thus prone to selection bias; the factors influencing patient preference and thus group allocation were not determined. Further research is required to look into this promising intervention that may benefit approximately 21% of the stroke population.

7.6 Conclusions

A few conclusions can be drawn from the studies presented in this thesis. They have clinical implications for the management of stroke patients with hearing impairment:

1. Our study demonstrates that hearing impairment of any type was present in the majority of stroke patients (86%), none of whom had been previously referred for a hearing assessment. Although the proportion of people with peripheral hearing loss did not significantly differ from the healthy control group, our results indicate that the most common type of hearing impairment in our stroke patients was the combination of ‘peripheral and CAPD’ hearing impairment in the 61-80-year-olds subgroup (55%), and disordered auditory processing in the 18–60-year-olds (40%), which were both significantly higher than in the controls. It is essential to identify hearing loss and to differentiate peripheral and central deficits for the evaluation and rehabilitation of stroke patients so that an effective intervention for this population can be reached.
2. The two validated questionnaires showed excellent specificity (100%) in identifying patients requiring a hearing assessment, although sensitivity was

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rather low (around 36% for the AIAD and 44% for the HHIE questionnaire). The highest hearing screening test accuracy was achieved when results of a handheld hearing screener and hearing questionnaires were combined. Based on the results of our study, an effective hearing screening protocol in stroke units should incorporate a handheld hearing screening device as well as validated hearing questionnaires.

3. The hearing questionnaires gave significantly different results in the stroke patients with hearing impairments vs. the stroke patients with normal hearing. Participants with CAPD, peripheral hearing loss, and combination hearing impairment scored significantly lower in all aspects of the Amsterdam Disability questionnaire, including speech in noise, speech in quiet, sound recognition, localisation, and detection of sound, in comparison to those stroke patients with normal hearing. Also, stroke patients with any types of hearing impairment, including those with normal PTA but CAPD, scored significantly worse in the HHIE questionnaire in comparison to those stroke patients with normal hearing.
4. Personal FM systems may substantially improve speech-in-noise deficits in stroke patients who are not eligible for conventional hearing aids. FM systems are feasible in stroke patients and show promise to address impaired AP after stroke.
5. Ten weeks of use of FM systems by adult stroke patients may lead to benefits in unaided speech in noise perception. Our findings may indicate auditory plasticity type changes, and require further investigation.

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9 Appendices

9.1 Appendix A: Amsterdam Inventory for Auditory Disability

Amsterdam Inventory for Auditory Disability and Handicap

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

Almost never	occasionally
frequently	almost always
2. **Can you carry on a conversation with someone in a quiet room?**

Almost never	occasionally
frequently	almost always
3. **Do you immediately hear from which direction a car is approaching when outside?**

Almost never	occasionally
frequently	almost always
4. **Can you hear cars passing by?**

Almost never	occasionally
frequently	almost always
5. **Do you recognise members of your family by their voices?**

Almost never	occasionally
frequently	almost always
6. **Can you recognise melodies in music or songs?**

Almost never	occasionally
frequently	almost always
7. **Can you carry on a conversation with someone in a crowded meeting?**

Almost never	occasionally
frequently	almost always
8. **Can you carry on a telephone conversation in a quiet room?**

Almost never	occasionally
frequently	almost always
9. **Can you hear from which corner of a lecture room someone is asking a question during a meeting?**

Almost never	occasionally
frequently	almost always
10. **Can you hear someone approaching from behind?**

Almost never	occasionally
frequently	almost always

HEARS

11. **Do you recognise a presenter on TV by his/her voice?**
- | | |
|--------------|---------------|
| Almost never | occasionally |
| frequently | almost always |
12. **Can you understand text that is being sung?**
- | | |
|--------------|---------------|
| Almost never | occasionally |
| frequently | almost always |
13. **Can you easily carry on a conversation with somebody in a car or bus?**
- | | |
|--------------|---------------|
| Almost never | occasionally |
| frequently | almost always |
14. **Can you understand the presenter of the news on TV?**
- | | |
|--------------|---------------|
| Almost never | occasionally |
| frequently | almost always |
15. **Do you immediately look in the right direction when somebody calls you in the street?**
- | | |
|--------------|---------------|
| Almost never | occasionally |
| frequently | almost always |
16. **Can you hear noises in the house like running water, vacuuming, a washing machine?**
- | | |
|--------------|---------------|
| Almost never | occasionally |
| frequently | almost always |
17. **Can you discriminate between the sound of a car and a bus?**
- | | |
|--------------|---------------|
| Almost never | occasionally |
| frequently | almost always |
18. **Can you follow a conversation between a few people during dinner?**
- | | |
|--------------|---------------|
| Almost never | occasionally |
| frequently | almost always |
19. **Can you understand the presenter of the news on the radio?**
- | | |
|--------------|---------------|
| Almost never | occasionally |
| frequently | almost always |
20. **Can you hear from which corner of the room someone is talking to you in a quiet house?**
- | | |
|--------------|---------------|
| Almost never | occasionally |
| frequently | almost always |

HEARS

21. **Can you hear the doorbell at home?**
- | | |
|--------------|---------------|
| Almost never | occasionally |
| frequently | almost always |
22. **Can you distinguish between male and female voices?**
- | | |
|--------------|---------------|
| Almost never | occasionally |
| frequently | almost always |
23. **Can you hear rhythm in music or songs?**
- | | |
|--------------|---------------|
| Almost never | occasionally |
| frequently | almost always |
24. **Can you carry on a conversation with someone in a busy street?**
- | | |
|--------------|---------------|
| Almost never | occasionally |
| frequently | almost always |
25. **Can you distinguish intonation and inflections in people's voices?**
- | | |
|--------------|---------------|
| Almost never | occasionally |
| frequently | almost always |
26. **Do you hear from which direction a car horn is coming?**
- | | |
|--------------|---------------|
| Almost never | occasionally |
| frequently | almost always |
27. **Do you hear birds singing outside?**
- | | |
|--------------|---------------|
| Almost never | occasionally |
| frequently | almost always |
28. **Can you recognise and distinguish between different musical instruments by their sound?**
- | | |
|--------------|---------------|
| Almost never | occasionally |
| frequently | almost always |

9.2 Appendix B: Hearing Handicap Inventory for the Elderly

Hearing Handicap Inventory for the Elderly

Name: _____ Date: _____

Instructions:

The purpose of this scale is to identify the problems your hearing loss may be causing you. Answer **YES**, **SOMETIMES**, or **NO** for each question. Do not skip a question if you avoid a situation because of your hearing problem. If you use a hearing aid, please answer the way you hear without the aid.

S-1. Does a hearing problem cause you to use the phone less often that you would like?

YES (4) SOMETIMES (2) NO (0)

E-2. Does a hearing problem cause you to feel embarrassed when meeting new people?

YES (4) SOMETIMES (2) NO (0)

S-3. Does a hearing problem cause you to avoid groups of people?

YES (4) SOMETIMES (2) NO (0)

E-4. Does a hearing problem make you irritable?

YES (4) SOMETIMES (2) NO (0)

E-5. Does a hearing problem cause you to feel frustrated when talking to members of your family?

YES (4) SOMETIMES (2) NO (0)

S-6. Does a hearing problem cause you difficulty when you attending a party?

YES (4) SOMETIMES (2) NO (0)

E-7. Does a hearing problem cause you to feel "stupid" or "dumb"?

YES (4) SOMETIMES (2) NO (0)

S-8. Do you have difficulty hearing when someone speaks a whisper?

YES (4) SOMETIMES (2) NO (0)

E-9. Do you feel handicapped by a hearing problem?

YES (4) SOMETIMES (2) NO (0)

S-10. Does a hearing problem cause you a difficulty when visiting friends, relatives, or neighbours?

YES (4) SOMETIMES (2) NO (0)

S-11. Does a hearing problem cause you to attend religious services less often than you would like?

YES (4) SOMETIMES (2) NO (0)

E-12. Does a hearing problem cause you to be nervous?

YES (4) SOMETIMES (2) NO (0)

S-13. Does a hearing problem cause you to visit friends, relatives, or neighbours less often than you would like?

YES (4) SOMETIMES (2) NO (0)

E-14. Does a hearing problem cause you to have arguments with family members?

YES (4) SOMETIMES (2) NO (0)

S-15. Does a hearing problem cause you difficulty when listening to TV or Radio?

YES (4) SOMETIMES (2) NO (0)

S-16. Does a hearing problem cause you to go shopping less often than you would like?

YES (4) SOMETIMES (2) NO (0)

E-17. Does any problem or difficulty with your hearing upset you at all?

YES (4) SOMETIMES (2) NO (0)

E-18. Does a hearing problem cause you to you want to be by yourself?

YES (4) SOMETIMES (2) NO (0)

HEARS

S-19. Does a hearing problem cause you to talk to family members less often than you would like?

YES (4) SOMETIMES (2) NO (0)

E-20. Do you feel that any difficulty with your hearing limits or hampers your personal or social life?

YES (4) SOMETIMES (2) NO (0)

S-21 Does a hearing problem cause you difficulty when in a restaurant with relative and friends?

YES (4) SOMETIMES (2) NO (0)

E-22. Does a hearing problem cause you to feel depressed?

YES (4) SOMETIMES (2) NO (0)

S-23. Does a hearing problem cause you to listen to TV or radio less than you would like?

YES (4) SOMETIMES (2) NO (0)

E-24. Does a hearing problem cause you to feel uncomfortable when talking to friends?

YES (4) SOMETIMES (2) NO (0)

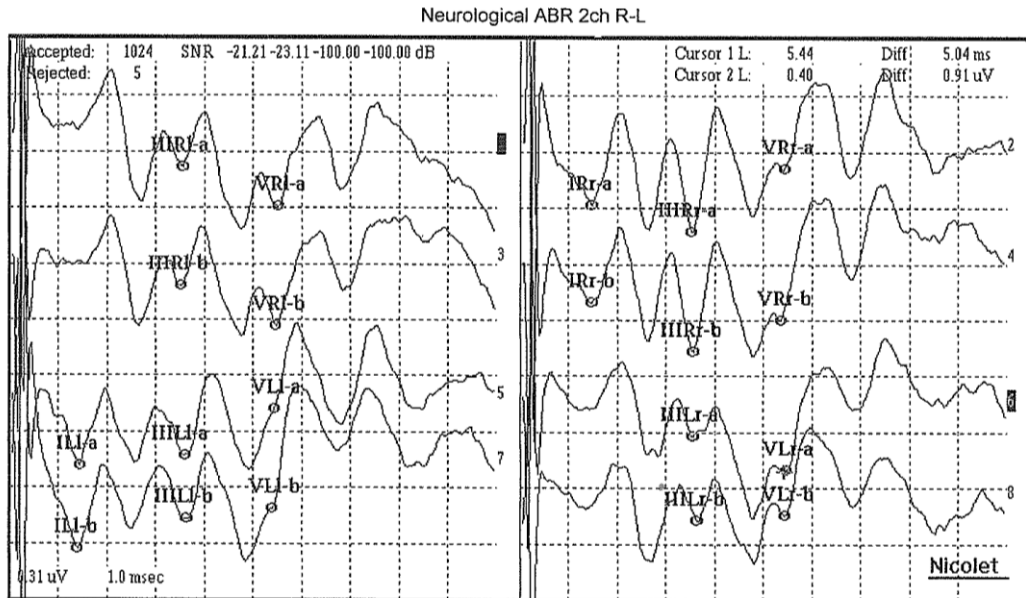
E-25. Does a hearing problem cause you to feel left out when you are with a group of people?

YES (4) SOMETIMES (2) NO (0)

HEARS

9.3 Appendix C: Example of normal ‘neurological’ ABR

Notes/Impressions: Stimulus @ 90 dB nHL



Sensitivity and Sweep Time Per Division								
1	0.31 uV	1.0 msec	2	0.31 uV	1.0 msec	3	0.31 uV	1.0 msec
5	0.31 uV	1.0 msec	6	0.31 uV	1.0 msec	7	0.31 uV	1.0 msec
4	0.31 uV	1.0 msec	8	0.31 uV	1.0 msec			

Neurological ABR							
IIR-a	1.48ms	IIRL-a	2.04ms	IL-a	1.44ms	IIRL-a	2.16ms
IIRr-a	3.52ms	III-VRr-a	1.92ms	III-L-a	3.60ms	III-VL-a	1.94ms
VRr-a	5.44ms	I-VRr-a	3.96ms	VLI-a	5.44ms	I-VLI-a	4.00ms
IIRr-b	1.48ms	I-VRr-b	2.08ms	ILI-b	1.40ms	I-III-L-b	2.24ms
III-VRr-b	3.56ms	III-VRr-b	1.80ms	III-L-b	3.64ms	III-VL-b	1.76ms
VRr-b	5.36ms	I-VRr-b	3.88ms	VLI-b	5.40ms	I-VLI-b	4.00ms
III-L-a	3.56ms	III-VL-a	1.92ms	III-RI-a	3.56ms	III-VRl-a	1.96ms
VLI-a	5.48ms	III-VL-b	1.80ms	VRI-a	5.52ms	III-VRl-b	1.96ms
III-L-b	3.64ms	IADV-1	0.00ms	IIRl-b	3.52ms		
VLI-b	5.44ms			VRl-b	5.48ms	IADV-2	0.04ms

HEARS

9.4 Appendix D: Hearing Screening and Medical Interview

2

ID Number: _____ Date: _____

Date of Birth: _____ Age: _____ Gender: _____

Case History: Circle Appropriate answers

Do you think you have a hearing loss? Yes No

Have hearing aids ever recommended for you? Yes No

If yes,

- a. Do you have a hearing aid?
 b. How many do you have and how often do you use them?

Is your hearing better in in one ear? Yes No

If yes, which is the better ear? Right Left

Have you ever had a sudden or rapid progression of hearing loss? Yes No

If yes, which ear? Right Left

Do you have ringing or noises in your ears? Yes No

Have you had a recent discharge from your ears? Yes No

If yes, which ear? Right Left

Do you have pain or discomfort in your ears? Yes No

If yes, which ear? Right Left

Visual/Otoscopic Inspection:

Right: _____ Left: _____

Pure Tone Screen (25, 30, 35 and 40 dB HL) (R = Response, NR = No Response)

Frequency	500 Hz				1000 Hz				2000 Hz				4000 Hz			
	25	30	35	40	25	30	35	40	25	30	35	40	25	30	35	40
dB HL																
Right																
Left																

Researcher: _____

Date: _____

2

9.5 Appendix E: Glasgow Benefit Inventory

The GBI questionnaire (all-purpose)

1. Has the result of the intervention (<i>FM system</i>) affected the things you do?				
Much worse	A little or somewhat worse	No change	A little or somewhat better	Much better
1	2	3	4	5

2. Have the results of the <i>intervention</i> made your overall life better or worse?				
Much better	A little or somewhat	No change	A little or somewhat worse	Much worse
5	4	3	2	1

3. Since your <i>intervention</i> , have you felt more or less optimistic about the future?				
Much more optimistic	More optimistic	No change	Less optimistic	Much less optimistic
5	4	3	2	1

4. Since your <i>intervention</i> , do you feel more or less embarrassed when with a group of people?				
Much more embarrassed	More embarrassed	No change	Less embarrassed	Much less embarrassed
1	2	3	4	5

5. Since your <i>intervention</i> , do you have more or less self-confidence?				
Much more self-confidence	More self-confidence	No change	Less self-confidence	Much less self-confidence
5	4	3	2	1

6. Since your <i>intervention</i> , have you found it easier or harder to deal with company?				
Much easier	Easier	No change	Harder	Much harder
5	4	3	2	1

1

HEARS

7. Since your *intervention*, do you feel that you have more or less support from your friends?

Much more support 5	More support 4	No change 3	Less support 2	Much less support 1
------------------------	-------------------	----------------	-------------------	------------------------

8. Have you been to your family doctor, for any reason, more or less often, since your *intervention*?

Much more often 1	More often 2	No change 3	Less often 4	Much less often 5
----------------------	-----------------	----------------	-----------------	----------------------

9. Since your *intervention*, do you feel more or less confident about job opportunities?

Much more confident 5	More confident 4	No change 3	Less confident 2	Much less confident 1
--------------------------	---------------------	----------------	---------------------	--------------------------

10. Since your *intervention*, do you feel more or less self-conscious?

Much more self-conscious 1	More self-conscious 2	No change 3	Less self-conscious 4	Much less self-conscious 5
-------------------------------	--------------------------	----------------	--------------------------	-------------------------------

11. Since your *intervention*, are there more or fewer people who really care about you?

Many more people 5	More people 4	No change 3	Fewer people 2	Many fewer people 1
-----------------------	------------------	----------------	-------------------	------------------------

**12. Since you had the *intervention*, do you catch colds or infections more or less often?
Answer.3**

Much more often 1	More often 2	No change 3	Less often 4	Much less often 5
----------------------	-----------------	----------------	-----------------	----------------------

HEARS

13. Have you had to take more or less medicine for any reason, since your <i>intervention</i>?				
Much more medicine 1	More medicine 2	No change 3	Less medicine 4	Much less medicine 5

14. Since your <i>intervention</i>, do you feel better or worse about yourself?				
Much better 5	Better 4	No change 3	Worse 2	Much worse 1

15. Since your <i>intervention</i>, do you feel that you have had more or less support from your family?				
Much more support 5	More support 4	No change 3	Less support 2	Much less support 1

16. Since your <i>intervention</i>, are you more or less inconvenienced by your <i>health</i>* problem?				
Much more inconvenienced 1	More inconvenienced 2	No change 3	Less inconvenienced 4	Much less inconvenienced 5

17. Since your <i>intervention</i>, have you been able to participate in more or fewer social activities?				
Many more activities 5	More activities 4	No change 3	Fewer activities 2	Many fewer activities 1

18. Since your <i>intervention</i>, have you been more or less inclined to withdraw from social situations?				
Much more inclined 1	More inclined 2	No change 3	Less inclined 4	Much less inclined 5

HEARS

GBI questions	Intervention Subject 1 score (1-5)	Intervention Subject 2 score (1-5)	Intervention Subject 3 score (1-5)
1	3	4	4
2	3	4	3
3	3	3	3
4	3	3	3
5	3	3	3
6	3	3	3
7	3	3	3
8	3	3	3
9	3	3	3
10	3	3	3
11	3	3	3
12	3	3	3
13	3	3	3
14	3	3	3
15	3	3	3
16	3	3	3
17	4	4	4
18	3	4	3

GBI results in three stroke patients in the intervention group (FM study Phase II). GBI was sent to all those stroke patients in the intervention group, however only three patients returned the questionnaire.

HEARS**9.6 Appendix F: Listening Strategies****Explain and educate**

Communication is a two-way process. Your friends and family and other people you come across may have the best intentions to try and communicate with you, but they may not understand the nature of your hearing difficulties, or how to make communication with you easier and better. You may want to discuss your hearing difficulties with them, and it may also be helpful to ask them to read this handout. They should know that it would be best to make sure that they get your attention first before they start talking to you. They should speak clearly and more slowly. It would be helpful if they emphasise their speech in order to highlight the key points of the message. They may also repeat or rephrase the message, and use additional visual or other cues. It may also be useful to see a hearing therapist together with your partner/family to discuss all this and your doctor can advise you and organise this for you.

Be aware of room acoustics and how they affect your hearing perception

Rooms with hard surfaces (hard tiles on the floor, walls, ceilings, etc.) will cause the sound to be reflected on the surfaces and create 'echoes' of the sounds. These rooms will have poor acoustics and will make it more difficult for you to hear. Avoid meetings or conversations in rooms with poor acoustics (those that have 'echoey' effects). Rooms with carpets, soft furniture and cushions, heavy curtains, acoustic ceiling tiles are best for your hearing. If you have an important meeting and you can choose where the meeting is taking place, try to plan ahead and choose a room with good acoustics.

Minimise background noise

If you need to conduct a meaningful conversation, try and minimise all noise, for example switch off the radio or the television. Move away from a window overlooking a busy road or from a fan, air conditioner or any other device emitting noise.

Localisation

When you are in a crowded room with many people talking and someone speaks to you, try to localise the sound as quickly as possible.. The quicker that you can localise, the quicker you can orient your hearing system as well as your visual system to pick up on cues that are important to communication. Localise by focusing you listening as well as your visual cues on the individual talking to you.

Position

You need to position yourself so that you are directly in front of the person speaking to you. If you are talking with someone, try to position yourself so that the person you are talking to is closer to the noise source than you.

Ask

HEARS

Ask individuals not to cover their mouths when they are speaking to you. Explain to them that you need to see their face and mouth when they are talking, because this helps you to understand their speech better. Ask individuals that are talking to you to repeat, speak up or speak slower if you don't understand what they are saying. **Do this as soon as you realise you are not following the conversation.** If you feel you are not following the conversation, stop the individual immediately and say "*please speak up/slower because I can't hear you well.*" Do not wait until you are into a lengthy conversation or the conversation is almost finished before you ask them to repeat. This is frustrating for both you as well as the speaker. Ask individuals to write down information that is extremely important such as directions to a given destination, telephone numbers, schedules, etc.

Concentrate and watch very carefully

When an individual is talking to you, it is very important that you devote all of your attention to this individual. Try not to be distracted by any visual or other auditory stimuli that may be around you. If someone else approaches you while you are talking with someone, stop the conversation and tell them to wait until you are finished talking with the person with whom you have initiated the conversation. Total attention and total concentration are needed for optimum communication. Many times this is not achieved due to the fact that individuals have other things on their mind and total attention is not devoted to the individual to whom they are speaking. Concentrate on key words in a conversation. Watch very closely all gestures and facial movements when the individual is talking to you. This will help you fill in the gaps with visual cues for some of the things that you may miss or not quite understand.

Avoid

Avoid going to meetings late. Try to go early so you can position yourself close to the speaker or where the speaker will be. This can be of great help. If you do go late to a meeting, ask someone to summarise what has happened so you get a good idea of what is going on at the meeting.

Telephone

Telephone conversations can be enhanced by holding the receiver as close to your ear as possible. This will attenuate outside interference noise. Do not hold the receiver so tight that it actually blocks your ear but rather hold it tight enough so that it covers the ear and keeps away extraneous sounds. Foam rubber around the perimeter of the receiver which can fit over your ear and next to your head can be a tremendous help in terms of attenuating background noise. When using a mobile telephone it may be helpful to hear with both ears by using the earphones provided.

Where can I get more information?

<http://www.nidcd.nih.gov/health/voice/auditory.asp>

9.9 Appendix I: Poster Presentation AAA Arizona 2016



Improved speech in noise test performance in stroke subjects after prolonged use of personal frequency modulation systems

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ABSTRACT

This study evaluated the potential benefits in speech-perception of personal frequency modulated (FM) systems, when used for a set period of time by stroke patients with a diagnosis of auditory processing deficits, and investigated whether plasticity occurs after a prolonged use of FM systems. The main results of this study were that prolonged use of FM systems significantly lowered the signal-to-noise ratio (SNR) for 50% correct performance in speech-in-noise test in case subjects for both with and without FM use test conditions.

BACKGROUND

Stroke can affect all levels of the auditory pathway (Häusler and Levine, 2000). Thus, stroke related auditory deficits are not constrained to pure tone detection/audiability deficits evidenced by raised audiometric thresholds (Formby et al., 1987; O'Halloran et al., 2009) but may also include auditory processing deficits (Rey et al., 2007; Bamiou et al., 2012; Bamiou, 2015) associated with patient reported auditory perceptual difficulties in the domains of speech, sound recognition and localisation (Bamiou et al., 2012). Approximately one in five of stroke survivors report severe difficulties with speech recognition in the presence of background noise, despite the presence of normal audiometric thresholds (Koohi et al., 2016); these deficits are attributed to the auditory processing deficits caused by the stroke, although cognitive or language related factors may also play a role. These deficits are treatable with personal FM (Frequency Modulated) systems, with a robust immediate improvement of 9 dB in signal to noise ratio when using the FM system (Koohi et al., 2016). Now our question is whether stroke patients who developed speech in noise and auditory processing deficits following the stroke would show improved speech in noise perception following FM system use even without using these systems.

PURPOSE

The present study aimed to evaluate the potential benefits in speech-perception of personal FM systems, when used daily over 10 weeks by non-aphasic stroke patients with a diagnosis of auditory processing deficits, in order to investigate whether plasticity occurs after prolonged use of FM systems.

METHODS

PARTICIPANTS & BASELINE ASSESSMENTS

- Nine stroke patients (age range 24 - 78 years old) in the subacute stroke stage (4 case subjects & 5 controls)
- Normal pure-tone audiogram
- Reported hearing-in-noise difficulties on the speech-in-noise subscale of Amsterdam Inventory of Auditory Disability
- Abnormal performance in one or both ears in a monaurally conducted speech in babble test and in at least one or more non-speech auditory processing test (Koohi et al., 2016)
- No severe aphasia or cognitive impairments

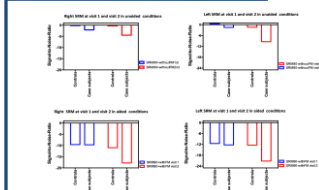
OUTCOME MEASURES

- Outcome assessments were conducted in both groups in a separate test session, during visit 1 taking place within 1 week from the baseline assessments, and visit 2 at 10 weeks later
- The outcome assessment tool was the Bamford-Kowal-Bench (BK) sentence test presented against a 20-talker babble noise, conducted within the "crescent of sound" booth (Koohi et al., 2016)
- The speech reception threshold (SRT) & the spatial release from masking (SRM) for speech were calculated. Right SRM = SRT(50°N=90°) - SRT(50°N0°) & Left SRM = SRT(50°N=90°) - SRT(50°N0°)

Lesion description, age, sex, PTA, disease duration

Case ID	Age	Sex	Lesion description	PTA	Disease duration
Case 01	61	M	Right middle cerebral artery	20	10
Case 02	61	M	Right middle cerebral artery	20	10
Case 03	61	M	Right middle cerebral artery	20	10
Case 04	61	M	Right middle cerebral artery	20	10
Case 05	61	M	Right middle cerebral artery	20	10
Case 06	61	M	Right middle cerebral artery	20	10
Case 07	61	M	Right middle cerebral artery	20	10
Case 08	61	M	Right middle cerebral artery	20	10
Case 09	61	M	Right middle cerebral artery	20	10
Case 10	61	M	Right middle cerebral artery	20	10

RESULTS



A repeated measures general linear model ANOVA was conducted for the SRM measures with time (visit 1, visit 2), FM condition (used, unused) and angle (left 90°, and right 90°) as within-subjects factors and case/control group as a between-subjects factor. There was a highly statistically significant effect of time and case/control group interaction. [F(1,7) = 18.84, p < 0.0001] with greater SRM change in cases vs no change in controls (see table 1). The time by angle interaction was only just significant [F(1,7) = 5.969, p = 0.045] and time by angle by case/control group interaction was close to significant [F(1,7) = 4.963, p = 0.056].

CONCLUSIONS

In conclusion, we found robust and clinically significant improvements in speech-in-noise perception even when not using the FM system, after prolonged use of personal FMs by stroke patients with speech-in-noise deficits due to disordered auditory processing. Our preliminary results suggest that a proportion of the stroke population (around 17% as per our previous study Koohi et al., 2016) might benefit by this intervention. Further research should investigate further the degree and mechanisms of this benefit.

ACKNOWLEDGEMENTS

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9.10 Appendix J: Poster Presentation AAA Orlando 2014

Are Personal FM systems of benefit for stroke patients? Hearing Evaluation and Auditory Rehabilitation after Stroke (HEARS)

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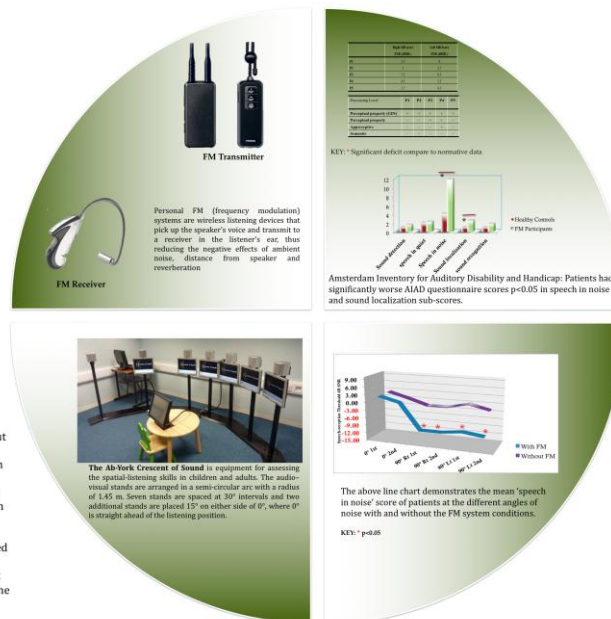
•Introduction

• **Stroke** is the most common neurological condition and the majority of survivors require rehabilitation. Peripheral hearing loss and/or central auditory processing deficits may be present after stroke, and several patients report **speech in noise difficulties** (Bamiou et al, 2012). Such hearing impairment may lead to reduced participation in activities of daily living (Hines, 1997), and may be associated with increased risk of physical decline of stroke patients long term (Landi et al, 2006).

• **Frequency Modulation (FM)** systems have been used to address speech in noise perception in patients with auditory processing difficulties (Rance et al, 2012). This study aims to assess the benefits of FM systems for patients with stroke who report difficulties in understanding speech in background noise, despite having normal/near normal peripheral hearing.

•Methods

• We recruited 5 stroke patients with normal/near normal peripheral hearing but speech in noise difficulties on the basis of Speech in Babble (SIB) test and Amsterdam Inventory for Auditory Disability (AIAD) questionnaire scores. Standardized speech perception assessments were conducted on the stroke patients, with and without FM devices, in the soundfield in a sound attenuating chamber, with speech presented from a fixed speaker (straight ahead) and noise presented from the same or different location speakers (90° to the right and to the left). A hearing therapy session was also provided.



•Results

• The speech perception scores were dramatically improved when patients were tested with FM systems with a significant interaction effect between the angle of noise and the use of FM systems, $F(2,3) = 15.3$, $p = 0.01$. Post hoc t-tests showed significantly improved speech scores with vs. without FM devices when the noise was presented 90° to the left; $t(2) = 5.18$, $p = 0.035$ and to the right ear; $t(2) = 5.09$, $p = 0.036$

•Conclusion

• To our knowledge, this is the first study assessing the **effect of the personal FM technology on speech perception** in noise among stroke patients with the diagnosis of APD.

• Consistent with outcomes reported for adult patients with similar difficulties due to neural auditory perceptual deficits (Rance et al., 2010).

• 'Normal' routine audiological examination (PTA, SRTs, ABR) in stroke patients does not mean patients do not have difficulty hearing and understanding speech in background noise.

• All participants in our study suffered from distorted temporal resolution of auditory events (deficits in property processing) and a great difficulty understanding speech in the presence of background noise.

• We found a **significant** speech perception improvement in noise in stroke patients when they used the FM systems. Our results provide compelling evidence for **auditory rehabilitation for stroke** patients who have normal/near normal hearing but great difficulty processing the sound in the brain.

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