BENEFIT AND PREDICTORS OF OUTCOME FROM FREQUENCY COMPRESSION HEARING AID USE

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ABBREVIATIONS

APHAB	Abbreviated profile of hearing aid benefit
ANOVA	Analysis of variance
BKB	Bamford-Kowal-Bench
CUNY	City University of New York
dB	Decibels
FRED	Frequency recoding device
GHABP	Glasgow Hearing Aid Benefit Profile
HL	Hearing level
IEEE	Institute of Electrical and Electronics Engineers
IHR	Institute of Hearing Research
(k)Hz	**(**kilo)-Hertz
Msec	Milliseconds
NHS	National Health Service
(NL)FC	**(**Non-linear) frequency compression
PSOLA	Pitch synchronous overlap add
RAU	Rationalised arcsine units
REIG	Real ear insertion gain
RST	Reading span test
S	Seconds
SIN	Sentence in noise
SINFA	Sequential information analysis
SNR	Signal to noise ratio
SPL	Sound pressure level
SSQ	Speech, Spatial and Qualities of Hearing Scale
TEN	Threshold equalising noise
TMT – A/B	Trail making test – A/B
UCL	University College London
UWO	University of Western Ontario
VCV	Vowel-consonant-vowel
VCVN	Vowel-consonant-vowel in noise
VCVQ	Vowel-consonant-vowel in quiet
WMS	Working memory span

ABSTRACT

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Non-linear frequency compression (NLFC) hearing aids are frequency lowering devices that compress a signal into a reduced bandwidth in order to maximise use of residual hearing. Only a few published studies have investigated benefit from NLFC hearing aids. Outcomes vary considerably between studies although most show large differences across listeners. This highlights the need for identification of reliable predictors of benefit. Furthermore, little is known about the time course and magnitude of perceptual learning associated with the use of NLFC amplification. A better understanding of these issues could potentially lead to significant clinical benefit and was therefore the focus of the present study.

Two preliminary experiments were conducted on a total of 27 listeners with normal hearing in order to investigate the effect of NLFC on categorical perception and the role of cognition on NLFC outcome. The findings were used to inform the development (particularly with regards to the selection of NLFC fitting parameters) of a longitudinal study of 12 experienced adult hearing aid users with moderate-to-severe high frequency hearing loss. Participants wore the hearing aids, with and without NLFC enabled, in an A-B-A design, for approximately 6-7 weeks in each condition. Speech recognition, in both quiet (nonsense syllables) and noise (nonsense syllables and sentences), was measured at the end of each trial period. It was also measured at several time points when frequency compression was enabled in order to investigate perceptual learning. The opportunity was taken to gather preliminary self-report data (Glasgow Hearing Aid Benefit Profile and Speech, Spatial and Qualities of Hearing Scale) in order to identify possible trends on which to base future research.

The results demonstrate that mean benefit on the speech recognition measures was greater when frequency compression was enabled. 9 out of 12 listeners obtained higher scores on the majority of outcome measures. There was no obvious difference on self report measures. Upon initial exposure to NLFC, there was an increase in confusions of some high frequency phonemes, especially of /f/ and /θ/ with /s/ (in both quiet and in noise); however, these confusions were less frequent after 6 weeks of NLFC hearing aid use. Limited evidence of perceptual learning of speech in noise was observed. In agreement with the findings of previous studies, large individual differences in benefit were evident. The relation between sentence in noise recognition (with and without NLFC enabled) and a variety of audiological (high frequency hearing loss and presence of dead regions) and cognitive factors (performance in the reading span and trail making tests) was examined. Audiological factors were shown to be predictive both of speech in noise recognition and of additional benefit obtained from NLFC. Listeners with the greatest high frequency loss derived the most benefit from NLFC. Once the effect of hearing loss had been partialled out, no other predictor correlated significantly with benefit from NLFC. However, the results support previous findings that cognitive functioning is predictive of benefit without NLFC, but suggest that this is primarily due to the influence of executive function rather than working memory span.

The novel findings of the study (particularly those relating to speech in noise perception, acclimatisation to NLFC, and predictors of benefit from amplification) may help influence clinical practice, in relation to the assessment of candidacy for NLFC hearing aids and subsequent counselling offered to device users.

DECLARATION

No portion of the work referred to in this thesis has been submitted in support of an application for another degree or qualification of this or any other university or other institute of learning

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CHAPTER 1

INTRODUCTION

According to Davis (2001), almost 50% of the British population over the age of 70 years have some degree of hearing loss, especially at the high frequencies.

Commercially available hearing aids are often unable to amplify frequencies above approximately 6 kHz, due to a limited bandwidth capacity. For people with a severe to profound high frequency hearing loss, the functional upper frequency limit of the hearing aid may, in practice, be much lower. This is due to difficulties in providing sufficient gain to restore audibility.

High frequency information is important for the perception of many speech and environmental sounds. According to Boothroyd and Medwetsky (1992), the upper frequency limit of a hearing aid needs to be at least 10 kHz to allow the listener to perceive a /s/ sound produced by a female speaker. At present, few digital hearing aids are able to attain functionally useful levels of gain at such high frequencies using conventional methods of amplification.

One method of increasing the upper frequency limit of a hearing aid is to employ some kind of frequency lowering algorithm. One such signal processing method, used in a range of hearing aids manufactured by Phonak AG (an international hearing aid manufacturer based in Switzerland), is non-linear frequency compression. Non-linear frequency compression causes sounds above a programmable cut-off frequency to be compressed and lowered in frequency, such that the higher the frequency, the more severe the compression applied. Frequencies below the cut-off point are simply amplified and are unaffected by the non-linear frequency compression.

To date, there has been limited research into the perceptual effects of frequency compression. Previous studies have reported mixed results, with some listeners showing significant improvements on some speech perception measures, and others receiving no additional speech perception benefit from frequency compression when compared to conventional amplification (see for example: Simpson et al, 2005 and Glista et al, 2009). Methodological differences between the studies and in some cases, lack of appropriate controls, mean that it is difficult to predict from these results whether a given person with a hearing loss would benefit from frequency compression or not. Furthermore, little is known about the time course and magnitude of auditory acclimatisation following the fitting of a frequency compression hearing aid. In order to enable clinicians to make an informed decision regarding the provision of frequency compression hearing aids, and subsequent verification and counselling, more information is required on both candidacy and acclimatisation periods. As such, the aim of this project was to investigate the following questions:

1. Does frequency compression provide significant benefit above that provided by conventional amplification?

2. Are there changes in perceptual abilities over time following the provision of frequency compression hearing aids?

3. Is it possible to predict benefit from frequency compression hearing aids using audiological or cognitive factors?

In order to investigate these questions, a number of studies were completed, using both normally hearing and hearing impaired listeners.

The thesis is presented in alternative format, that is to say that the experimental chapters have been written in the style of a journal manuscript. This means that there will be some repetition of material between information in the experimental and non-experimental chapters (this is allowed under the University regulations). A brief introduction to each of the chapters, along with the respective experimental hypotheses is presented below.

Literature Review (Chapter 2)

The aim of this chapter is to outline the history and development of frequency lowering hearing aids. Recent clinical studies on this topic will be reviewed, and important unanswered questions in this area will be identified. Finally, the aims and hypotheses of the present studies are presented.

General Methods (Chapter 3)

The purpose of this chapter is to outline details of the methodological choices adopted in the experimental studies conducted. An outline of the structure of the longitudinal study is presented along with details of the participants and tests used in each of the studies that were carried out.

Study 1 (Chapter 4): To what extent does frequency compression affect the identification and discrimination of /s/ and /ʃ/ in adults with normal hearing?

The aim of this study was to investigate how frequency compression affects the categorical perception of /s/ and /ʃ/ in listeners with normal hearing. The rationale behind the study was to investigate whether the identification and discrimination of fricatives was differentially affected by frequency compression. The aim is to use this information to direct future research, using hearing impaired listeners, investigating different ways to fit frequency compression hearing aids and potential training regimes. It was hypothesised that frequency compression would have a greater impact on the identification of /s/ and /ʃ/, than on their discrimination. Data from this study was presented at the British Society of Audiology Short Papers Meeting held September 17th-18th 2009 in Southampton, UK (see publications list below).

Study 2 (Chapter 5): Does cognitive function predict frequency compressed speech recognition in listeners with normal hearing?

The purpose of this study was to investigate whether performance on tests of working memory and executive function predict the ability of young normally hearing listeners to recognise frequency compressed speech in noise. Young listeners with normal hearing were used in order to minimise the influence of confounding factors relating to aging and/or hearing loss. The goal was to use this study to inform the design of a later study using hearing impaired listeners. It was hypothesised that listeners with better cognitive performance would score more highly on a sentence in noise recognition task. Some data from this study were presented at the British Society of Audiology Annual Conference held September 8th-9th 2010 in Manchester, UK. Further data from the study was presented at the International Hearing Aid Research Conference held August 11th-15th 2010 in Tahoe City, USA. The manuscript has also been submitted for publication in the International Journal of Audiology (see publications list below).

Study 3 (Chapter 6): Benefit and predictors of outcome from frequency compression hearing aid use

A group of older listeners with sensorineural hearing loss were fitted bilaterally with frequency compression hearing aids. The hearing aids were used for a total of six weeks with the frequency compression enabled and six weeks with the frequency compression disabled. The study aimed to investigate three questions. The first aim of this study was to investigate perceptual changes over time to frequency compression. Performance on a number of speech perception tasks was assessed immediately after frequency compression was enabled and at one, three and six weeks post fitting. Scores were also obtained with frequency compression disabled to serve as a control for task learning effects. It was hypothesised that speech perception scores would improve over time.

The second aim was to investigate whether frequency compression hearing aid use conferred additional benefit to that provided by conventional amplification. In order to assess this, scores on a number of speech tests and self report measures were obtained. It was hypothesised that frequency compression would provide significant benefit to speech perception, particularly in tasks in which high frequency cues are important. A large degree of individual differences in performance was expected.

The final aim of the study was to investigate possible predictors of benefit from frequency compression. Predictors that were examined comprised of both audiometric and cognitive variables. The role of these variables in predicting speech in noise recognition with the use of conventional amplification was also assessed. It was hypothesised that a substantial amount of variance in speech perception performance could be accounted for using a combination of these predictors. Data from this part of the study was presented at the Cognitive Hearing Science for Communication Conference held June 19th – 22nd 2011 in Linköping, Sweden (see publications list below).

Conclusions and recommendations for future research (Chapter 7)

The purpose of this chapter is to discuss the implications of the combined findings of each of the studies presented in this thesis. Limitations of the studies and directions for future research will also be discussed.

It is hoped that the results of the studies will shed further light on factors contributing to the successful use of frequency compression hearing aids and to influence clinical practice, and the direction of future research, accordingly.

Publications derived from work presented in this thesis:

Journal articles:

Ellis, R. J. and Munro, K. J. Does cognitive function predict frequency compressed speech recognition in listeners with normal hearing? *International Journal of Audiology* (under revision)

Conference presentations:

2011	Cognitive Hearing Science for Communication Conference, Linköping, Sweden. June 19-22. Poster: ‘Correlations between Reading Span and speech perception test scores in frequency compression hearing aid users.’
2010	British Society of Audiology Annual Conference, University of Manchester, UK. September 8-10.

Poster: ‘Can performance on the Trail Making Test predict the ability of listeners with normal hearing to perceive frequency compressed speech in noise?’

2010 International Hearing Aid Research Conference, Lake Tahoe, USA. August 11-15.
Poster: ‘Can working memory capacity predict the perception of frequency compressed speech in noise in listeners with normal hearing?’

2009 British Society of Audiology Experimental Short Papers meeting, University of Southampton, UK. September 17-18.
Poster: ‘The effect of frequency compression on the perception of /s/ and /ʃ/ in listeners with normal hearing’

Professor Kevin J. Munro has co-authored all publications. However, the designing of all experiments, data collection and analysis was done by Rachel Ellis, as was the writing of all material presented in the thesis.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

The aim of this literature review is to outline the history and development of frequency lowering hearing aids. Recent clinical studies on this topic will be reviewed, and important unanswered questions in this area will be identified. Finally, the aims and hypotheses of the present studies will be presented.

2.2 The human auditory system

In order for sound to be perceived a number of processes must take place. The sound is first collected by the pinna (outer ear) and channelled down the ear canal towards the ear drum (or tympanic membrane). Sound hitting the ear drum causes it to vibrate, stimulating the movement of a chain of three small bones known as the ossicles. The ossicles are enclosed in a hollow space behind the ear drum and are part of the middle ear which encompasses the area between the ear drum and the oval window. The movement of the ossicles transmits sound to the inner ear by stimulating the vibration of a membrane covering the oval window, which is essentially a hole in the bone surrounding the cochlea and serves as the boundary between the middle and inner ear. The vibration of the membrane covering the oval window transmits the sound to the fluid filled cochlea which is part of the inner ear.

The cochlea is shaped like a spiral and, amongst other structures, contains the organ of Corti which receives the incoming sound. The organ of Corti consists of the basilar membrane, the tectorial membrane and the inner and outer hair cells, all of which run along the length of the cochlea (viewed as if the spiral is unwound). Both the inner and outer hair cells are anchored to the basilar membrane whilst the tips of the outer hair cells are attached to the tectorial membrane. The hair cells vibrate selectively to sound waves of a particular frequency and incoming sounds are tonotopically represented. Specifically the hair cells at the basal end of the basilar membrane (closest to the oval window) detect high frequency sounds whilst those towards the apical end of the basilar membrane respond to sounds of a low frequency. The hair cells convert the mechanical motion induced by the sound wave into an electrical impulse which is transmitted to the brain via the cochlear nerve. A hearing impairment may be caused by disruption to any process along the chain. A disruption occurring in the outer or middle ear is called a conductive loss whilst a disorder of the inner ear or auditory nerve is referred to as a sensorineural loss.

2.3 Sensorineural hearing loss

According to Davis (2001), almost 50% of the British population over the age of 70 years have a hearing impairment, with sensorineural hearing losses accounting for the majority of cases. By far the most common cause of acquired sensorineural hearing loss is damage to the hair cells in the cochlea, which often occurs as a result of either the aging process (presbyacusis) or excessive noise exposure.

Sensorineural hearing impairments are typically associated with increased hearing thresholds, and therefore reduced audibility, at the high frequencies as compared to the low frequencies, resulting in a sloping audiogram (a graph displaying hearing thresholds against frequency). As a result of the frequency specificity of the cochlea, normally functioning ears are adept at discriminating between the different frequencies represented in an auditory signal. However, if a person has a sensory loss, the outer hair cells at the basal end of the basilar membrane are often damaged. Damage to the outer hair cells results in degradation to the frequency selectivity of the cochlea as the mechanical motion in the outer hair cells (that facilitates frequency selectivity) is disrupted. This, in turn, affects the nature of the electrical impulses that are transmitted via the cochlear nerve to the brain. This means that for many patients with a sensorineural hearing loss, the damage to the high frequency hair cells may be so severe that it can be difficult to attain a useable level of audibility with amplification alone as provided by a conventional acoustic hearing aid. This is due to the hearing aid being unable to provide sufficient gain at the high frequencies for normal level speech to be presented above the listeners hearing threshold without acoustic feedback occurring.

These issues may be further exacerbated by the presence of a cochlear dead region. A dead region is an area of the cochlea in which damage to the inner hair cells (or the auditory nerve) is so severe that frequencies normally detected by the damaged area of the cochlea are not perceived at all (Moore and Glasberg, 1997; Moore et al, 2000), or detected by off-place listening (Moore, 2004). According to Vinay and Moore (2007), at least 59% of ears with an absolute threshold of 70 dBHL or greater have a dead region. The issue of whether to fit hearing aids differently to patients who show evidence of dead regions is unresolved. Previous research has shown that for adult participants with a dead region, amplification above 50 – 100 % of the estimated lower edge of the dead region may be of limited or no benefit for speech perception in both quiet (Vickers et al, 2001) and in noise (Baer et al, 2002).

A number of perceptual difficulties are known to be associated with a loss of high frequency sensitivity. In particular, people with a high frequency hearing loss often complain that whilst they may be able to hear speech, they find it very difficult to understand and interpret what has been said. This is particularly a problem when background noise is present or if many people are talking at once. This deficit is due primarily to the reduced frequency selectivity that often results from a sensorineural hearing loss and affects the perceived signal to noise ratio of speech in noise (see Moore, 1998 for a review of this topic).

A further complication affecting those with a high frequency hearing loss is that the perception of many phonemes, particularly fricatives (such as /s/, /ʃ/ and /z/), and voiceless consonants (for example /p/ and /k/) which contain much of their energy in the high frequencies, is likely to be impaired due to the reduced audibility of high frequencies. In English, the fricatives /s/ and /z/ are used to indicate possession and plurals amongst other linguistic and grammatical functions. According to Blamey et al (1990) these sounds carry the heaviest morphemic load of all English phonemes. Even if the consonant is audible, a person with a high frequency hearing loss may struggle to discriminate between different high frequency sounds.

In order to discriminate between consonants, one must be able to accurately perceive the acoustic cues that indicate the articulatory features of the phonemes in question. These cues can be split into three main categories: manner of articulation, place of articulation and voicing. Manner of articulation refers to the degree and type of constriction necessary to produce a given consonant. Cues as to the manner of articulation tend to be based on the degree and abruptness of attenuation of the sound and on the characteristics of the lower frequency formants. Place of articulation refers to the position where constriction takes place. Cues relating to place of articulation tend to be concentrated in the high frequencies and normally relate to the spectral characteristics of the second and third formants. Voicing refers to whether the vocal folds vibrate during production of the sound (voiced) or not (voiceless). Cues to voicing are normally provided by voice onset time, however, other cues such as relative intensity of a sound (where voiceless consonants tend to be more intense) may also be important when attempting to discriminate consonants on the basis of voicing. This means that individuals with a high frequency hearing loss are more likely to have difficulty discriminating between consonants that differ in place of articulation than in manner or voicing, due to the fact that cues to place of articulation tend to be high in frequency, whilst cues to manner of articulation of articulation and voicing tend to be either temporal or low frequency in nature. Further details of speech articulation and acoustics can be found in Miller and Nicely (1955) and Fry (1979).

Numerous studies have shown that the information provided by consonants is more useful than that provided by vowels for the perception of words and sentences (Fletcher, 1929; Miller, 1951; Owens et al, 1968). Thus, high frequency hearing losses generally result in a significant impairment in speech perception in both noise and quiet. In addition to the deficit in speech perception, many people with a high frequency hearing loss may also be unable to perceive many environmental sounds such as running water or birdsong, the energy of these sounds being primarily concentrated at the high frequency end of the spectrum.

2.4 Conventional hearing aids and the role of audibility

Conventional hearing aids primarily aim to restore audibility by increasing the level of the input signal so that it exceeds the listeners' hearing threshold at frequencies between 0.25 kHz and 4 kHz. The majority of hearing aids are not currently able to amplify sounds above 6 kHz, well below the 10 kHz bandwidth recommended by Boothroyd and Medwetsky (1992), who suggest that this is the necessary bandwidth to allow a /s/ sound, spoken by a female talker, to be heard in the majority of cases. Furthermore, conventional hearing aids are often unable to provide large amounts of gain at the high frequencies without acoustic feedback occurring. Whilst this may be an effective method of improving the perception of speech for many patients, a number of studies have indicated that simply increasing audibility is not always sufficient to improve the speech perception scores of people with a high frequency hearing loss (Ching et al, 1998; Hogan and Turner, 1998; Simpson et al, 2005). Hogan and Turner (1998) found that in some cases increasing high frequency audibility actually led to a decrease in the speech perception scores of listeners with a severe high frequency hearing loss. In addition, Hogan and Turner (1998) found that the audibility index, which is used to assess potential benefit from conventional hearing devices, greatly overpredicted the aided speech perception in quiet scores of individuals with a high frequency hearing loss.

2.5 Frequency lowering hearing aids

In order to provide optimal benefit from hearing devices, it is therefore necessary to investigate alternative signal processing strategies. One such alternative strategy for potentially improving the speech perception of individuals with a high frequency hearing loss involves altering the input signal so that high frequency components are manipulated to fall within the low frequencies where residual hearing is better. There are a number of approaches to achieving this objective, including frequency transposition, slow playback and non-linear frequency compression. A diagram showing the different methods of frequency lowering is shown in Figure 1, with a discussion of each method presented below.

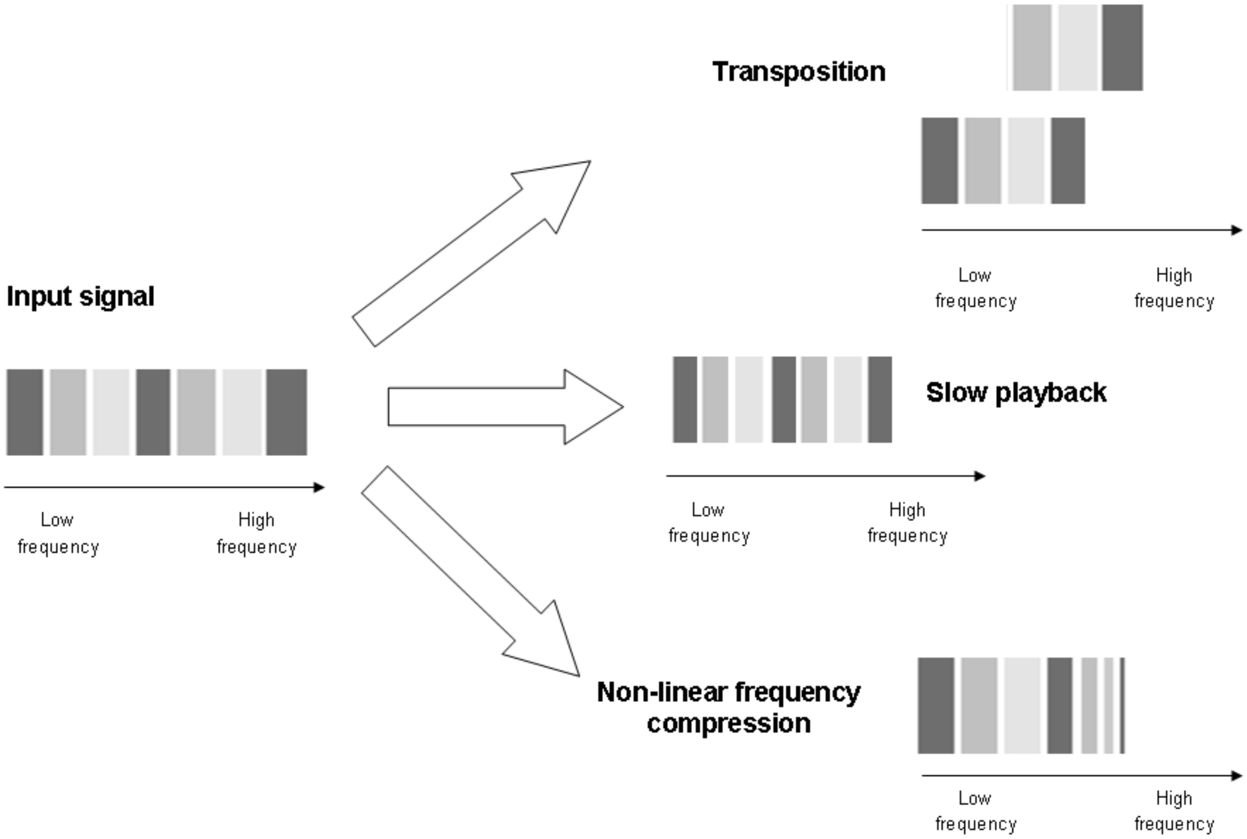

Figure 1. Schematic representation of different methods of frequency lowering.

2.5.1 Frequency transposition

Frequency transposition essentially involves moving components of a signal in a particular band of frequencies into a different frequency band. The earliest methods of frequency transposition were vocoder based and developed initially for use in the telecommunications industry (Dudley, 1939; Bogert, 1956). A vocoder is a device that converts acoustic signals into electrical signals then uses an algorithm to recreate the original acoustic signal in a reduced bandwidth. In order to achieve this, the original signal is passed through a series of band pass filters and the temporal envelope information is extracted. This temporal information is then used to modulate a lower frequency carrier signal, resulting in a lower frequency version of the original sound. The potential utility of the vocoder in improving the perception of people with a hearing impairment was first investigated by Ling and Druz (1967). Ling and Druz (1967) recognized that if one could reproduce intelligible speech using a reduced bandwidth, this technique may benefit those with a high frequency loss, for whom the bandwidth of audibility has essentially been reduced by the nature of their hearing loss.

Initial results with the Ling – Druz vocoder showed that speech discrimination scores with the device were not significantly different to those obtained with a conventional hearing aid (Ling and Druz, 1967). Frequency transposition using a vocoder was later investigated by Lippmann (1980) who reported that participants with a simulated high frequency hearing loss showed a 10% improvement in consonant discrimination and identification when speech was lowered in frequency using a vocoder when compared to unprocessed speech low pass filtered at 0.8 kHz. Lippman (1980) suggested that much of this improvement was due to an increased perception of affricate phonemes (such as /tʃ/ and /ʤ/), a finding that has been observed in many studies of frequency lowered speech. In agreement with Lippman (1980), Posen et al (1993) demonstrated that the perception of affricates, stops and fricatives was improved, by 6-9%, by vocoder based frequency lowering. However, Posen et al (1993) observed that this improvement came at the expense of the perception of nasals and semivowels which were degraded (by up to 12%) by frequency lowering and had not been investigated by Lippman (1980). It is worth noting that Posen’s (1993) results are based on data from only two participants.

Another early method of frequency lowering was reported by Johansson (1961) and later incorporated into a hearing aid manufactured by Oticon (the TP-72 device) in the early 1970s, making it the first commercially available frequency lowering hearing aid. Johansson (1961) developed a device in which high frequency speech components (3 – 6 kHz) were shifted and compressed into the lower frequencies (0 – 1.5 kHz) so as to maximize use of the listeners' residual hearing and, in theory, increase the identification and discrimination of high frequency speech sounds, particularly fricatives and voiceless consonants. In doing so, amplitude compression was applied to low frequency components whilst high frequency information was subject to both amplitude compression and frequency lowering.

A series of studies conducted by Johansson and Wedenberg (Johansson, 1961; Wedenberg, 1961; Johansson, 1966) reported improved speech discrimination and identification scores with the transposition device following a period of auditory training. However, the design and reporting of many of their experiments was biased in favour of the transposition device, due to factors such as training only with the transposition device and reporting detailed results for only some participants despite acknowledging that individual differences in performance were large. A more rigorously designed study, conducted by Ling (1968), found no evidence that the Johansson transposition device resulted in speech perception scores greater than those achieved with a conventional device.

The poor results found with the Johansson transposer may be due in part to the fact that the processing strategy employed in this device initially converted the high frequency components of the signal into broadband noise. In doing so, both the waveform envelope and frequency ratios of the signal were destroyed resulting in the obliteration of some cues and a resulting sound pattern very different to the original signal. Many listeners reported that the sound quality produced by this aid was poor and that fricatives sounded like 'different scratch sounds' (Wedenberg, 1961, p.658). The device was also unable to differentiate speech from noise resulting in the transposition of high frequency noise which may mask lower frequency speech sounds.

In order to improve the subjective quality of sounds lowered in frequency, Velmans (1973, 1974, 1975) described a device which transposed signals in the 4 to 8 kHz range downwards by a constant value of 4 kHz. Velmans referred to this device as FRED (frequency recoding device) and published a number of studies reporting a beneficial effect of transposition on speech production (with group mean improvements of up to 20% for high frequency phonemes; Velmans, 1973, 1975) and discrimination (with group mean improvements of up to 16%; Rees and Velmans, 1993) although individual differences were still large. The sound quality of the output signal produced by FRED was also compared to that produced by Johansson's (1961) transposition device and a significant subjective preference for FRED was observed. Listeners reported that the sound produced by FRED was much more natural sounding although 'shooshy' if too great a degree of transposition was applied (Velmans and Marcuson, 1983, p.23).

Currently, the only commercially available hearing aids incorporating a frequency transposition algorithm are produced by Widex (a hearing aid manufacturer based in Denmark). The Widex devices transpose sounds above an identified start frequency (which is set according to the configuration of the listener's audiogram) downwards by a constant one octave and mixes the transposed high frequency information with the original low and mid frequency components of the signal. As with FRED, in lowering the high frequencies by one octave, the frequency ratios of the transposed sound are maintained meaning that the transposed signal will have a more natural quality than that transposed using earlier signal processing methods. However, the issues of transposing high frequency noise and potentially masking important lower frequency speech components remain. There is currently only limited clinical data evaluating the benefit of the transposition scheme used in the Widex Inteo aid. Kuk et al (2007) report that group scores indicate a significant benefit for speech perception in quiet (with group mean improvements of up to 12%), however it is difficult to evaluate the results as individual data are not presented and speech in noise tests were not conducted. Furthermore, all fifteen participants in the study had aidable hearing up to at least 3 kHz meaning that relatively high cut-off frequencies could be used (3.2 – 4 kHz) which may affect the generalisability of these results to listeners with more severe high frequency losses. In interpreting the results of this study, it should be noted that the study was funded by Widex (for whom the lead author works) and was not peer reviewed prior to publication.

A further study (Korhonen and Kuk, 2008) evaluated the effect of frequency transposition on phoneme identification in nine normally hearing listeners with a simulated hearing loss (stimuli were low pass filtered above 1.6 kHz). The results showed that prior to auditory training, there was no significant difference between scores obtained with and without frequency transposition. However, after thirty minutes of self paced training (during which time the participant was able to listen to and compare different phonemes), mean scores with transposition enabled were 14.4% higher than those with the transposition setting disabled. Whilst this initially sounds impressive, it should be noted that participants only received training with the transposed sounds which may have biased the results in favour of transposition.

Recent research conducted by Robinson et al (2007, 2009) investigated the utility of frequency transposition for adults with high frequency cochlear dead regions. The experimental transposition scheme they developed worked by lowering frequencies from well within the dead region into an area up to 70% above its estimated edge frequency (Vickers et al, 2001, Baer et al, 2002). Initial experiments were laboratory based (Robinson et al, 2007) and showed promising results, reporting that five out of seven participants showed significant improvement, of up to 7%, in their perception of affricates when transposition was activated.

However, the results of the most recent study (Robinson et al, 2009), in which five participants with high frequency dead regions wore the experimental device for five weeks, were less impressive. In this study, performance on a number of speech perception tests was compared between transposition and a control condition, in which transposition was disabled. Tests included a nonsense syllable identification task and sentence in noise recognition task. Also included was a task measuring the ability to discriminate between singular and plural (those containing a word final /s/ or /z/) words. Testing was conducted at one, three and five weeks after fitting. No significant group improvement over time was observed in either condition. Throughout the testing period, participants were encouraged to wear the hearing aid as much as possible, and to use the transposition and control settings equally. The results showed no significant difference between the mean scores obtained in the transposition and control conditions in either the speech in noise (less than 0.5 dB difference) or plural discrimination tasks (with a difference of approximately 0.5 d'). Results of the nonsense syllable identification task showed that one participant received significant benefit from transposition, whilst two participants showed a significant decrease in performance when compared to the control condition. The group mean scores for the nonsense syllable test obtained with frequency transposition was within 1% of the score obtained with conventional processing. Subjective preferences were also obtained, revealing that no participant favoured the transposition over the control condition.

There are a number of methodological issues that may explain the poor results with transposition in this study. The fact that participants were encouraged to use both the control and transposition settings at home may have meant that they did not acclimatise to frequency transposition effectively. It should be noted that the average time participants reported using the transposition setting was less than five hours a day (with similar results using the control setting), with three participants reporting using the transposition setting for less than three hours a day. Furthermore, at the beginning of each session, participants received training on each of the tests whilst wearing their own hearing aids. It is unclear whether the same stimuli were used in the test and training sessions, or indeed what form the training took. It is, however, possible that this training biased the results in favour of the control condition, as processing in the participants' own hearing aids would have been much more similar to the control condition than the transposition condition. Robinson et al (2009) suggest that the poorer results in the field study as compared to their earlier laboratory based study (Robinson et al, 2007) may be due to differences in the amplification provided. In the field study, the amplification factor had to be reduced as participants complained that some sounds that were high in both intensity and frequency were uncomfortably loud when transposition was enabled. This had not been an issue in the earlier study as the stimuli were pre-recorded and thus the level of presentation was carefully controlled. The modest sample sizes used in these studies may also have influenced the generalisability of the results.

Despite the mixed findings, the research conducted by Robinson et al (2007, 2009) demonstrate the potential benefit of frequency transposition. Furthermore, the results highlight the need to consider the possibility of dead regions when fitting a frequency lowering hearing aid. Vinay and Moore (2007) found that steeply sloping hearing loss and/or an absolute threshold of greater than 70dBHLare associated with the occurrence of dead regions. It is possible that many of the participants in previous studies of frequency lowering, particularly those with severe to profound high frequency losses or steeply sloping audiograms, may have had high frequency dead regions. The presence of dead regions may therefore have affected the efficacy of frequency lowering for these participants as processed stimuli may still fall at frequencies over 70 to 100 % above the estimated lower edge of the dead region and may have thus provided limited benefit (Vickers et al, 2001, Baer et al, 2002). A study conducted by Vickers et al (2009) reported promising results of transposing (and compressing) high frequency information selectively into the area up to 70% above the edge frequency of a dead region. The results suggest that transposition of frequencies into this region leads to improved consonant recognition scores when compared to simply ensuring audibility of the frequencies that fall in that region. It should be noted that this study was conducted on normally-hearing listeners with simulated high frequency dead regions, thus whether these findings apply to hearing-impaired listeners has yet to be determined.

2.5.2 Slow playback

In order to attempt to overcome some of the problems associated with frequency transposition, researchers began to look for other methods of processing speech such that high frequencies would still be transposed into the lower frequencies whilst at the same time maintaining the spectral structure shown to be important for the perception of vowels (Nearey, 1989). One very simple method of achieving this is to simply play the signal back at a reduced speed thus lowering all frequencies proportionately and maintaining the spectral relationship between the different speech components. Unlike speech processed by a frequency transposition aid, the slow playback method of signal processing does not result in overlapping high and low frequency information since all frequencies present in the input signal are lowered. Essentially, this method of processing is an example of linear frequency compression, albeit in the temporal domain.

The first study to directly investigate the effect of slow playback on speech perception in listeners with a high frequency hearing loss was conducted by Bennett and Byers (1967). The results of the laboratory based study showed that intelligibility scores were greatest for eleven of the fifteen participants when speech was played at 80% of the original speed (whereby a lower speed results in an output signal lower in pitch). However, it is reported that as a group, participants preferred the slowest speeds (60 and 70% of the original speed) in terms of sound quality despite the fact that intelligibility scores in these conditions were lower than with normal speech or 80% speed.

Despite the speech perception improvements noted with this method of signal processing, a number of practical limitations prevented the incorporation of such a processing strategy into hearing aids. Most notable being that in order to be beneficial in perceiving live speech, the processed speech would need to be time compressed and edited after processing to maintain synchrony between the speaker and the output signal. Such technology was not available until the 1990s with the advent of segment deletion, whereby short segments of the signal are deleted at regular intervals. The remaining segments of the signal are then played at a lower speed, time compressed and sent to the receiver of the aid fast enough to maintain synchronicity with the speaker in perceptual real time. It is possible however that segment deletion may lead to distortion and may also result in the deletion of cues important for the accurate perception of speech.

Frequency lowering using the slow playback method has been available commercially since the mid 1990s in a series of hearing aids developed by AVR - Sonovation, the most recent of which are the Nano Xp, ImpaCt Xp and Logicom Xp aids. All the AVR - Sonovation hearing devices use the same slow playback frequency lowering algorithm which allows separate compression ratios to be programmed for voiced and voiceless sounds. Similarly to the Widex Inteo, the compression settings are only enabled when the input signal is dominated by high frequency components, although in the AVR aids all frequencies present in the selected segment are compressed. The fact that frequency lowering is only selectively enabled means that sounds dominated by low and mid frequency components (such as vowels) are not affected by the signal processing strategy. However, this method of frequency lowering may result in speech that sounds unnatural. This is due in part to the selective frequency lowering strategy employed which has an activation time of 2 – 4 msecs. It is possible that this may lead to distortion and desynchronisation between the speaker and the output signal. Another factor that may contribute to an unnatural sound quality is that when frequency lowering is activated, all frequencies are shifted downwards, meaning that the output signal will sound distinctly lower in frequency than surrounding segments of speech that have not been processed.

A number of studies have assessed the benefit of these aids with mixed results. Parent et al (1997) reported that two out of four participants with a severe to profound high frequency hearing loss demonstrated significantly better performance in a variety of speech perception tests with the AVR TranSonic (an early slow playback hearing aid) as opposed to a conventional device, thus highlighting both the potential benefit of frequency lowering and also the need to evaluate benefit individually for each listener. This notion was supported by the results of McDermott et al (1999) who reported that two out of five participants with severe to profound high frequency losses obtained a statistically significant benefit from frequency lowering (using the TranSonic device) in a test of speech perception in quiet(with group mean improvements of up to 10%). These results remained statistically significant once differences in the amplification characteristics of the conventional and frequency lowering devices had been taken into account.

However, in a later study of the AVR ImpaCt hearing aid reported by McDermott and Knight (2001), no significant benefit of frequency lowering was observed in three participants with moderate to profound high frequency losses. Notable, however, is the fact that whilst no significant difference in speech perception in quiet scores was observed, scores of speech perception in noise, which had not been previously investigated, revealed that frequency lowering actually resulted in a decrease in scores (of 8% at the group level) for all participants. It is possible that the lack of benefit of frequency lowering for speech perception in quiet observed in McDermott and Knight's (2001) study may be due in part to the small sample used (n = 3) which, given the well documented individual differences observed with benefit from frequency lowering devices, may have significantly affected the results. The decrease in scores of speech perception in noise cannot be explained solely by the small sample used, and indicates in contrast to earlier studies, that frequency lowering may actually have a detrimental effect on speech perception for some listeners.

McDermott and Knight (2001) proposed that the negative effect of frequency lowering on perception in noise may be related to high frequency distortion introduced by the lowering method employed in the ImpaCt aid. This suggests that participants may have benefitted from more extensive frequency lowering, however, given the distortion introduced, subjectively listeners disliked these settings. It is also possible that the results of their study may have been affected by the characteristics of the listeners' hearing loss, specifically participants in this study had severely sloping losses.

2.5.3 Non-linear frequency compression

In addition to slow playback and frequency transposition, a further method of frequency lowering, that is now available commercially in a range of hearing aids manufactured by Phonak, is non-linear frequency compression. Similarly to the slow playback method, non-linear frequency compression compresses the high frequency component of the incoming signal into a narrower bandwidth. In doing so, the high frequency elements of the incoming signal are compressed into a lower frequency range in order to maximise use of residual low frequency hearing in individuals with a high frequency loss. Whereas the slow playback method essentially results in proportional frequency shifting (albeit in the temporal domain), the spectral relationship between high frequency components is maintained, non-linear frequency compression subjects components above a programmable cut-off point to higher levels of compression with increasing frequency. Further technical details of the NLFC algorithm can be found in Simpson et al. (2005) and in the registered patent (Phonak, 2009).

The rationale for implementing a non-linear frequency compression scheme is to maximize the availability of high frequency cues in order to facilitate better perception of high frequency consonants and environmental sounds, whilst leaving the mid and low frequency information, important for the perception of vowels and mid frequency consonants, relatively unchanged by the processing scheme. Unlike slow playback schemes, high frequency signals processed by the non-linear frequency compression scheme are not mixed with the low and mid frequency components of the signal.

According to Plomp (1994), frequency lowering schemes that leave the low and mid frequency components of the signal unaffected are preferable as the utility of these cues is not under question whilst the benefit of artificially lowered cues is. Thus, non-linear frequency compression theoretically ensures that low and mid frequency components of the signal that the listener may already successfully use in perceiving speech are not affected, whilst only the high frequency cues that the listener may be unable to perceive or utilise successfully with a conventional hearing aid are altered. In doing so however, this means that the spectral relationship between high frequency speech components is not preserved.

To date, there have been only a few clinical trials investigating the potential benefit of non-linear frequency compression, the first of which was conducted by Simpson et al (2005). 17 experienced hearing aid users with moderate to severe sloping hearing losses wore prototype non-linear frequency compression hearing aids for four to six weeks, during which time they were encouraged to wear the devices as much as possible. Twelve of the participants were fitted bilaterally, whilst five participants were fitted monaurally (due to the loss being too severe in one ear for a successful hearing aid fitting).

Testing was conducted with the frequency compression devices towards the end of the trial period. After this period, participants wore their own hearing aids for two weeks and were retested with these devices. Testing consisted of a monosyllabic word recognition task (in quiet), in which the stimuli were recorded using a single female speaker. The results showed that eight of the seventeen participants obtained statistically significant increases in their performance with frequency compression when compared to the control condition. Of the remaining participants, eight showed no significant difference in scores, whilst one participant performed significantly better with their own hearing aid than with the frequency compression device. A subsequent study with a subset of the original participants confirmed that these differences were not the result of possible variations in the amplification characteristics of the participants' own hearing aids and the frequency compression devices. An analysis at the group level showed that frequency compression significantly improved detection of fricative and affricate consonants (with a group mean improvement of approximately 11%) without impairing the perception of vowels and mid frequency consonants.

A second study conducted by Simpson at al. (2006) investigated the effect of frequency compression on the perception of seven adult hearing aid users with steeply sloping high frequency losses (participants in the earlier study had gently sloping losses). Again, the experimental devices were worn for four to six weeks and tested was conducted towards the end of the trial period. In addition to the monosyllabic word recognition task, medial consonant recognition (both in quiet and with a male speaker) and sentence recognition in noise (with a female speaker) tests were also conducted. Results showed that there was no significant difference in group scores with and without frequency transposition in either of the tests of speech in quiet, with the group mean scores showing that frequency compression lead to a deficit in performance of 2%

in the consonant recognition task and of 6% in the monosyllabic word recognition task. Confusion matrices were analysed indicating that the processing scheme seemed to lead to increased confusions between /s/ and /ʃ/ (with /s/ being mistakenly labelled as /ʃ/) suggesting that the increased perception of some phonemes may come at the expense of others. It is possible, however, that a period of training focussing on the discrimination of consonants that appear to be confused in frequency compressed speech may further increase speech perception scores in participants that appeared to obtain overall benefit from the frequency compression device. The results may also have been affected by the fact that three of the seven participants in this study had not used hearing aids previously, whereas all participants in the previous study (Simpson et al, 2005) were experienced hearing aid users.

The results of the sentence in noise test revealed that only one participant obtained significant benefit (of 6 dB) from frequency compression (it is worth noting that only five participants took part in this part of the experiment). Subjective opinion was also assessed using the Abbreviated Profile of Hearing Aid Benefit questionnaire (APHAB, Cox and Alexander, 1995), the results of which showed that only one participant preferred the frequency compression aid. It should be noted that this person did not actually obtain any objective benefit from the device (at least on the tests administered).

A more recent study to investigate the effect of non-linear frequency compression on perception was conducted by Glista et al (2009). A total of 24 participants with moderate to profound sloping high frequency hearing losses took part in this study. Of the 24 participants, 13 were adults and 11 were children. Participants were provided with a non-linear frequency compression hearing aid and asked to use it as much as possible in their everyday lives. Performance on a number of speech perception tests in quiet, including detection of /s/ and /ʃ/ and a series of phoneme recognition tasks was assessed. In order to compare performance with conventional processing to that with frequency compression enabled, a modified withdrawal design was employed. This meant that the trial was essentially split into three parts. Initially participants wore the hearing aid with the frequency compression disabled for a number of weeks (2 – 12 weeks, mean: 4.17 weeks), after which the experimental tests were administered to familiarise participants with the procedures (results were not analysed).

During the second stage of the trial, the frequency compression setting was enabled and participants again wore the devices for a number of weeks (3 weeks to 1.3 years, mean: 10.75 weeks). All tests were then re-administered. For the final part of the trial, the hearing aids were programmed with both the conventional and frequency compression settings and participants were able to switch between them as preferred. This part of the trial lasted between 2 weeks and 5 months, following which the tests were administered again and performance with conventional processing only was assessed.

The results showed that group scores in the consonant and plural recognition tasks were significantly higher when frequency compression was enabled than with conventional processing, whilst vowel recognition was not significantly affected by the processing strategy. The individual results of the adult participants revealed that one participant showed a significant increase in consonant recognition, four demonstrated a significant increase in plural recognition and one participant showed a significant decrease in vowel recognition when frequency compression was enabled. It is likely that the decrease in vowel perception scores observed in the aforementioned participant was due to the very low cut-off frequency used in their case (1.5 kHz). At a group level, frequency compression led to improvements in the order of 5 RAU (rationalised arcsine units) in the consonant recognition task and 10 RAU in the plural recognition task. Frequency compression led to a small decrease (of 3 RAU) in performance in the vowel recognition task. An inspection of the individual results of the child participants showed that seven showed a significant increase in plural recognition and five showed significantly improved consonant recognition scores when frequency compression was enabled. At a group level, frequency compression led to improvements in performance of 5 RAU in the consonant recognition task, 20 RAU in the plural recognition task and 1 RAU in the vowel recognition task.

Group scores in the speech detection test revealed that the mean threshold at which the stimulus could be detected 50% of the time was significantly lower (i.e. better) when frequency compression was enabled than when conventional processing alone was used. Interestingly, the mean threshold for the detection of /s/ was found to be significantly lower than the threshold for /ʃ/. Individual results revealed that ten participants received a significant benefit from frequency compression, whilst two participants performed significantly better with the conventional processing strategy.

Self reported preferences were also obtained, revealing that two of the adult participants favoured the frequency compression setting along with seven of the child participants. Only three participants preferred the conventional setting, the remainder showing no preference for either processing strategy.

In addition to assessing the effect of processing strategy on the scores obtained in the speech perception tests, a number of possible predictors of benefit were also assessed. Specifically, the effect of age group (whether adult or child), the magnitude of the high frequency loss and the audiometric drop-off frequency were investigated as possible predictors of benefit. The results of a multiple regression analysis showed that none of these factors predicted performance on the consonant recognition task, whilst all three predicted performance in the plural recognition task. Regarding performance in the speech sound detection test, both audiometric drop off frequency (the point at which the threshold in the better ear was 70 dB HL or worse) and the magnitude of high frequency hearing loss were retained as significant predictors. Finally, self reported preference was significantly predicted by age group alone. Together these results suggest that children with greater high frequency losses and higher audiometric drop off frequencies were the most likely to receive a benefit from frequency compression.

To summarise, the results of the study showed that five out of 13 adults and seven out of 11 children showed a significant speech perception benefit from frequency compression on at least one measure (Glista et al, 2009). This may be compared to the earlier results reported by Simpson et al (2005, 2006), who found that 8 out of 17 adults with moderate-to-severe losses and none of the seven participants with steeply sloping losses obtained a significant benefit from frequency compression. Indeed, frequency compression led to a small decrease in performance for the majority of listeners in Simpson et al’s 2006 study.

There are, however, a number of methodological issues which may influence the interpretation of these results. Much of the benefit reported related to the results in the speech sound detection and the plural recognition tasks. One would expect thresholds in the speech sound detection test to be lower with frequency compression. This is due to the fact that the high frequency energy that dominates /s/ and /ʃ/ sounds is compressed into a lower frequency region, in which it is easier to provide a sufficient level of audibility. This is due in part to the configuration of the participants’ losses and also due to technical limitations of hearing aids (in that they are unable to provide amplification at high frequencies). It should be noted that the ability to detect sounds is not the same as being able to discriminate between them or identify them correctly.

This argument may also be applied to the results of the plural recognition task which may be viewed as more of a detection task than a recognition task. This task was very similar to the /s/ detection task used by Robinson et al (2007, 2009) in their work on frequency transposition. Specifically, the participant was presented with a word in either its singular or plural form and then had to determine which it was. Again, one may argue that the ability to determine that the word was plural may just be indicative that they were able to detect an additional phoneme, not that they were able to correctly recognize it.

Another issue of interest is the discrepancy between the results of Simpson et al (2006) and Glista et al (2009). Simpson et al (2006) found no benefit of frequency compression to participants with a steeply sloping hearing loss, with frequency compression leading to a small decrease in speech perception scores for many of the participants in this study. However, Glista et al (2009) found that participants with such a loss were the most likely to receive benefit from a frequency compression hearing aid. There are a number of possible reasons for this difference in findings. One such explanation is that it may have been due to differences in the hearing aids used in the two studies, those used by Glista et al (2009) being more technologically advanced than those used by Simpson et al (2006). The difference may also have been related to the tests used or to the duration of time that the frequency compression aid was used, which was much longer in the later study. Another factor in which the studies differed was in their methods of determining the frequency compression settings. Specifically, when fitting the hearing aids, Glista et al (2009) based their NLFC settings on those prescribed by the manufacturer (Phonak AG) but adjusted these settings to ensure that participants were able to correctly identify /s/ and /ʃ/ when frequency compression was enabled. If the participant was unable to identify these phonemes correctly, it was assumed that the frequency compression setting was too high and the compression ratio was reduced accordingly. Thus, the results of the different studies may not be directly comparable.

More recently, Wolfe et al (2010, 2011) have reported that the use of frequency compression led to significant improvements in the perception of some high frequency speech sounds in a group of 15 children (aged 5-13 years) with moderate hearing loss. However, only group mean scores are presented so it is not possible to determine the degree of variation in benefit from frequency compression between different listeners.

Taken together, the results of the clinical trials mentioned above demonstrate that frequency compression may provide a significant perceptual benefit to some patients. However, the issue of how best to determine which patients are more likely to gain benefit remains controversial.

2.6 Predictors of benefit from hearing aid use

The results of studies evaluating the various frequency lowering schemes available indicate mixed results, whilst no frequency lowering scheme has been shown to be uniformly beneficial for all listeners. Discrepancies in the findings of different studies of frequency lowering devices mean that it is very difficult to compare the results of different experiments and is thus difficult to assess the potential benefit of different frequency lowering aids for listeners with a high frequency hearing loss.

Individual differences play a huge role in determining the success of a hearing aid fitting, be that in terms of speech perception scores, hearing aid usage or satisfaction (see for example, Humes, 2007). Determining the specific nature of the individual differences that relate to, and may be predictive of, hearing aid outcome has been the subject of much research. As such, a number of factors have been investigated as possible predictors of hearing aid outcome. These factors can be broadly split into 3 categories: audiological, cognitive and psycho-social. A further factor that is often associated with hearing aid outcome is age. It is probable that the contribution of age to hearing aid outcome is down to its relationship with cognitive, psycho-social and audiological factors. As such, age as a predictor will be discussed in relation to these factors rather than as an independent contributor of variance in hearing aid outcome.

Psychosocial factors affecting hearing aid outcome may include gender/sex (Cox et al, 1999), personality traits (Gatehouse, 1994; Saunders and Cienkowski, 1996) and social support and education (Garstecki and Erler, 1998). Much of the research conducted into psychosocial factors has focussed on their role in predicting hearing aid uptake, adherence and satisfaction. Whilst it is important to understand why some people choose to seek, and to continue, treatment for their hearing problems whilst others do not, this is outside the remit of the current review. As such, the rest of this section will be devoted to discussing audiological and cognitive predictors of speech perception following amplification. Potential predictors of benefit from frequency compression aids will then be discussed.

The contribution of audiological factors as a predictor of speech perception outcomes following amplification is normally limited to a discussion of hearing thresholds. However, a number of other variables may also fall within this category. Specifically, duration of deafness (or auditory deprivation), previous hearing aid use, or the presence of cochlear dead regions. There is evidence to show that the level of background noise the listener is willing to tolerate, or Acceptable Noise Level, (Nabalek et al, 1991) is a strong predictor of hearing aid use, which in turn is correlated with improvements in aided speech perception scores (Nabalek et al, 2006). However, as all listeners in the present study were experienced hearing aid users and were asked to wear their devices as often as possible, this will not be investigated as a predictor.

Unsurprisingly, most studies seeking to explain individual differences in aided speech perception have identified differences in hearing thresholds as the main source of variance (see for example, Humes, 2007; Tun and Wingfield, 1999). However, the influence of hearing thresholds on speech perception outcome seems to be affected by the type of speech test administered. Specifically, audiometric thresholds (with poorer thresholds associated with poorer performance) tend to account for more variance in relatively easy tasks (such as identifying words in a quiet background) than for more complex tests (such as sentence in noise recognition) (Humes, 2007). This is supported by the finding that predictions of the speech in noise recognition scores of older adults, based on audiometric factors, normally predict levels of performance greater than those observed, whilst speech in quiet predictions are, as a rule, much more accurate (Hargus and Gordon-Salant, 1995).

Thus, once a task becomes more demanding, the influence of audibility on performance is diminished and the influence of cognitive factors becomes more pronounced. This stands to reason given that in order to perceive any sound, the signal must first be detected by the ear, transferred successfully to the brain and then interpreted using cognitive skills. If the signal is relatively intact upon reaching the brain (and not degraded to begin with), fewer cognitive resources are needed to decipher the signal. If, however, the signal is degraded in some way, be it via a noisy background, an impaired auditory system or a hearing aid processor, more cognitive resources are required to make sense of the degraded signal.

One way of investigating the influence of cognition on speech perception is to investigate the amount of benefit obtained by the provision of contextual cues. There is evidence to show that older listeners, with or without hearing loss, continue to gain benefit from contextual information, particularly when speech is degraded in some way (Pichora-Fuller, 2008; Aydelott et al, 2011). In some cases, older listeners get more benefit than younger listeners from contextual information (Pichora-Fuller et al, 1995). It has been suggested that the increased reliance of older listeners on contextual information to understand degraded speech, may be a compensatory response to an age related decline in perceptual abilities (Schneider et al, 2002; Aydelott et al, 2011).

In order to make use of contextual information or degraded perceptual cues, one must have the capacity to allocate sufficient cognitive resources to the task at hand. This process is likely to involve a number of specific cognitive abilities, but seems to be most accurately indexed using complex working memory span tests. Working memory (Baddeley and Hitch, 1974) is a limited capacity system used to temporarily store and manipulate incoming information and, to an extent, to allocate attentional resources accordingly. Working memory span tasks such as the reading span test (Daneman and Carpenter, 1980; Rönnberg et al, 1989) consist of two parts: a processing element, and a storage element. In the reading span test, participants are presented with a sequence of sentences in blocks of 3-6. Immediately after reading each sentence, the participant must state whether the sentence made sense or not (processing component). At the end of each block, participants are asked to recall either the first or last word of every sentence in that group (storage component). The percentage of words correctly recalled is then calculated. In a review of studies investigating the relationship between cognition and speech in noise perception, measures of working memory span were found to be the most reliable predictor of test performance once the influence of audibility had been accounted for (Akeroyd, 2008). Lunner (2003), for example, found that, after controlling for the effects of audibility and age, reading span test score was correlated with both aided and unaided recognition of speech in noise.

Whilst it is generally agreed that cognitive factors are more predictive of speech perception performance when the stimulus is degraded in some way, there is some evidence to suggest that the degree to which working memory span predicts speech recognition may be dependent on the degree to which the stimuli differs from phonological representations stored in the long term memory, rather than simply the degradation itself. Rönnberg and colleagues (2003, 2008) proposed a working memory model for ease of language understanding. The model suggests that as long as listening conditions are favourable, speech stimuli are implicitly processed and compared to representations stored in the long term memory. If listening conditions are compromised in some way, be it via noise, hearing loss or hearing aid processing, a mismatch may occur between the stimuli being presented and the representation stored in the long term memory. The model suggests that when such a mismatch occurs, explicit storage and processing resources are required and listening becomes more effortful (Rudner and Rönnberg, 2008). The reading span test provides an index of the explicit processing and storage capacities available to the listener. Therefore, in situations where a degraded signal has led to a mismatch between phonological representations in the long term memory and the percept of the degraded stimulus, it is predicted that working memory capacity will correlate with speech perception.

Rudner et al (2008) found that in a sample of 102 experienced hearing aid users, working memory span scores did indeed show greater correlation with aided speech in noise perception scores in situations where a mismatch between speech representations in the long term memory and the speech stimuli was created. The mismatch was created either by altering the compression release time characteristics of the listeners' hearing aids such that the input signal differed from the sound the listener would normally receive. When listeners were tested with a novel compression release time (mismatch condition), speech scores were more highly correlated with reading span test scores than when they were tested using the compression release time to which they were accustomed (match condition).

These results are of particular interest as they demonstrate that the characteristics of the signal processing strategy used in hearing aids can affect the relationship between cognition and speech in noise perception. Lunner (2003) also suggested that it is important to note that the hearing aid processing method may in itself be cognitively demanding. This is in agreement with the results reported by Gatehouse et al (2006) and

Cox and Xu (2010) who showed that listeners with greater cognitive skills were more likely to benefit from fast acting compression than those with poorer cognitive performance.

Therefore, whilst there is some evidence that cognition mediates benefit from different amplitude compression settings, the relationship between frequency compression and cognition is yet to be explored. The implication from the mismatch theory is that the more the hearing aid processing causes the signal to differ from the representation stored in the long term memory, the greater the predictive role of cognitive ability. It may be, therefore, that due to the differences introduced by frequency compression, cognitive factors may prove to be more predictive of speech in noise recognition than is the case with conventional hearing aid processing.

Currently, predictors of benefit from frequency compression remain elusive, although work by Glista et al (2009) suggests that age (adult versus child) and severity/configuration of hearing loss may predict performance on some, but not all, speech perception tasks. The results suggested that children and those were poorer high frequency thresholds were most likely to benefit from NLFC. However, it is possible that this reported age effect may be due to differences in the adult and paediatric prescriptions used to fit the frequency compression hearing aids (the paediatric targets recommended stronger frequency compression settings when compared to the adult targets). One may also infer an effect of severity and/or configuration of loss from the differing results reported in the studies by Simpson et al (2005, 2006). In the earlier study, some participants with moderately sloping losses obtained significant benefit from frequency compression whilst in the later study, none of the participants with severely sloping losses showed any benefit. Whilst these differences may be evidence of a predictive effect of hearing loss on outcome with frequency compression aids, it is possible that these differences were influenced by the fact that all listeners in the 2005 study were experienced hearing aid users whilst three of the seven participants in the 2006 study were new hearing aid users. Furthermore, the studies used prototype frequency compression hearing aids as opposed to the commercially available aids used by Glista et al (2009).

It is important to remember that there are likely to be further factors which have not yet been explored that may influence speech in noise performance (Houtgast and Festen, 2008)

2.7 Acclimatisation to hearing aid use

Auditory acclimatisation was defined by Arlinger et al (1996, p.S87) as ‘a systematic change in auditory performance with time, linked to a change in the acoustic information available to the listener. It involves an improvement over time that cannot be attributed purely to task, procedural or training effects.’ Some of the earliest studies to investigate auditory acclimatisation to amplification were conducted by Gatehouse and colleagues in the late 1980s and 1990s and focussed on monaurally aided adult listeners with bilateral sensorineural hearing loss (see Munro, 2008 for a review of this topic). Gatehouse (1989) measured unaided speech recognition in noise scores in each of the participants’ ears and found that when sounds were presented at 95 dB SPL, scores from the normally aided ear were better whilst at a presentation level of 65 dB SPL, the scores from the normally unaided ear were better. Gatehouse suggested that this was evidence of the ears having adapted to the presentation level to which they had been accustomed to receiving. Subsequent studies investigated the effect of acclimatisation on intensity discrimination (Robinson and Gatehouse, 1995; 1996), again in monaurally aided listeners, and found differential changes in performance between the aided and unaided ears, consistent with the effect of amplification.

The effect of acclimatisation on the speech perception scores in monaurally fitted listeners with sensorineural hearing loss was further investigated by Munro and Lutman (2003). The results of the study showed that speech perception scores 12 weeks post monaural fitting of a hearing aid were significantly better (with group mean improvements of 4%) than those obtained within the first week of fitting. This effect was observed only in the ear that had been fitted with a hearing aid. Furthermore, the effect of acclimatisation was only significant for higher presentation levels, consistent with the results obtained by Robinson and Gatehouse (1995, 1996).

Acclimatisation in the case of binaurally fitted hearing aids was investigated by Philibert et al (2005). In this study of new hearing aid users, unaided performance on an intensity discrimination and a loudness scaling task was measured at four stages (pre fitting, and one, three and six months post fitting). The results showed that the acclimatisation effect was greatest for stimuli that were either high in frequency or intensity. That is, changes were observed only in relation to the stimuli that were most affected by amplification.

Whilst the results of the aforementioned studies are all consistent with the notion of auditory acclimatisation, some studies have failed to find any significant evidence for this effect. Saunders and Cienkowski (1997) tested 24 new binaural hearing aid users on speech perception in backgrounds of both quiet and noise. Participants were tested on the day of fitting and 30, 60 and 90 days post fitting. A group of 24 experienced binaural hearing aid users were tested at the same intervals and served as a control group. The results showed evidence of small improvements in the performance of both groups on both tests. These improvements did not reach statistical significance and more listeners showed no evidence of change over time in performance than did. However, the lack of evidence of acclimatisation observed in this study may relate to the fact that the test stimuli used were presented at a comfortable listening level and performance on the tests administered did not rely heavily on high frequency information. Thus, the authors note that it is possible that acclimatisation did occur, but for high frequency information only.

To date, there has been very little research on acclimatisation to frequency compression hearing aids. Previous studies of frequency compression have always provided an acclimatisation period prior to speech perception testing. However, in most studies, baseline tests were not conducted (see for example; Simpson et al, 2005; 2006; Glista et al, 2009).

Whilst there has not yet been an investigation into acclimatisation to frequency compression hearing aids in adult listeners, there has been some research of acclimatisation to frequency compression hearing aids in paediatric hearing aid users. Wolfe et al (2010) provided fifteen children, aged 5-13 years old, with moderate to moderately severe hearing losses, with bilateral frequency compression hearing aids. A within subjects design was employed, in which the children wore the hearing aids with frequency compression enabled for six weeks and with frequency compression disabled for six weeks. Half of the participants had the frequency compression enabled for the first six weeks, whilst the remaining participants had the frequency compression disabled for the first six weeks of the study. After each six week period, aided thresholds and performance on a number of speech tests were assessed.

Speech perception in quiet was assessed using the University of Western Ontario (UWO) plural test and the Phonak logatom test (Boretzki and Kegel, 2009). The UWO plural test is an open set word recognition test consisting of 15 words in both their singular and plural forms spoken by a female talker. The test allows for the assessment of how well a listener can hear the high frequency information required to perceive the presence of a /s/ or /z/ at the end of a word. The Phonak logatom test is an adaptive test that measures the threshold (in dB SPL) for the correct identification of a stimulus 50% of the time. The stimuli used are VCV syllables in which the vowel remains constant, whilst one of six high frequency consonants are presented. Speech recognition in noise was assessed by measuring the SNR needed to get 50% correct on the Bamford-Kowal-Bench speech in noise test (BKB-SIN, Bench et al, 1979).

The group mean results showed that aided thresholds for high frequency speech and pure tone stimuli were significantly reduced (and therefore, better) when frequency compression was enabled. Performance on the UWO plural test was also significantly better, with a group mean increase in performance of 16%, when frequency compression was enabled compared to when using conventional processing alone. Frequency compression also led to significantly reduced thresholds for two of the six stimuli tested in the Phonak Logatom test (/asa/ and /ada/). However, frequency compression had no significant effect on scores in the BKB-SIN test, with frequency compression leading to an SNR advantage of only 0.7 dB.

Participants were then re-tested on all speech measures after 6 months of using frequency compression hearing aids. The results of this portion of the study are presented in Wolfe et al (2011). Neither the aided thresholds nor scores on the UWO test obtained after 6 months of using frequency compression hearing aids differed significantly from those obtained after 6 weeks of frequency compression hearing aid use. Thresholds for one of the VCV stimuli used in the Phonak logatom test (/ada/) were significantly lower after 6 months of frequency compression use than after 6 weeks of wearing frequency compression hearing aids. Whilst scores on the BKB-SIN test did not differ significantly between 6 weeks and 6 months of frequency compression use (with an improvement of only 0.8 dB), the scores after 6 months were significantly better than those obtained after 6 weeks of hearing aid use with frequency compression disabled. This was also the case with one of the stimuli (/ata/) from the Phonak logatom test.

The results of Wolfe et al (2010, 2011) provide some evidence of acclimatisation to frequency compressed speech, albeit limited. It is important to note that baseline measures were not obtained immediately after fitting so it is impossible to ascertain from the data how much acclimatisation may have taken place within the initial six weeks. A further issue that may influence the validity of these results stems from the fact that there was no control group for the measurements taken after 6 months of frequency compression use. It is possible, therefore, that the differences in scores may be down to maturational effects or to acclimatisation to other features of the hearing aids, rather than to frequency compression specifically. In particular, maturational effects may have influenced scores on the BKB-SIN as the stimuli used contain large amounts of contextual information, which a child may be better able to use as they age and their receptive vocabulary improves. Furthermore, no individual data is presented, so the level of individual differences in amount of acclimatisation to frequency compression cannot be assessed.

2.8 Categorical perception and the learning of novel phonemic boundaries

In order to examine the effect of acclimatisation and training on the perception of specific phonemes, one may turn to studies of learning in the context of categorical perception. Categorical perception (Liberman et al, 1957) refers to the perception of stimuli that change gradually along a continuum for example, on the basis of voice onset time, as belonging to discrete categories, as opposed to being perceived continuously. Liberman and colleagues originally believed that categorical perception was specific to speech and was related to speech production. However, numerous studies have now shown that this is too narrow a definition with evidence of categorical perception being reported for non-speech stimuli (see for example, Raz and Brandi, 1977) and in research on visual and spatial perception (see for example, Gavault et al, 2004). It has also been shown that the perception of vowels is much less categorical than the perception of consonants (see for example, Schouten and van Hessen, 1992) The definition of categorical perception has therefore evolved over time with Harnad

(1987) suggesting that a more modern understanding of categorical perception is that it occurs when within-category differences (differences falling within a spectrum that would be identified as one category) are compressed and between-category differences (differences falling within a spectrum that crosses a category boundary) are separated relative to a baseline measure. The baseline measure may be either the objective physical difference between stimuli, or in the case of learned categorical perception, perceived discriminability prior to training (Harnad, 1987).

A number of studies have highlighted the effects of linguistic experience on the perception of phonemic boundaries. Research suggests that infants up to the age of six months are able to discriminate between both phonemic contrasts that are present in their home language and those that are not (see for example, Eimas, 1974, Best et al, 1988), however, by the age of 12 months, the ability to discriminate between phonemic contrasts not present in the infants home language is lost (Werker and Tees, 1984). The inability to discriminate between non-native phonemic contrasts has been shown to persist into adulthood. Williams (1977) showed that native Spanish speakers showed significantly higher sensitivity to the phonemic boundary between stop consonants at the Spanish voice boundary than at the English voice boundary.

Of interest in assessing the benefit of frequency lowering hearing aids is the notion that the ability to discriminate between non-native phonemic boundaries, of which phonemic boundaries lowered in frequency may be an example, can be acquired following a period of training. Tees and Werker (1984) conducted a series of experiments investigating the ability of native English speakers to discriminate between phonemic contrasts present in Hindi but not in English. The results of the study showed that prior to training, six out of thirty participants with no prior experience of Hindi were able to discriminate between the Hindi phonemic contrasts. Following a short period of training (consisting of trial by trial feedback), 16 of the 24 remaining participants were able to discriminate between the Hindi phonemic contrasts. Interestingly, the results showed that acquiring the ability to categorically perceive Hindi contrasts differing along a voice onset time continuum was significantly easier than learning to perceive a contrast in non native phonemes that differed along a place of articulation contrast. This is consistent with research on frequency lowering hearing aids which consistently shows that participants have difficulty discriminating between /s/ and /ʃ/ (which differ in place of articulation) even after a period of acclimatisation (for example, Simpson et al, 2005).

Another place of articulation contrast that has been the subject of research into the perception of non native phonemic boundaries is the /r/ to /l/ distinction, present in English yet not in Japanese. MacKain et al (1981) found that following a period of intense training, native Japanese speaking adults were able to discriminate between /r/ and /l/. The training employed in this study consisted of the participant engaging in conversational English for eight to ten hours a day over a period of one year. Therefore, the results of this study show that it is possible to acquire the ability to discriminate between novel place of articulation contrasts, albeit requiring a lengthy training period. It is possible that the length of training required may have been lessened if the training given was focussed more on the particular contrast under investigation, perhaps by employing a trial by trial feedback approach such as that used by Tees and Werker (1984). However, it is possible that results obtained following such training may not be generalisable as the training and test materials are likely to be fairly similar and may not be representative of the real world environment. It is also probable, although not explicitly stated, that participants in this study continued to be exposed to Japanese as well as English throughout the training period. This may have created similar problems to those identified by Ling (1968) regarding the assumption that auditory experience outside of the training regime does not affect the ability to improve perception of novel speech sounds.

Together, the results of the above studies suggest that normally hearing participants are able, following a period of training to acquire the ability to categorically perceive novel phonemic contrasts. Very few studies however have investigated the effect of a hearing loss on the categorical perception of phonemic boundaries. Oates et al (2002) investigated the ability to discriminate between /ba/ and /da/ in twenty normally hearing participants and twenty participants with a mild to profound sensorineural hearing loss. The results of both behavioural and electrophysiological tests showed that only those participants with a moderate to profound sensorineural hearing loss (tested without the use of a hearing device) showed significantly reduced discrimination ability compared to the control group of normally hearing participants. However, these results are likely to be due to the fact that the stimuli were presented at 60 and 80 dB SPL, thus participants with a severe to profound loss would have been unable to hear the majority of the stimuli without the provision of a hearing aid. As such, these findings were further investigated by Tremblay et al (2003) who observed that older adults with a mild to moderate sensorineural hearing loss showed reduced sensitivity to categorically perceive a continuum of tokens from /ba/ to /pa/ than a comparison group of normally hearing adults matched on age, even when the presentation level was sufficient to be audible for all listeners.

A similar study conducted by Harkrider et al (2006) found that older adults showed reduced ability to discriminate between tokens on a /ba/ to /da/ to /ga/ place of articulation continuum compared to younger adults regardless of the presence of an age related hearing loss. The results of these studies therefore seem to indicate that discrimination between voicing contrasts (such as /ba/ to /pa/) is affected by hearing loss whilst place of articulation contrasts are primarily affected by aging. It should be noted however that the hearing impaired participants in Harkrider et al's (2006) study had only mild to moderate hearing losses. It may be that older adults with a more severe sensorineural loss may demonstrate reduced place of articulation discrimination compared to those with normal hearing or a mild to moderate loss. It is also possible that the choice of stimuli may have affected results as the speech components necessary to discriminate between /ba/, /da/ and /ga/ are lower in frequency than those needed to discriminate between /ba/ and /pa/, thus individuals with a sensorineural hearing loss may be expected to show relatively poorer discrimination ability on the /ba/ to /pa/ contrast because their hearing thresholds are likely to be higher (indicating poorer hearing) with increasing frequency.

In all the above studies participants with a hearing impairment were tested without the use of a hearing device. The question of whether a conventional hearing aid affects the phonemic discrimination sensitivity of people with a sensorineural hearing loss was investigated by Korczak et al (2005). The study compared the performance of fourteen adults with moderate to profound sensorineural hearing losses on behavioural and electrophysiological tasks focussing on the discrimination between /ba/ and /da/ when presented at 65 and 80 dB SPL. The results of the study showed that, as would be expected, participants' performance was significantly better in the aided compared to the unaided condition at both stimulus intensities. Thus, it is likely that the results can be attributed to increased audibility alone.

To date there has been no research on the effect of frequency lowering on categorical perception, although confusion matrices from many studies indicate that /s/ is often confused for /ʃ/ in speech lowered in frequency (for example, Simpson et al, 2005). This suggests that in processed speech the phonetic boundary is moved so as to result in the over-labelling of /ʃ/ and the under-labelling of /s/. This may be caused by a possible similarity between the spectrum of a frequency lowered /s/ and an unprocessed /ʃ/. It is also likely that frequency lowering leads to the development of phonetic boundaries in instances where, prior to frequency lowering, certain high frequency phonemes such as fricatives may have been entirely inaudible to the listener. As the majority of cases of sensorineural hearing loss are acquired postlingually it is likely that the majority of candidates for a frequency lowering aid will have had some previous experience of perceiving fricatives.

There is, however, reason to suspect that training participants with the aim of improving the discrimination and/or identification of /s/ and /ʃ/ following frequency compression may be of limited benefit. According to Newman et al (2001), there is a large degree of variation in the acoustics of /s/ and /ʃ/ produced by different speakers, although the overlap between the two is greatly reduced within a particular speaker. They suggest that with exposure, listeners are able to learn the characteristics of a given speakers productions of these phonemes and identify and discriminate between them accordingly. This ability is, however, speaker specific. The results of this study are supported by work conducted by Kraljic and Samuel (2005, 2006, 2007) who found that learning related to non-spectral contrasts such as /t/ and /d/ was generalisable to different speakers whilst learning relating to spectral contrasts such as /s/ and /ʃ/ was speaker specific. Therefore, training users of frequency compression hearing aids to better discriminate or identify /s/ and /ʃ/ may be of limited value in real world settings, even if results in the laboratory are encouraging. Furthermore, one of the criteria for verifying the suitability of a given frequency compression setting, is to ensure that the listener is able to discriminate between and to correctly identify, /s/ and /ʃ/ at the initial fitting stage (Glista et al, 2009). Thus, active training will not be provided in the current study and the effect of acclimatisation alone will be investigated.

2.9 Summary

To date, there has been limited research into the perceptual effects of frequency compression. Previous studies have reported mixed results, with some listeners showing significant improvements on some speech perception measures, and others receiving no additional benefit from frequency compression when compared to conventional amplification (see Simpson et al, 2005 and Glista et al, 2009). Methodological differences between the studies and in some cases, lack of appropriate controls, mean that it is difficult to predict from these results whether a given person with a hearing loss would benefit from frequency compression or not. Furthermore, little is known about the time course and magnitude of acclimatisation following the fitting of a frequency compression hearing aid. In order to enable clinicians to make an informed decision regarding the provision of frequency compression hearing aids and subsequent verification and counselling, more information is required on both recommended candidacy and acclimatisation periods. Therefore, the aim of this study is to investigate the following research questions:

1. Does frequency compression provide significant benefit above that provided by conventional amplification?

2. Are there changes in perceptual abilities over time following the provision of frequency compression hearing aids?

3. Is it possible to predict benefit from frequency compression hearing aids using audiological or cognitive factors?

This study is the first to examine the:

- effect of NLFC on the recognition of consonants in noise
- time course of auditory acclimatisation to NLFC in adults
- effect of NLFC on categorical perception
- relationship between cognition and benefit from NLFC
- relationship between dead regions and benefit from NLFC

CHAPTER 3

GENERAL METHODS

The purpose of this chapter is to outline details of the methodological choices adopted in the studies conducted. An outline of the structure of the longitudinal study will be presented along with details of the participants and tests used in each of the studies that were carried out. Further details concerning project-specific methodological issues are provided in the experimental chapters of the thesis.

3.1 PARTICIPANTS

3.1.1 Normally hearing listeners

The first two studies reported used listeners with normal hearing to investigate the effect of frequency compression on the discrimination and identification of fricatives (chapter 4) and the role of cognition on the perception of frequency compressed speech in noise (chapter 5).

A total of 12 participants (4 male, 8 female) aged between 22 and 49 years old (mean = 28 years old) took part in the study reported in chapter 4. All participants reported having normal hearing, which was confirmed using pure tone audiometry (hearing thresholds of less than 20 dB HL were taken to indicate normal hearing).

A sample of 15 participants (8 female, 7 male), with self reported normal hearing, was recruited to take part in the study reported in chapter 5. Participants were aged between 18 and 50 years with a mean age of 26 years.

3.1.2 Hearing impaired listeners

The same 12 listeners (9 male, 3 female) with bilateral sensorineural hearing loss took part in the experiments reported in chapters 6-8. Listeners were aged between 65 and 84 years old (mean = 74 years old) and were experienced hearing aid users. Details of the selection criteria employed are presented in Table 1. Details of each participant's hearing loss and relevant history are provided in Table 2. Participants were recruited from a local audiology clinic (n=3), a participant database held in the Audiology department at the University of Manchester (n=5) and via word of mouth (n=4). A clinically significant difference over time was estimated, based on the experience of the authors, to be an improvement in mean performance of 5% (1 SD +/-5). A minimum of 10 participants were required for a statistical power of >80% on a 2-tailed paired t-test at a significance level of 5%. 12 participants were recruited to allow for attrition. It was not possible to calculate power more accurately before the experiment as no previous studies were sufficiently similar to the current study as to allow this.

Table 1. *Selection criteria employed in the longitudinal study, the results of which are reported in chapter 6.*

Selection criteria	Defined as:
Sensorineural hearing loss	No air-bone gap of greater than 15 db at any frequency. Moderate-to-severe high frequency loss.
Symmetrical hearing loss	No asymmetry of greater than 20 db at more than two frequencies
Previous hearing aid experience	Of at least 1 year, wearing the device(s) for at least 4 hours per day
Native speaker level fluency in English	n/a
No previous experience of frequency lowering hearing aids	n/a
No abnormalities of middle ear function	Normal tympanometric readings
No reports of significant cognitive impairment	n/a

Participants were required to meet certain selection criteria relating to the nature of their hearing impairment and previous experience of using hearing aids. Details of the selection criteria can be seen in Table 1. One participant (002) was not a native English speaker, however had been resident in the UK for 15 years. As the analyses focus on differences in scores over time or between signal processing conditions, as opposed to simply mean scores, this participant was accepted onto the study on the basis that their

Table 2. *Characteristics of the participants' hearing loss, previous hearing aid use and the non-linear frequency compression settings used in the trial*

Participant	Age at start of trial (years)	Duration (years) of hearing loss	Duration (years) of previous HA use*	Ear	NLFC settings applied: cut-off freq. (CR)**	NLFC settings prescribed: cut-off freq. (CR)**	Dead regions (kHz) ***	Hearing threshold at specified frequencies (dB HL)								
								250	500	1000	1500	2000	3000	4000	6000	8000
001	69	10	10 (L)	Right	3700	4500	None	5	0	20	40	45	55	50	50	70
001				Left	(2.6:1)	(2.8:1)	None	0	0	35	65	70	70	70	70	60
002	80	20	20 (B)	Right	2000	3300	3 & 4	25	15	20	50	65	90	90	85	80
002				Left	(1.8:1)	(2.1:1)	3 & 4	35	30	25	50	60	80	85	90	75
003	80	10	7 (B)	Right	3300	2800	None	20	25	35	45	55	65	80	85	80
003				Left	(2.4:1)	(2.3:1)	4	25	25	30	35	40	55	60	70	75
004	66	10	4 (R)	Right	3100	4400	None	10	30	45	65	60	60	60	65	65
004				Left	(2.4:1)	(2.7:1)	None	15	20	30	45	45	55	60	80	65
005	77	5	3 (L)	Right	3100	4400	3	20	5	20	35	40	55	45	75	70
005				Left	(2.4:1)	(2.7:1)	None	20	15	35	45	55	60	60	95	85
006	74	8	4 (R)	Right	3000	4300	None	50	60	60	55	50	55	55	75	65
006			3 (B)	Left	(2.3:1)	(2.7:1)	3	50	55	60	60	60	55	40	85	75
007	73	5	1 (L)	Right	3100	4500	None	35	45	45	45	50	50	60	55	60
007			2 (B)	Left	(2.5:1)	(2.7:1)	None	30	50	55	50	45	65	60	90	80
008	84	9	3 (R)	Right	2000	2700	3 & 4	30	40	60	60	55	80	95	105	110
008			5 (B)	Left	(1.7:1)	(1.8:1)	3 & 4	35	30	50	70	75	70	95	115	105
009	65	8	4 (R)	Right	2800	3700	None	25	35	50	55	60	60	65	85	85
009				Left	(2.4:1)	(2.3:1)	None	15	35	45	55	55	60	55	90	70
010	79	10	8 (B)	Right	2600	4100	None	40	40	45	55	45	65	75	80	90
010				Left	(2.1:1)	(2.5:1)	None	30	30	40	45	50	55	60	75	85
011	75	5	5 (L)	Right	3100	4500	None	20	20	30	30	25	35	50	55	80
011				Left	(2.5:1)	(2.8:1)	None	30	30	30	25	45	35	40	85	85
012	65	6	3 (L)	Right	2400	3400	1.5, 2(i),3 (i), 4	15	10	25	70	75	70	80	85	75
012			3 (B)	Left	(2.0:1)	(2.1:1)	2 (i), 3(i), 4	10	10	10	70	80	85	90	90	75
Mean	71.9	8.8	7.1	n/a	n/a		n/a	24.8	27.3	37.5	50.7	54.4	61.9	65.8	80.6	77.7

* (L) = left, (R) = right, (B) = bilateral ** CR = compression ratio *** i = inconclusive

level of English language proficiency was unlikely to change over the course of the trial. Auditory functioning was assessed using otoscopy, pure tone audiometry (both air and bone conduction thresholds) and tympanometry. The Threshold Equalising Noise (TEN) test was also administered in order to identify potential dead regions. Participants were not paid to take part in the study; however, travel expenses were reimbursed.

3.2 ETHICS

For the studies using listeners with normal hearing, ethical approval was obtained from the University of Manchester, School of Psychological Sciences Research Ethics Committee (Approval codes: 671/07P and 417/07P).

For the studies involving listeners with a hearing impairment, ethical approval was granted by Greater Manchester West Research Ethics Committee on behalf of the NHS (Approval code: 10/H1014/44).

3.3 FITTING AND VERIFICATION OF HEARING AIDS

Participants were fitted bilaterally with Phonak Naida V SP hearing aids. The Naida V SP is a fully programmable, 16 channel behind-the-ear hearing instrument that is suitable for moderate-to-severe hearing impairment. The hearing aids have a maximum output of 140 dB SPL and a maximum gain of 75 dB, both measured in a 2-cc coupler. The hearing aids were programmed to match NAL-NL2 prescription targets (Keidser et al, 2011). The settings were then verified using real ear insertion gain (REIG) measurements taken using an Aurical Plus (Type 2A, GN Otometrics) measurement system along with Noah 3 software (Hearing Instrument Manufacturers' Software Association). All measurements were taken with the frequency compression setting disabled. The hearing aid settings were verified using modulated speech-type noise at 50, 65 and 80 dB SPL. Once the hearing aid response had been matched as closely as possible to the target values, subjective listening checks were carried out (that is, the listeners assessed the quality and comfort of sounds of differing levels and frequencies). Further alterations were then made to the hearing aid settings if the listener was unhappy with the sound. Table 3 shows the group mean targets and match achieved (after fine tuning).

Table 3. *Targets (using the NAL-NL2 prescription method) and real ear insertion gain measurements obtained at the initial fitting and final test session*

Level (dB SPL)	Mean targets and deviation (target – match, in dB) in real ear insertion gain from target prescribed using the NAL-NL2 fitting formula.							
	250	500	1000	2000	3000	4000	6000	8000
Target (65)	3.1 (4.5)	2.9 (4.6)	11.1 (5.6)	19.4 (4.5)	22.7 (5.4)	25.9 (5.2)	26.6 (4.7)	26.6 (4.5)
Initial fitting (65)	2.4 (4.5)	1.4 (4.0)	-2.7 (4.8)	-3.0 (4.7)	-2.0 (7.5)	5.1 (10.4)	9.8 (6.6)	22.5 (7.8)
Initial fitting (50)	7.7 (7.0)	4.6 (4.8)	-3.3 (3.8)	0.7 (6.4)	3.8 (8.4)	11.2 (10.4)	17.4 (6.6)	21.6 (6.6)
Initial fitting (80)	-0.7 (1.5)	-0.6 (2.0)	-3.1 (3.8)	-3.9 (6.0)	-2.8 (6.9)	2.8 (10.3)	5.3 (6.9)	17.4 (9.5)
End of trial (65)	0.7 (3.8)	2.4 (5.7)	-2.8 (5.0)	-4.5 (4.2)	-1.0 (5.6)	7.7 (8.7)	11.0 (8.8)	24.2 (7.7)

Once the initial gain settings were finalised, frequency compression was enabled. This signal processing method works by applying non-linear frequency compression to frequencies above a given cut-off point. Frequency compression is not applied to sounds lower in frequency than the cut-off point. The gain provided by the hearing aid is unaffected by the use of frequency compression. Further technical details of the algorithm can be found in Simpson et al (2005) and in the registered patent (Phonak, 2009). Using the Phonak fitting software (iPFG, 2.6), it is only possible to alter the cut-off point and compression ratio together. The fitting software provides a recommended frequency compression setting, based on the manufacturer’s guidelines. However, it was felt in many cases that this setting was not strong enough to allow the listener to obtain any benefit from frequency compression. Therefore, in all cases bar one (where the listener preferred the recommended setting), the frequency compression setting enabled was stronger (reflected in a lower cut-off frequency and higher compression ratio) than the recommended default setting. In order to ensure than the frequency compression setting was appropriate, a number of criteria were assessed. The frequency compression ratio that allowed the audibility of the highest frequencies whilst maintaining a cut-off frequency of > 2 kHz (so as not to adversely affect sound quality) was selected. Participants were then asked to discriminate between recordings of /s/ and /ʃ/, spoken by a female talker and presented at a comfortable listening level, using a same-different procedure. If the participant was unable to consistently discriminate between these stimuli, or reported problems with the sound quality (for example, a 'lisping' quality), a weaker frequency compression setting (reflected in a higher cut-off frequency and lower compression ratio) was applied. The selected frequency compression settings are shown in Table 2, along with details of the settings recommended by the manufacturer. Figure 1 depicts the relationship between input and output frequency when a NLFC setting with a cut off frequency of 3.1 1 kHz and a compression ratio of 2.4:1 is enabled.

Automatic program selection and noise reduction features were disabled for the duration of the trial, as were the manual volume controls. Participants were provided with an additional program, in which noise reduction features were enabled and instructed to use this program only in situations in which the noise was so intrusive as to make them consider removing the hearing aids. Hearing aid usage was monitored throughout the trial using the data logging feature of the hearing aids. All participants wore the devices for an average of at least 8 hours per day throughout the trial.

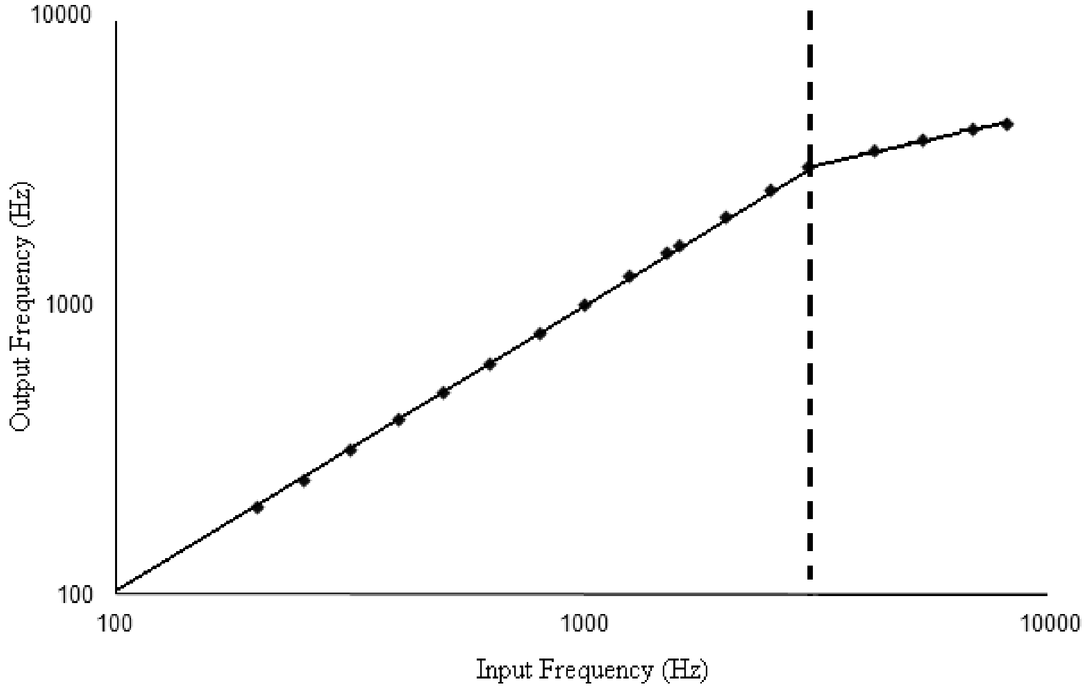

Figure 1. *Diagram showing the relationship (measured using a 2 cc coupler and 2 test boxes) between input and output frequency when a NLFC setting with a cut-off frequency of 3.1 kHz (marked by the dashed line) and a compression ratio of 2.4:1 is enabled.*

The frequency compression setting was then disabled and participants wore the hearing aids at home for one week. Any alterations to the hearing aid settings were made at this appointment. Three participants requested reductions in the low frequency gain of between 2 and 6 dB. No further alterations were made later in the trial.

Real ear insertion gain measurements were repeated at one session in the middle of the trial and again at the final testing session in order to check that the hearing aids were functioning consistently. The group mean REIG measurements obtained at the initial and final testing sessions can be seen in Table 3 along with the prescribed targets. The measurements obtained in the middle of the trial are not presented as data from 3 participants are missing.

In order to minimise the possible influence of placebo effects, participants were not told whether frequency compression was enabled or disabled at any point in the trial. Recruitment materials specified that listeners may or may not benefit from frequency compression, a fact highlighted by the experimenter at the initial testing session.

3.4 TESTS ADMINISTERED

An outline of which tests were used in each study can be seen in Table 4. A variety of tests were selected for use in the study. Nonsense syllable recognition tests in both quiet and noise were administered so as to allow for the examination of consonant recognition without the influence of contextual cues. A sentence in noise test was also administered to give an indication of speech perception performance in a context similar to that experienced in real life. The cognitive tests were selected as they provide indices of functions known to relate to speech in noise perception (namely, working memory span and executive function). The Speech, Spatial and Qualities of Hearing Scale (SSQ) and the Glasgow Hearing Aid Benefit Profile (GHABP) were included to enable the examination of subjective ratings of the signal processing methods being investigated. In addition, tests of fricative identification and discrimination were included to examine the relative effects of frequency compression on these processes. Further details of the tests administered are provided below.

3.4.1 Cognitive Tests

3.4.1.1 Reading Span Test

The Reading Span Test (Daneman and Carpenter, 1980; Rönnberg et al, 1989) is a measure of working memory span consisting of a sequence of sentences (such as, 'the horse trotted nicely') in blocks of 3-6 sentences. Sentences were presented to the participant word by word on a computer screen at the rate of one word every 800 msec. Immediately after reading each sentence, the participant must state whether the sentence made sense giving a yes-no response (processing component). At the end of each block, participants were asked to recall either the first or last word of every sentence in that group (storage component). Participants were told at the beginning of the test that the order in which they would be asked to recall either first or last words of each sentence was randomised. In the first trial, three sentences were presented. In each subsequent trial the number of sentences presented was increased by one, up to six sentences in the final trial. The presentation of each sentence was separated by a 1750 msec gap. The test took approximately ten minutes to complete. Upon completion of the test, the percentage of words correctly recalled was then calculated. This method of scoring has been shown to be more reliable than alternative techniques such as scoring based on the highest set in which participants correctly recalled the majority of words (Friedman and Miyake, 2005).

Traditionally, only the scores from the storage component of working memory span tests are analysed; however, according to Unsworth et al (2009), scores on the processing element of working memory span tasks contribute substantial unique variance when trying to predict higher order cognition. Therefore, in addition to analysing the percentage of words correctly recalled, the percentage of errors in the processing element of the RST (that is, whether or not the sentences made sense) was also calculated.

3.4.1.2 Trail Making Test

The Trail Making Tests A and B (TMT-A/B, 1958, 1992) are paper-and-pencil-based tasks. The participants' task is to join together a series of points on a sheet of paper in the correct order. The TMT was included in the study as it has been shown that performance on the TMT may predict the ability of listeners with a hearing loss to perceive speech in a novel accent (Adank and Janse, 2010). As frequency compression alters the spectral relationship between speech components, perception of speech processed in this way may require similar skills to those needed to perceive speech in a novel accent.

In the TMT-A, the points are labelled from 1-25, the task being to join the points in the correct numerical order. In the TMT-B, the points are labelled 1-12 and A-L and the participants' task was to join the points in the correct alphabetical and numerical order, alternating between the two (for example, 1-A-2-B-3-C and so on). Prior to completing the TMT tests, the participants were given a sample task on which to practice.

Performance on the task was assessed by measuring the total time taken to complete each task. If the participant made a mistake, the experimenter pointed out their error and asked the participant to correct it. Errors were penalised only in that they increased the time taken to complete the task. Participants were aware that the time taken to complete the task was the outcome measure of interest.

3.4.2 Self-Report Outcome Measures

3.4.2.1 Glasgow Hearing Aid Benefit Profile

The Glasgow Hearing Aid Benefit Profile (GHABP; Gatehouse, 1999) is a self report questionnaire assessing six dimensions consisting of initial disability, initial handicap, hearing aid use, hearing aid benefit, residual disability and satisfaction. Each dimension is assessed in relation to four pre specified listening situations (if they occur in the participants life and cause them difficulty) with the option of including up to four additional listening situations specified by the respondent. The participant responds using a five point scale. In this case, only responses relating to three of the four pre-specified listening situations were measured (hearing aid use was excluded as participants were asked to wear their hearing aids as much as possible throughout the duration of the trial). This decision was made as both individual and group differences in scores were assessed, thus it was felt that consistency both between and within participants should be maximised. The decision to use the GHABP as opposed to the

Glasgow Hearing Aid Difference Profile was in order to minimise the influence of confusions being made in memory of the different hearing aid settings.

The first two dimensions, initial disability and initial handicap, are normally used to assess the respondents perceived hearing problems prior to hearing aid fitting. However, in this instance, these scales were used to assess perceived hearing difficulties experienced with the participants' own hearing aid(s). Disability refers to the types and degrees of listening difficulty the respondent is experiencing whilst handicap denotes the perceived impact of these difficulties on the participants' everyday life (Gatehouse, 1999).

The final four dimensions relate to experiences post hearing aid fitting, or in this case, post fitting the study hearing aids. Hearing aid use indexes the proportion of time the respondent wears their hearing aids when required. The benefit dimension refers to the perceived difference in hearing ability pre and post hearing aid fitting, or between different hearing aid fittings. Residual disability assesses the hearing difficulties that remain following hearing aid fitting whilst the satisfaction is thought to capture facets of a hearing aid fitting extending beyond audition, for example comfort and cosmetic factors (Gatehouse, 1999).

The GHABP was administered by the experimenter as a structured interview. Ratings for the final three dimensions were obtained at four intervals (detailed in Table 5), giving two measures with frequency compression disabled (after three and six weeks of use with this setting) and two measures with frequency compression enabled (at one and six weeks post fitting). Ratings for the two initial dimensions, based on participants' experiences with their own hearing aids, were obtained at the first instance of administering the questionnaire, that is at three weeks post fitting of the study hearing aids. Responses were then scored out of a maximum of 100 for each dimension. The overall mean score for each version of the test was also calculated.

Table 4. *Outline of the tests administered in each study*

Test Subgroup	Test	Study reported in:		
		Chapter 4	Chapter 5	Chapter 6
Cognitive tests	Reading Span Test		X	X
	Trail Making Tests A&B		X	X
Self-Report Measures	Glasgow Hearing Aid Benefit Profile			X
	Speech, Spatial & Qualities of Hearing Scale			X
Speech Recognition in Quiet	VCV recognition in quiet			X
	High frequency VCV recognition in quiet			X
Speech Recognition in Noise	VCV recognition in noise			X
	Sentence in noise recognition		X	X
Categorical Perception	Fricative Discrimination	X		
	Fricative Identification	X		

3.4.2.2 Speech, Spatial and Qualities of Hearing Scale

The Speech, Spatial and Qualities (SSQ) Hearing Scale (Gatehouse and Noble, 2004) is a self-report measure consisting of three subscales. The three subscales relate to speech perception, spatial hearing and quality of sound. Each subscale is comprised of a series of listening situations which the respondent marks out of 10, where a score of 10 indicates complete ability and a score of zero indicates minimal ability (Noble and Gatehouse, 2006). A total of 50 listening situations are rated.

The SSQ Hearing Scale was administered in the form of a structured interview. The decision to administer the questionnaire in this way was based upon research indicating that this method of administration results in the highest test-rest reliability when compared to self administration of the scale (Singh and Pichora Fuller, 2010). The SSQ Hearing Scale was administered at four intervals as detailed in Table 5. Mean scores for each subscale as well as the overall mean score for the entire test were calculated.

3.4.3 Speech Perception in Quiet

3.4.3.1 VCV recognition in quiet

Stimuli consisted of 20 nonsense syllables in /i/ - consonant - /i/ context (for example, /iki/) spoken by a female talker. The stimuli were taken from the IHR VCV test package (Faulkner, 1998; IHR Products, Nottingham).

Stimuli were presented via a loudspeaker situated one metre in front of the listener at zero degrees azimuth. The level at which the stimuli were presented was set individually for each listener (between 55 and 70 dB SPL) to minimise the risk of floor and/or ceiling effects occurring. The level was set at the point at which participants achieved mean scores of between 65 and 87.5% correct without frequency compression enabled. One participant achieved scores above this level (91.3%) and three participants were only able to achieve scores below this range even at a presentation level of 70 dB SPL (47.5%, 53.8% and 62.5% respectively). The level was kept constant between test sessions. Each test run consisted of one practice block and four test blocks of 20 presentations each (one presentation of each VCV token). Participants were given a response sheet with a matrix showing each of the 20 possible consonants. Participants pointed to the sound corresponding to the speech stimulus they heard. Responses were then recorded on the computer by the experimenter.

3.4.3.2 High frequency VCV recognition in quiet

Stimuli consisted of a total of 20 speech tokens in the format vowel-consonant-vowel. 8 syllables, the identification of which relies on high frequency information, were presented in both /a/ - consonant - /a/ and /u/ - consonant - /u/ formats. The consonants presented were /tʃ/, /z/, /θ/, /f/, /ʃ/, /ʤ/, /s/ and /v/. The stimuli were taken from the IHR VCV test package (Faulkner, 1998; IHR Products, Nottingham). The procedure used was identical to that described under the ‘VCV in quiet recognition’ subheading.

3.4.4 Speech Recognition in noise

3.4.4.1 VCV recognition in noise

Stimuli consisted of 20 nonsense syllables in /i/ - consonant - /i/ context spoken by a female talker. The stimuli were presented in a background of multi-talker babble noise (20 speakers). The stimuli were taken from the IHR VCV test package (Faulkner, 1998; IHR Products, Nottingham).

The procedure was almost identical to that described under the ‘VCV in quiet recognition’ subheading. The level of presentation varied between participants but was consistent the level used for in VCV in quiet task for each listener. The speech to noise ratio (SNR) was also determined on an individual basis to prevent ceiling or floor effects (and varied from +2 to -2 SNR, with the exception of one participant, 008, who was tested with an SNR of +10 due to floor effects). An SNR that resulted in approximately a 10-20 % decrease in score relative to performance in quiet was selected.

3.4.4.2 Sentence in Noise recognition

3.4.4.2.1 Stimuli and Procedure (normally hearing listeners)

The sentence stimuli used were IEEE (Rothauser et al, 1969) sentences spoken by a female talker with a standard English accent. IEEE sentences were selected due to the relative lack of contextual information provided in these sentence lists. The stimuli were presented in a background of multitalker (20 speakers) babble (Auditec, St Louis, USA). Stimuli were presented using a laptop computer and played over Sennheiser HD 215 headphones.

Six sentence lists were administered to each participant. Each list was presented in one of three conditions: no frequency compression, frequency compression with a cut-off frequency of 1.6 kHz and a compression ratio of 2:1, and frequency compression with a cut-off frequency of 1.6 kHz and a compression ratio of 3:1. The settings were selected to provide medium and high levels of compression with the relatively low cut-off frequency chosen to combat predicted ceiling effects due to the use of listeners with normal hearing in the study, who do not have the reduced frequency selectivity and audibility associated with sensorineural hearing loss.

The allocation of lists to each condition was counterbalanced as was the order of testing. Within each list, all sentences were presented at 65 dB SPL, and the level of the noise varied in 3 dB steps from +12 to -15 dB in a fixed order, similar to the method recommended by Wilson et al (2007). The participants' task was to repeat each sentence back to the experimenter and the percentage of keywords (five per sentence) correctly recognized in each condition was calculated.

3.4.4.2.2 Stimuli and Procedure (hearing impaired listeners)

Lists of IEEE sentences (Rothauser et al, 1969) spoken by a female talker were presented in a background of 20 talker babble noise (Auditec, St Louis, USA). The stimuli were again presented via a loudspeaker situated at head height one metre in front of the listener. The presentation level of the sentences remained constant throughout each list but the level of the noise varied from +15 to -12 dB in a fixed order, similar to the method recommended by Wilson et al (2007). Sentences were presented at 55 dB

SPL for all participants except one (participant 008) who was unable to complete the task at this level. For this listener, sentences were presented at 65 dB SPL.

The participants’ task was to repeat each sentence back to the experimenter and the percentage of keywords (5 per sentence) correctly recalled was calculated. Three sentence lists were administered on each occasion of testing.

3.4.5 Categorical Perception

3.4.5.1 Fricative Discrimination

3.4.5.1.1 Stimuli

Stimuli consisted of a continuum of twelve tokens falling between natural recordings of /s/ and /ʃ/, with a sampling rate of 22.05 kHz, uttered by the same female speaker. The two phonemes of interest were extracted, at zero crossing points using Audacity (Sourceforge, Ltd.), from utterances of the nonsense syllables /asa/ and /aʃa/ (originally recorded at UCL). The phonemes were edited such that none of the formant transitions were retained, thus only the frication itself, of 200 msec duration, was extracted. The decision to edit the stimuli in this manner was based on research suggesting that people with a hearing impairment are, unlike those with normal hearing, unable to use these formant transitions to aid the identification of /s/ (Zeng and Turner, 1990).

To create the 12-step continuum used in the experiment, the stimuli were manipulated using the software programme ‘Morphing’ (created by Peter Zorn, 2000). This software works by analyzing the temporal and frequency characteristics of the two natural phonemes and using the Pitch Synchronous Overlap Add (PSOLA) technique to modify and mix the characteristics of the two stimuli to create the desired number of stimuli (in this case 12) in the continuum. In order to prevent the perception of clicking sounds at the onset and offset of the stimuli, a 10msec fade in/out to the zero crossing point was applied.

The choice to use a continuum derived from natural speech as opposed to wholly artificial stimuli (taken from Hazan and Barrett, 2000)was based on the outcome of a pilot study (the results of which can be seen in Appendix 1 along with further details of the stimuli and procedure). The results of the pilot study showed that participants identified the naturally derived stimuli more consistently than those created artificially. Participants also reported, perhaps unsurprisingly, that the ‘natural’ continuum of stimuli sounded much more like normal speech than the continuum of artificially synthesised speech.

The continuum of stimuli was then manipulated to create four conditions. Stimuli in one condition were manipulated no further and used as a baseline condition. The remaining three conditions were processed using the non-linear frequency compression algorithm employed in a range of hearing aids manufactured by Phonak (see the patent registered to Phonak AG, 2009, for technical details of the algorithm used). The stimuli were processed by Phonak AG using custom software to apply the patented frequency compression algorithm to the stimuli. For each of these conditions, a cut-off frequency of 1.6 kHz was selected, above which frequency compression was applied. As participants in this study had normal hearing and therefore did not have the poorer frequency resolution associated with a sensorineural loss, it was felt that a higher cut-off frequency may have resulted in ceiling effects. Three compression ratios were applied to give low (compression ratio of 1.43:1), medium (compression ratio of 2:1) and high (compression ratio of 3.3:1) degrees of frequency compression.

3.4.5.1.2. Procedure

A 3-alternative forced-choice 1-up/3-down adaptive staircase procedure, corresponding to 79.4% accuracy (Levitt, 1971), was employed in the discrimination tasks. Participants were presented with 3 speech tokens, 2 of which were the same, and were asked to determine which token was different. Therefore, this test was essentially an odd one out task, performance relying on acoustic rather than phonemic information. The stimuli were presented with an interstimulus interval of 500 msec. Participants registered their responses by using the mouse to click on the appropriate button on the computer screen (1, 2 or 3). Following their response, the participant had to click a button on-screen for the next trial to be administered (in order to allow the participant to take breaks when required). The next trial was then presented after a 2 second gap. Two blocks of trials were completed for each condition. In one block the standard stimuli, that is the two stimuli that were the same, consisted of the natural /s/ token. The standard stimuli in the second block consisted of the natural /ʃ/ token, thus the adaptive track was run in both directions. Both blocks for each condition were completed one after the other, however, the conditions were separated. Thus, participants completed four sets of discrimination trials each consisting of two blocks and requiring approximately ten minutes to complete. Both the order in which the conditions were given and in which the blocks were presented was counterbalanced.

Prior to the start of the adaptive procedure for each condition, participants completed 10 practice trials that had been randomly selected from both possible blocks. Following completion of the practice trials, the experimental procedure began. As the test was adaptive, the easiest contrast (s0 – s11, where s0 is the natural /s/ token and s11 is the natural /ʃ/) was always presented first. For each correct answer given, the contrast was made more difficult by one step size. If the participant gave an incorrect response, the contrast was made easier by three step sizes. The point at which the direction of the contrast changed will be termed a ‘turnaround’ from here on. Once 16 turnarounds had been recorded the block was terminated. In order to obtain a measure of the discrimination threshold, the mean value of the final twelve turnarounds was calculated, as suggested by Stillman (1989)

3.4.5.2 Fricative Identification

3.4.5.2.1 Stimuli

The stimuli used were identical to those detailed in the section on the fricative discrimination task

3.4.5.2.2 Procedure

The identification task consisted of a series of two-alternative forced-choice trials, in which participants were presented with one token at a time and asked to determine whether it sounded more like /s/ or /ʃ/. Again, trials for each condition were presented separately, meaning that the participants completed four blocks of trials, each taking approximately eight minutes to complete. At the beginning of each block, participants were presented with ten randomly selected practice trials. After completing the practice trials, the experimental trials were administered. For each condition, 120 trials were completed, consisting of ten presentations of each stimulus. The order in which the stimuli were presented was randomized. Participants registered their response by using the mouse to click on the appropriate button on the computer screen (/s/ or /ʃ/). After giving their response, the participant had to click on a button on screen to progress to the next trial, which was then administered two seconds later. The mean proportion of /s/ responses to each stimulus was then calculated.

3.5 CALIBRATION

In order to calibrate the stimuli presented via headphones, repeats of each stimulus were concatenated so as to run continuously and the long term average sound pressure level measured using a Bruel and Kjaer artificial ear (type 4152) and the A-weighted slow response scale of a Hewlett Packard real time frequency analyser (3569a). Details of the presentation levels used can be found in the Method sections of each experimental chapter. A similar procedure was used to calibrate the level of the stimuli presented via loudspeaker. In this case, the sound pressure level was measured at head height one metre in front of the speaker (at zero degrees azimuth) using a CEL 254 digital impulse sound level metre. The program used to administer the VCV syllables includes a reference tone which was used to calibrate the presentation level of these stimuli. Presentation levels were rechecked at various points throughout the duration of the longitudinal trial to ensure consistency. Head position was monitored visually in each test session. Details of the presentation levels used can be found in the Method sections of each experimental chapter.

3.6 STRUCTURE OF LONGITUDINAL STUDY

3.6.1 Design

An outline of the longitudinal study can be seen in Table 5. The trial took approximately 18 weeks to complete and was split into four parts. A single group design was used. Prior to wearing the frequency compression hearing aids for the study, there were 3 sessions comprising of the initial screening tests and familiarisation with the speech tests.

After fitting the hearing aids, an A-B-A design was used. All participants wore the hearing aids with frequency compression disabled first (for a mean duration of 3.6 weeks, SD = 0.81), then enabled (for a mean duration of 6.6 weeks, SD = 0.95) then disabled again (for a mean duration of 4 weeks, SD = 2.75). Thus, the participants wore the devices at home for approximately six to seven weeks with each setting. According to Gatehouse (1992), at least six weeks are required to show evidence of acclimatisation to a new hearing aid setting. The order was not counterbalanced for two reasons. The first reason is that previous research has indicated that benefit from frequency compression is hugely variable and cannot be predicted based on features of the audiogram. Therefore, it would be difficult to ensure that the two groups were comparable, especially given the small sample size used in the study. The second reason is that in order to investigate acclimatisation to frequency compression, it was felt that it was necessary to allow the listener to adapt to the differences in gain between the new hearing aids and their own devices first. Therefore, the final scores with frequency compression disabled will consist of the mean of the scores obtained at the end of the first and second periods of wearing the devices at home without frequency compression. This was done to help minimise the influence of any potential order effects.

3.6.2 Testing environment

All testing was conducted in a quiet room (dimensions: 5.5 metres long, 3.4 metres wide and 2.7 metres high). Reverberation times were measured, in octave intervals from 0.125 to 8 kHz, with a Brüel and Kjaer 2250 sound analyser. Reverberation times were all < 0.3 s.

3.6.3 Active listening task

In addition to attending testing sessions, participants were asked to spend one hour a week listening to an audiobook whilst at the same time following the text. A choice of three books was provided. Participants were asked to do this as an aide to help them acclimatise to their new hearing devices. In particular, as frequency compression may alter the nature of certain high frequency sounds, it was felt that it may be beneficial for participants to be able to see text of the sounds they were hearing in order to make them aware of any phonemic confusions they may have been making. Audio equipment was provided where required and participants were requested to keep a diary detailing time spent on the active listening task. Participants were asked to do the active listening task both when the frequency compression was enabled and disabled as shown in Table 5.

Table 5*. Structure of the longitudinal trial.*

Week	Hearing aid Setting*	Session Number	Activities												
			Active listening task	Hearing screening	HA fitting/REMs	RST	TMT-A&B	Practice speech tests	VCV-Q	VCV-N	VCV-HF	SIN	GHABP	SSQ	Counselling questionnaire
1	0	1		X		X	X								
2	0														
3	0	2						X							
4	0														
5	1	3	X		X			X							
6	1	4	X					X							X
7	1		X												
8	1	5							X	X		X	X	X	
9	2	6	X						X	X		X			X
10	2	7	X						X	X		X	X	X	
11	2		X												
12	2	8	X		X				X	X		X			X
13	2		X												
14	2		X												
15	2	9							X	X	X	X			
16	1	10	X			X	X						X	X	X
17	1		X												
18	1		X												
19	1	11			X				X	X	X	X	X	X	

*Hearing aid setting: 0=own aids; 1=Naida without NLFC; 2=Naida with NLFC

3.6.4 Familiarisation sessions

Prior to fitting the study hearing aids, the hearing impaired participants attended two familiarisation sessions in which they were introduced to the speech tests to be used throughout the study. Participants completed repeated runs of the VCV in quiet and in noise tests along with the sentence in noise test whilst wearing their own hearing aids. The IEEE sentence lists used in the familiarisation sessions were different to those used in later test sessions. Practice on the VCV in quiet and in noise tests was done with stimuli in an /a/ context spoken by a female talker. Thus the test was exactly the same procedurally but used different stimuli to the version of the test used in later test sessions. The reason for not using exactly the same stimuli in both the familiarisation and testing sessions was that it was felt that the amplification provided by the participants own hearing aids would be more similar to the amplification given in the no frequency compression condition of the study hearing aid. Thus, it was felt that were participants trained with exactly the same stimuli as used in the test sessions, this may bias the results in favour of the no frequency compression condition. However, at the end of each familiarisation session, VCV in quiet and in noise were completed with stimuli in an /i/ context.

This was to help inform the experimenter of the appropriate level/SNR to try after fitting the study hearing aids. Participants completed between 8 and 11 complete runs of the VCV tests and between 6 and 12 sentence lists. At the end of the two sessions, the final consecutive scores had to be within 5% of each other. If this was not the case, further familiarisation tests would have been administered. This was not necessary for any participant.

3.6.5 Counselling questionnaire

A brief questionnaire was developed in order to monitor the participants' experiences with the hearing aids. The questionnaire was delivered in the format of a semi – structured interview. A copy of the questionnaire can be seen in Appendix 2. Responses from this questionnaire were not analysed but served only to monitor the participants' experience with the hearing aids and to highlight any potential problems with the fitting or hearing aid usage.

3.6.6 Debrief and follow up care

At the final test session, participants were given details of their performance on both settings of the hearing aid. Participants were also asked whether they would like to receive details of the main findings of the trial upon its completion. If participants wished to keep the study hearing aids, the settings were altered in accordance to their preferences. Responsibility for the maintenance of the study hearing aids after completion was transferred to the participants' local NHS audiology department upon agreement with the Head of Department.

3.7 STATISTICAL ANALYSIS

The results were analysed using correlational analyses, t-tests or ANOVA depending on the research question. Parametric statistics were used whenever the appropriate assumptions were met. Results were analysed at both the group and, where appropriate, the individual level. Specific details relating to the analyses of results can be found in the relevant experimental chapters.

CHAPTER 4

INTERNATIONAL JOURNAL OF AUDIOLOGY MANUSCRIPT

TO WHAT EXTENT DOES FREQUENCY COMPRESSION AFFECT THE PERCEPTION OF /s/ AND /ʃ/ IN ADULTS WITH NORMAL HEARING?

Additional material relating to this chapter is presented in Appendix 1.

To what extent does frequency compression affect the perception of /s/ and /ʃ/ in adults with normal hearing?

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Key words

Frequency compression

Discrimination

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Fricatives

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ABSTRACT

Objective: The present study sought to investigate the effect of non-linear frequency compression on the identification and discrimination of /s/ and /ʃ/. *Design:* Participants completed behavioural identification and discrimination tasks with a continuum of 12 stimuli between /s/ and /ʃ/. The stimuli were compressed in frequency to varying degrees. Baseline measures were obtained using unprocessed stimuli. *Study Sample*: 12 participants with normal hearing took part in the study. *Results:* The results show that frequency compression significantly affected performance in the identification task, with greater amounts of frequency compression leading to the over identification of /ʃ/ (when compared to performance in the baseline condition). However, no such effect was observed in the discrimination task. *Conclusions:* The findings highlight the need to be aware that the ability to perform these tasks is reliant on different processes, which may not be affected in the same way by signal processing strategies.

According to Davis (2001), almost half of the British population over the age of seventy years old have a hearing impairment, the majority of these losses being sensorineural in origin. Typically, a sensorineural hearing impairment results in greater losses at the high frequencies than in the low and mid frequency regions of the spectrum. High frequency information is important for many facets of perception. In particular, listeners with a high frequency hearing loss may report difficulty in perceiving some high frequency consonants and in understanding speech in background noise.

A major issue in the manufacturing and fitting of hearing aids is determining ways of providing effective audibility in the high frequencies. If high levels of gain are required, acoustic feedback often becomes a problem. Furthermore, most hearing aids are only able to provide effective amplification to frequencies up to around 4 – 5 kHz, well below the 10 kHz bandwidth recommended by Boothroyd and Medwetsky (1992) as necessary in order to perceive the spectral peak of a typical female utterance of /s/.

Frequency lowering hearing aids were developed in an attempt to overcome the problems associated with providing high frequency audibility. The idea behind frequency lowering devices is to shift high frequency information into the low and mid frequency ranges. This is done in order to maximise both the patients' residual hearing and to minimise problems caused by the aforementioned technical limitations of hearing aids.

There are a number of methods of implementing frequency lowering in hearing devices, a schematic representation of which can be seen in Figure 1. These include frequency transposition, slow playback and non-linear frequency compression. Currently devices using frequency transposition and frequency compression are available commercially (see McDermott, 2011, for a technical comparison of the two algorithms). Frequency transposition simply involves lowering all frequencies above a certain cut-off point by a set amount, normally one octave. This method of frequency lowering is currently utilised (under the name 'Audibility Extender') in a series of hearing aids manufactured by Widex (Denmark). The advantage of this method is that it maintains the frequency ratios of the transposed components of the signal. This means that speech processed in this way sounds fairly natural, albeit slightly lower in pitch. However, the transposed portion of the signal overlaps with the original low and mid frequency parts of the signal, which may negatively affect the perception of vowels and some consonants.

Furthermore, high frequency noise may also be transposed which may also lead to the masking of lower frequency speech sounds, important for the perception of vowels and many consonants.

Figure 1 here

An alternative method of frequency lowering that is available commercially (in a series of devices manufactured by Phonak (Switzerland) is non-linear frequency compression, and it is on this method that the present paper will focus. Non-linear frequency compression (NLFC) works by compressing frequencies above a variable cut-off point, such that the degree of compression applied increases with frequency. The results of clinical trials of a non-linear frequency compression algorithm, similar to that available in the Phonak range of hearing aids, indicate that this scheme may provide significant speech perception benefit to some patients with moderate to profound high frequency losses (Simpson et al, 2005, Glista et al, 2009). Results for participants with steeply sloping losses have, however, been mixed. Simpson et al (2006) reported that none of the seven participants they tested with this type of loss showed any significant additional benefit from frequency compression when compared to conventional processing, with group mean scores showing a 2% deficit in consonant identification with the use of NLFC. This is in stark contrast with the findings reported by Glista et al (2009) who observed that the participants with steeply sloping losses in their study were in fact the most likely to benefit from non-linear frequency compression. Thus, how best to assess candidacy for frequency compression hearing aids remains unclear.

Simpson et al (2005) report that frequency compression significantly improved detection of fricative and affricate consonants without impairing the perception of vowels and mid frequency consonants. However, an analysis of confusion matrices indicated that frequency compression seemed to lead to increased confusions between /s/ and /ʃ/, suggesting that the improved perception of some phonemes may come at the expense of others (Simpson et al, 2006). This effect is not surprising given that non-linear frequency compression results in the creation of a novel sound pattern in which the spectral and temporal characteristics of the signal are altered. The cues provided by these spectral and temporal cues are important in discriminating between different phonemes. According to Boothroyd and Medwetsky (1992), the average value for the lowest spectral peak in the phoneme /s/ is around 4.3 kHz for men and 7.2 kHz for women, with this value increasing to around 9 kHz for some female speakers. As the compression is non-linear, higher frequency phonemes such as /s/ and /ʃ/ will be more affected by this method of signal processing. /s/ and / ʃ/ differ in terms of place of articulation and are discriminated between on the basis of bandwidth of the frication noise band (with / s/ having a narrower bandwidth than / ʃ/) and on the frequency of the spectral peaks (with /s/ containing most of its energy in frequency regions higher than those contained in / ʃ/; see Fry, 1979 for further details of speech acoustics). Thus, frequency compression may result in the processed spectral peaks of /s/ being compressed into a frequency region normally associated with /ʃ/. Furthermore, frequency compression will affect the relative bandwidths of these phonemes, making them more similar, and potentially more difficult to discriminate between. As such, it is expected that different degrees of frequency compression will affect the presence/position of perceived phonemic boundaries between these fricatives.

If this proves to be the case, parallels may be drawn between the perception of non-native phonemic contrasts and phonemic contrasts in frequency compressed speech. Research investigating the perception of non-native phonemic contrasts suggests that active training is necessary in order to discriminate between the contrasts effectively (see, for example, Tees and Werker, 1984). It is therefore possible that a period of training, focussing on the discrimination and identification of consonants that appear to be confused in frequency compressed speech, may further increase speech perception scores in participants that appeared to obtain overall benefit from the frequency compression device.

In order to allow for the investigation of the effect of acclimatisation and training on the perception of high frequency phonemes that have been subjected to frequency compression, it is first necessary to conduct a preliminary examination of the way in which this method of processing affects the perception of /s/ and /ʃ/. The aim of the present study is to investigate the degree to which frequency compression affects the position of the perceived phonemic boundary between these phonemes in normal hearing adults. Also of interest is whether performance on the discrimination and identification tasks is equally affected, as previous studies of frequency compression have focussed on identification only. The results will inform the design of future experiments investigating the effect of training and acclimatisation on the perception of frequency compressed speech. The results will also allow for the evaluation of current fitting methods which often assess the suitability of the compression setting based in part on a listener's ability to correctly identify the phonemes /s/ and /ʃ/ (Glista et al, 2009).

METHOD

Participants

A total of 12 participants (4 male, 8 female) aged between 22 and 49 years old (mean = 28 years old) took part in the study. All participants reported having normal hearing, which was then confirmed using pure tone audiometry (where thresholds of less than 20 dB HL were taken to indicate normal hearing). Ethical approval was obtained from the University of Manchester, School of Psychological Sciences Research Ethics Committee.

Equipment

The experiment was run using a Dell laptop computer (Latitude D630). Stimuli were presented via insert earphones (ER-2s, Etymotic Research Inc.) which were connected to the laptop via a 24 bit external soundcard (Edirol, Audio capture UA-25). The software programme used to administer the experiment was written using C++.

Stimuli

Stimuli consisted of a continuum of twelve tokens falling between natural recordings of /s/ and /ʃ/, with a sampling rate of 22.05 kHz, uttered by the same female speaker. The two phonemes of interest were extracted, at zero crossing points using Audacity (Sourceforge, Ltd.), from utterances of the nonsense syllables /asa/ and /aʃa/ (originally recorded at UCL). The phonemes were edited such that none of the formant transitions were retained, thus only the frication itself, of 200 msec duration, was extracted. The decision to edit the stimuli in this manner was based on research suggesting that people with a hearing impairment are, unlike those with normal hearing, unable to use these formant transitions to aid the identification of /s/ (Zeng and Turner, 1990).

To create the 12-step continuum used in the experiment, the stimuli were manipulated using the software programme 'Morphing' (created by Peter Zorn, 2000). This software works by analyzing the temporal and frequency characteristics of the two natural phonemes and using the Pitch Synchronous Overlap Add (PSOLA) technique to modify and mix the characteristics of the two stimuli to create the desired number of stimuli (in this case 12) in the continuum. In order to prevent the perception of clicking sounds at the onset and offset of the stimuli, a 10msec fade in/out to the zero crossing point was applied.

The choice to use a continuum derived from natural speech as opposed to wholly artificial stimuli (taken from Hazan and Barrett, 2000)was based on the outcome of a pilot study (the results of which can be seen in Appendix 1 along with further details of the stimuli and procedure). The results of the pilot study showed that participants identified the naturally derived stimuli more consistently than those created artificially. Participants also reported, perhaps unsurprisingly, that the ‘natural’ continuum of stimuli sounded much more like normal speech than the continuum of artificially synthesised speech.

The continuum of stimuli was then manipulated to create four conditions. Stimuli in one condition were manipulated no further and used as a baseline condition. The remaining three conditions were processed using the non-linear frequency compression algorithm employed in a range of hearing aids manufactured by Phonak (see the patent registered to Phonak AG, 2009, for technical details of the algorithm used). The stimuli were processed by Phonak AG using custom software to apply the patented frequency compression algorithm to the stimuli. For each of these conditions, a cut-off frequency of 1.6 kHz was selected, above which frequency compression was applied. As participants in this study had normal hearing and therefore did not have the poorer frequency resolution associated with a sensorineural loss, it was felt that a higher cut-off frequency may have resulted in ceiling effects. Three compression ratios were applied to give low (compression ratio of 1.43:1), medium (compression ratio of 2:1) and high (compression ratio of 3.3:1) degrees of frequency compression.

The spectra of selected stimuli are presented in Figure 2. The spectra show that as the amount of frequency compression increases, the spectral peaks become closer together in frequency, effectively reducing frequency selectivity. All stimuli were used in both the discrimination and the identification tasks.

Figure 2 here

Calibration

In order to calibrate the stimuli, repeats of each stimulus were concatenated so as to run continuously and the sound pressure measured using a Bruel and Kjaer artificial ear (type 4152) and the A weighted slow setting of a Hewlett Packard real time frequency analyser (3569a). Calibration of the stimuli in the baseline condition revealed a large difference in the level of the natural /s/ and /ʃ/ to the order of 11 dB (where /ʃ/ is higher in level), with all other stimuli in the continuum falling in between. This is to be expected as more high frequency energy is generated in the production of /ʃ/ than /s/. Thus, stimuli in this condition were presented at levels between 65 and 76 dB SPL, so as to be at a comfortable listening level. The level of presentation was not roved in order to maintain any level cues (due to differences in the spectral bandwidth of the two sounds) that would be used in real life to aid discrimination or identification of /s/ and /ʃ/.

Once the baseline stimuli had been calibrated, the levels of the stimuli in the remaining conditions were measured. Stimuli in the low frequency compression condition were between 70 and 76 dB SPL. Stimuli in the medium frequency compression condition were between 70 and 75 dB SPL and in the high frequency compression condition, between 67 and 70 dB SPL. The differences in level between the frequency compression conditions and the baseline may be expected, as frequency compression essentially makes the stimuli more similar, thus reducing the level differences between /s/ and /ʃ/.

Procedure

Discrimination task

A 3 alternative forced choice 1 up 3 down adaptive staircase procedure, corresponding to 79.4% accuracy (Levitt, 1971), was employed in the discrimination tasks. Participants were presented with 3 speech tokens, 2 of which were the same, and asked to determine which token was different. Therefore, this test was essentially an odd one out task, relying on acoustic rather than phonemic information. The stimuli were presented with an interstimulus interval of 500 msec. Participants registered their responses by using the mouse to click on the appropriate button on the computer screen (1, 2 or 3). Following their response, the participant had to click a button on screen for the next trial to be administered (in order to allow the participant to take breaks when required). The next trial was then presented after a 2 second gap. Two blocks of trials were completed for each condition. In one block the standard stimuli, that is the two stimuli that were the same, consisted of the natural /s/ token. The standard stimuli in the second block consisted of the natural /ʃ/ token, thus the adaptive track was run in both directions. Both blocks for each condition were completed one after the other, however, the conditions were separated. Thus, participants completed four sets of discrimination trials each consisting of two blocks and requiring approximately ten minutes to complete. Both the order in which the conditions were given and in which the blocks were presented was counterbalanced.

Prior to the start of the adaptive procedure for each condition, participants completed 10 practice trials that had been randomly selected from both possible blocks. Following completion of the practice trials, the experimental procedure began. As the test was adaptive, the easiest contrast (s0 – s11, where s0 is the natural /s/ token and s11 is the natural /ʃ/) was always presented first. For each correct answer given, the contrast was made more difficult by one step size. If the participant gave an incorrect response, the contrast was made easier by three step sizes. The point at which the direction of the contrast changed will be termed a 'turnaround' from here on. Once 16 turnarounds had been recorded the block was terminated. In order to obtain a measure of the discrimination threshold, the mean value of the final twelve turnarounds was calculated, as suggested by Stillman (1989)

Identification task

The identification task consisted of a series of 2 alternative forced choice trials, in which participants were presented with one token at a time and asked to determine whether it sounded more like /s/ or /ʃ/. Again, trials for each condition were presented separately, meaning that the participants completed 5 blocks of trials, each taking approximately 8 minutes to complete. At the beginning of each block, participants were presented with ten randomly selected practice trials. After completing the practice trials, the experimental trials were administered. For each condition, 120 trials were completed, consisting of ten presentations of each stimulus. The order in which the stimuli were presented was randomized. Participants registered their response by using the mouse to click on the appropriate button on the computer screen (/s/ or /ʃ/). After giving their response, the participant had to click on a button on screen to progress to the next trial, which was then administered 2 seconds later. The mean proportion of /s/ responses to each stimulus was then calculated.

All testing was completed in one session lasting approximately 2.5 hours (including breaks).

RESULTS

Discrimination task

Prior to the analysis, the data was checked for outliers and to ascertain whether the assumptions required for parametric statistics to be reliable were met. On inspection of the data it was noted that the responses from one participant were extremely inconsistent and did not seem to reliably converge on a threshold. This observation was supported by an analysis of extreme values which revealed that this participant contributed 34% (or 17 out of 50 of the 5 most extreme values for each condition in each block) of these responses. These extreme responses did not appear to be systematic and thus data from this participant was excluded from further analyses. No other outliers were removed.

Data were analysed using repeated measures ANOVAs and paired samples t-tests. In addition, a series of one way ANOVAs were conducted to investigate whether the order in which the conditions were presented had a significant effect on the results. The tests showed that no significant order effects were present in the data thus both group means and individual results will be discussed below.

The effect of condition on the thresholds obtained in each block will be assessed in order to investigate whether frequency compression affects the position of the discrimination thresholds. The mean thresholds obtained in the block in which /s/ was the standard will then be subtracted from those obtained in the block in which /ʃ/ was the standard in order to give a measure of overall sensitivity. The effect of condition will again be assessed.

The effect of condition on the thresholds obtained in the /s/ as standard block

In order to obtain a threshold value for each participant, the mean of the last 12 turnaround points in the adaptive test was calculated. The overall mean thresholds obtained in this block of trials are shown in Figure 3 with individual results displayed in Figure 4. In this block, a higher threshold indicates poorer discrimination performance (as stimuli lower in number were closer to /s/ whilst those higher in number were closer to /ʃ/). On inspection, the group means suggest that participants performed most poorly in the high frequency compression condition and best in the baseline condition, with the remaining two frequency compression conditions falling in between. However, the differences were small. The individual results also indicate that this pattern was not observed in all participants.

Figure 3 here

A repeated measures ANOVA was conducted to investigate the effect of condition on the mean threshold obtained in the /s/ as standard trials. This effect was not statistically significant (F[3, 393] = 1.48, p = 0.219).

Figure 4 here

The effect of condition on the thresholds obtained in the /ʃ/ as standard block

The mean thresholds for the group are shown in the bar chart in Figure 3 with the individual results depicted in Figure 4. In these trials, a higher score corresponds to better discrimination performance. Participants performed most poorly in the baseline condition and best in the low frequency compression condition. These differences were, however, very small. Unlike the /s/ as standard trials, all participants exhibited a similar pattern, albeit to different degrees. The results of a repeated measures ANOVA confirm that this effect was not significant (F[2.76, 361.6] = 1.93, p = 0.124).

The effect of condition on the difference in thresholds obtained in the /s/ and /ʃ/ as standard blocks.

In order to obtain a measure of overall sensitivity, the thresholds obtained in the /s/ as standard trials were subtracted from the thresholds obtained in /ʃ/ as standard trials and the effect of condition was again assessed. The group results, presented in Figure 3, show similar ranges of discrimination in all conditions. The individual results, shown in Figure 4, again indicate that all participants demonstrate this pattern. The results of the repeated measures ANOVA show that this effect was not significant (F[3, 393] = 0.38, p = 0.768).

Identification task

In order to investigate the effect of frequency compression on the identification of the continuum of stimuli under study, the mean proportion of /s/ responses given for each stimulus was calculated for each participant in all conditions. The analyses were split by stimulus to enable the distribution of /s/ responses to be examined, as opposed to looking only at the overall mean proportion which may obscure subtle effects.

Data were analysed using repeated measures ANOVA's. In addition, the slope and midpoint of the response functions were calculated by fitting a sigmoid curve to the data in accordance with the non-linear least squares fitting method suggested by Bates and Chambers (1992). Finally, the effect of the order in which the conditions were presented was once more analysed using a series of one way ANOVAs. The results indicated that there was no significant effect of order on mean response (F[4, 719] = .43, p = 0.785).

The effect of condition on the proportion of /s/ responses given to each stimulus

The mean proportion of /s/ responses given by the group to each stimulus, split by condition, are presented in Figure 5. The results in the baseline condition show that stimuli 0 to 2 are almost always identified as /s/ whilst 8 to 11 are normally identified as /ʃ/ .The responses to stimuli 3 to 7 show a steady decrease in /s/ responses. The results in the low frequency compression condition also show the same pattern. A different pattern of responses is evident from the data from the medium frequency compression condition. Specifically, whilst responses to stimuli 8-11 remain relatively unchanged, the proportion of /s/ responses to stimuli 0-2 is substantially lower, with no stimuli being consistently identified as /s/ in either condition. Instead, the proportion of /s/ responses simply decreases steadily from stimuli 1-7, stimulus 0 being identified as /s/ slightly less than stimulus 1. The results in the high frequency compression condition show a similar pattern of responses to those obtained in the medium frequency compression condition, albeit with an even lower proportion of /s/ responses to stimuli 0-2.

Figure 5 here

In order to investigate the significance of the effect of condition on proportion of /s/ responses given, a series of repeated measures ANOVAs split by stimulus number were conducted, the results of which are reported below. Where a significant effect was revealed, a series of paired samples *t*-tests were conducted to look at how the responses in each condition compared to the baseline responses. A Bonferroni correction was applied to these comparisons and thus only results that were significant at $p \leq .004$ will be retained as support for the rejection of the null hypothesis. The results of the repeated measures ANOVAs and where appropriate, the paired samples *t*-tests, are presented in Table 1.

Table 1 here

The results of the repeated measures ANOVAs indicate a significant main effect of condition on proportion of /s/ responses given to stimuli 0 to 4. The results of the paired samples *t*-tests show that the only significant differences in responses given in the baseline and low frequency compression conditions was to stimulus 4. Comparisons between the baseline and medium frequency conditions reveal significant differences in responses to stimuli 0-1 only. Comparisons between the high frequency compression and baseline conditions show that the only significant differences are in the responses given to stimuli 0-3. This indicates that the proportion of /s/ responses given to these stimuli was significantly greater in the baseline condition than in the medium or high frequency compression conditions.

Inspection of the individual results presented in Figure 6 show that within the baseline and each of the frequency compression conditions, there was very little variation in responses between participants. The exceptions to this being participants 103, 104 and 110 whose responses appeared to be largely unaffected by even large degrees of frequency compression.

Figure 6 here

The slope and midpoint values for the individual and group response functions are presented in Table 2. A higher slope value indicates a more refined identification function (meaning that fewer stimuli seemed to be on the category border) and thus better performance in the task. An inspection of the group means shows that the highest slope values were found in the low FC condition, followed by the baseline condition then decreasing with increasing amounts of frequency compression, although this pattern varied between participants. The results of a repeated measures ANOVA revealed no significant effect of condition on slope (F [3,30] = 2.02, p=.152).

Table 2 here.

The midpoint values show whether the pattern of responses has shifted along the stimulus continuum between conditions. The lowest midpoint (meaning the responses were shifted more towards the /s/ end of the continuum) was found in the low FC condition, followed by the baseline, then increasing with increasing frequency compression. Again, this pattern varied between participants. The results of a repeated measures ANOVA revealed a significant effect of condition on midpoint (F [3,30] = 4.24, p = .013), however post-hoc tests (including an n=4 Bonferroni correction) showed no significant differences between the baseline condition and any of the frequency compression conditions.

DISCUSSION

The results of the study show that the discrimination and identification of /s/ and /ʃ/ are affected differently by frequency compression. The results of the discrimination task indicate that even large amounts of frequency compression appear to have little effect on the ability to discriminate between the phonemes /s/ and /ʃ/. This is in contrast to the results of the identification task, which provide clear evidence of an effect of frequency compression.

The results in the baseline condition of the identification task demonstrate the pattern that would be expected in this type of task. Namely, that the first three stimuli were always identified as /s/, the proportion of /s/ responses then declining steadily until the remaining stimuli were consistently identified as /ʃ/. That this pattern was also observed in the low frequency compression condition is unsurprising. As such a small amount of frequency compression was applied, one would expect it to have a minimal effect on the perceptual abilities of adults with normal hearing. The results in the medium and high compression conditions of the identification task do, however, show evidence of an effect of frequency compression. This effect was only evident in responses to stimuli that were usually identified as /s/ in the baseline condition, and was more pronounced in the high frequency compression condition than in the medium frequency compression condition. This concurs with the prediction that larger amounts of compression may result in the under-identification of /s/ (and therefore, the over identification of /ʃ/), based on the results of an earlier study of frequency compression in a hearing impaired population (Simpson et al, 2006). This is to be expected as due to the fact that the frequency compression applied is non-linear, the stimuli that have greater energy in the higher frequencies, that is those closest to /s/, will be more affected by this method of processing.

Individual results in the identification task varied, with the responses of some participants being much more affected by frequency compression than others. This is somewhat surprising as all participants in the study had normal hearing thresholds; thus, one may have expected the effect of frequency compression to be fairly consistent between participants. The wide range of individual differences observed in this study is again consistent with earlier studies of frequency compression in hearing impaired populations (Simpson et al, 2005; Glista et al, 2009), and suggests that factors other than audiometric measurements need to be taken into account when assessing candidacy for a frequency compression hearing aid.

The results of the discrimination task provide no evidence of an effect of frequency compression on performance in the task. This suggests that frequency compression does not significantly affect the ability to discriminate between /s/ and /ʃ/. There are, however, a number of methodological issues that may explain these findings. A number of participants performed at or close to ceiling level in the discrimination task, particularly in the trials in which /s/ was the standard. It is in these trials that one would expect the effect of frequency compression to be most evident, thus it is possible that such an effect may have been obscured by the fact that some participants performed at ceiling level. Another methodological issue that may have affected the results of the discrimination trial is the difference in presentation level between different stimuli and conditions. It is possible that level differences aided performance in the discrimination trials, however, this would also be the case with natural speech. If participants were relying heavily on level differences to discriminate between stimuli, one would expect this to result in an overestimation of the effect of condition on performance in this task (as there was a level range between stimuli of 11dB in the baseline condition falling to only 3 dB in the high frequency compression condition). However, this effect was not observed.

It is also possible that the continuum of stimuli used in this study was not sensitive enough to detect an effect of frequency compression on discrimination, even though it may exist. This is perfectly plausible, however, as a significant effect of frequency compression on identification was observed using the same stimuli, it can be concluded that frequency compression has a greater effect on identification than discrimination.

As participants in this study had normal hearing, the results cannot be directly applied to hearing impaired populations. We can assume, however, that any effect observed with normally hearing participants is likely to exist, and to be greater in magnitude, in hearing impaired participants. This is due to the fact that people with a sensorineural hearing loss commonly have poorer frequency resolution than those with normal hearing. This means that the task of discriminating between and identifying phonemes that have been compressed in frequency is likely to be much more difficult for people with a hearing loss.

The findings of this study highlight the need for additional research in this area. It is necessary to determine whether the differing effect of frequency compression on discrimination and identification performance is observed in participants with a hearing loss. If so, the results of the study may have important implications for the fitting of frequency compression hearing aids. Currently it is recommended that clinicians assess a patient’s ability to correctly identify the phonemes /s/ and /ʃ/ when fitting a frequency compression hearing aid (Glista et al, 2009). One may argue that selecting the frequency compression ratio on this basis might result in lower compression ratios than would be optimal for the patient. It may therefore be more effective to assess whether a patient is able to discriminate between these phonemes rather than whether they can identify them correctly.

It is possible that patients fitted with a frequency compression aid may not have heard fricatives at all for a number of years; thus, it is reasonable to expect that it may take some time to learn to identify them correctly. Therefore, it could be that when identifying phonemes, these patients initially rely more on how discriminable they are, learning the correct labels over time via acclimatisation. Patients who were able to hear fricatives without frequency compression are likely to base their responses on their memories of the criteria they used to identify these phonemes previously. If this proves to be the case, this might suggest that current fitting methods mean that hearing aids for patients with severe losses are initially fitted with relatively greater degrees of compression than patients with better residual hearing. This may allow more room for an acclimatisation effect and lead to greater improvements in performance with frequency compression when compared to conventional processing, a pattern that was observed by Glista et al (2009).

This notion is based on two assumptions. Firstly, that the results of this study are replicable in hearing impaired populations, that is to say that the effect of frequency compression would be greater on identification than discrimination. Secondly, that a period of auditory acclimatisation (and possibly active training) would result in greater improvements to identification than discrimination. This is not to suggest that there will be no improvement in discrimination performance, only that it is likely to be smaller in magnitude than improvement in identification. This is based on the idea that the ability to identify a stimulus is more strongly influenced by higher cognitive processes than the ability to discriminate between two stimuli, and is thus more likely to be affected by a period of auditory acclimatisation or training. Further research is needed to investigate the validity of these assumptions.

CONCLUSIONS

To summarise, the findings presented here suggest that whilst the identification of /s/ and /ʃ/ appears to be affected by frequency compression, discrimination between the phonemes is not. The findings therefore highlight the need to be aware that the ability to perform these tasks is reliant on different processes, which may not be affected in the same way by signal processing strategies. Whilst these results cannot be directly applied to a hearing impaired population, the findings may be used to inform the design of future studies in which the effect of frequency compression is investigated directly in participants with a hearing loss.

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TABLE LEGEND

Table 1. A summary of the results of statistical tests performed on data from the identification trials, split by stimulus. The second column shows the results of a series of repeated measures ANOVAs showing the effect of condition on the proportion of /s/ responses given to each stimulus. The final four columns show the results of paired samples *t*-tests comparing the proportion of /s/ responses given in the low pass filtered and three frequency compression conditions, to the proportion of /s/ responses given in the baseline condition. Statistically significant results are marked with an asterisk.

Table 2. Midpoints (M) and slopes (S) of the identification functions at the individual and group levels.

Stimulus	**Main effect - F values**	**Comparisons to performance in the baseline condition - *t* values**		
		Condition		
		Low frequency compression	Medium frequency compression	High frequency compression
0	9.2*	-0.7	3.1**	3.7*
1	22.5*	0	2.9**	6.1*
2	10.5*	-0.3	2.8	4.1*
3	7.2*	-1.5	0.5	3.2**
4	7.3*	-3.4*	-1.7	1.1
5	2.4			
6	2.3			
7	2.1			
8	1.3			
9	1.7			
10	1.5			
11	0.8			

* = p ≤ .001
** = p ≤ .004

Table 1

Participant	Baseline		Low FC		Medium FC		High FC	
	M	S	M	S	M	S	M	S
101	3.1	2.1	3.9	12	4.9	1.6	2.7	0.3
102	3.8	12	4.5	2.6	4	0.6	1.1	0.4
103	4.9	1.6	5.8	2.5	4.9	3.4	4.1	1.3
104	5.1	0.7	5.9	12	7.4	1.2	5.6	3.3
105	3.8	6.4	4.2	1.1	3	0.9	3.2	0.6
106	4.5	0.8	4.4	1.2	4.7	1.0	4.8	1.3
107	4.9	1.8	5.4	1.5	3.9	0.7	3.5	1.0
108	6.1	2.7	6.4	3.5	4.4	1.3	4.8	0.7
109	6.0	1.0	5.5	2	2.1	0.6	2.9	0.5
110	5.2	3.1	5.5	2.0	5.4	2.4	5.8	1.9
111	3.7	0.7	3.9	1.1	2.1	0.7	0.3	0.6
112	2.7	3.1	4.6	0.4	5.7	0.8	3.4	0.7
Group Mean (SD)	4.4 (0.30)	3.0 (3.41)	4.9 (0.23)	3.49 (4.3)	4.4 (0.48)	1.3 (0.89)	3.4 (0.51)	1.1 (0.89)

Table 2

FIGURES LEGEND

Figure 1. Schematic representation of the different frequency lowering methods currently available.

Figure 2. Spectra of selected stimuli. In all conditions s0 = /s/ and s11 = /ʃ/. The upper panel shows the spectra of every second stimulus in the baseline condition. The remaining panels show the spectra of the first and last stimuli in the continua in the low frequency compression (upper middle panel), medium frequency compression (lower middle panel) and high frequency compression (lower panel) conditions.

Figure 3. Bar charts showing the group mean scores obtained in the discrimination task. Condition is plotted along the x-axis and threshold against the y-axis. The first two graphs show the mean thresholds obtained in each condition of the /s/ as standard block. The mean thresholds obtained for each condition of the /ʃ/ as standard block are displayed in the second graph. The final graph depicts the mean difference between the thresholds obtained in the /s/ and /ʃ/ as standard blocks in each condition. Error bars show +/- one standard error.

Figure 4. Bar charts showing the individual mean scores obtained in the discrimination task. Participant number is plotted along the x-axis and threshold against the y-axis. The different conditions are represented by differently coloured bars as indicated in the key. The first two graphs show the mean thresholds obtained in each condition of the /s/ as standard block. The mean thresholds obtained for each condition of the /ʃ/ as standard block are displayed in the second graph. The final graph depicts the mean difference between the thresholds obtained in the /s/ and /ʃ/ as standard blocks in each condition.

Figure 5. A series of line graphs showing the group mean proportion of /s/ responses given in the identification trials for each stimulus split by condition. Stimulus number is presented along the x-axis, where 0 indicates the natural /s/ and 11 the natural /ʃ/ token. The first graph shows responses given in the baseline condition. The remaining three graphs depict the responses given in the low, medium and high frequency conditions respectively. Error bars show +/- one standard error.

Figure 6. A series of line graphs showing the mean proportion of /s/ responses given by each participant. Stimulus number is plotted along the x-axis, whilst the proportion of /s/ responses given is plotted against the y-axis. The black line shows performance in the baseline condition. The grey line depicts performance in the low frequency compression condition (left hand column), medium frequency compression condition (middle column) and high frequency compression condition (right hand column).

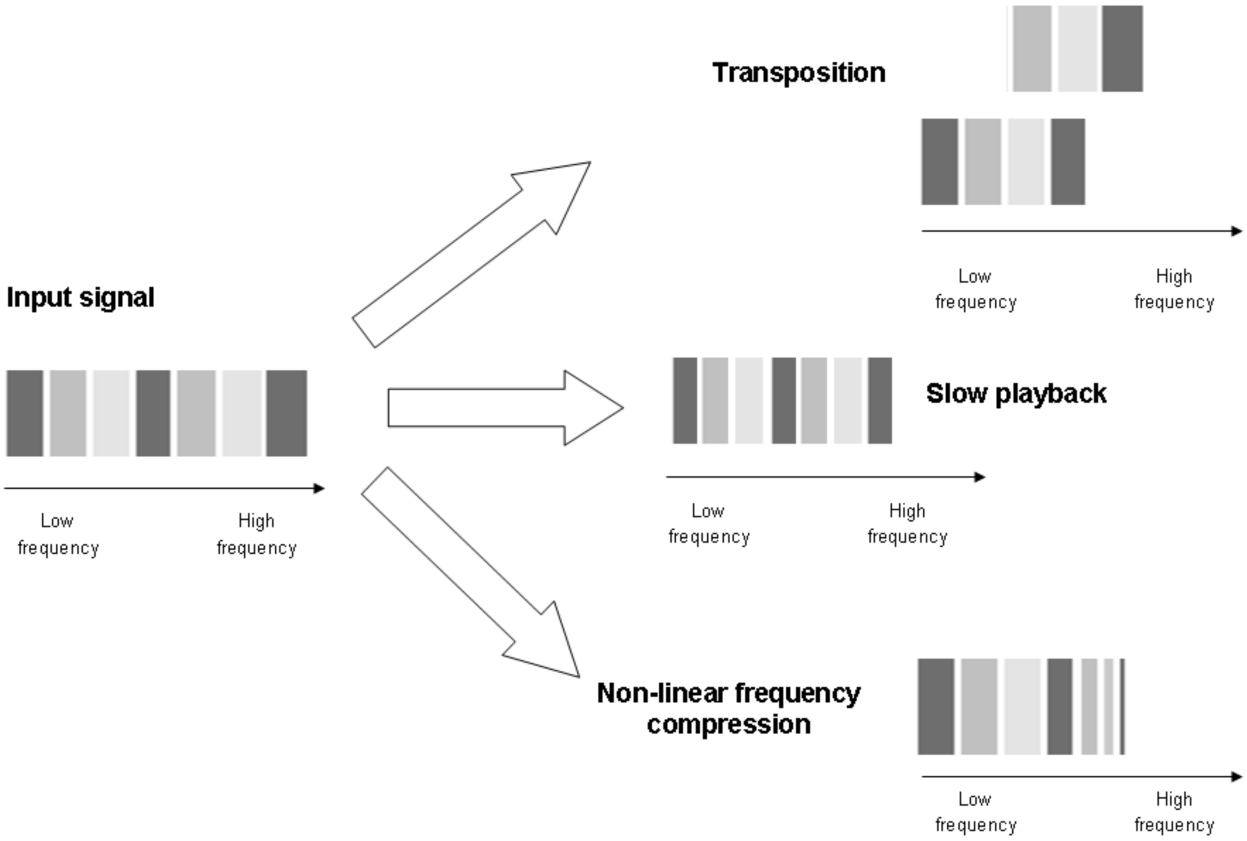

Transposition
Input signal
Low frequency
High frequency
Slow playback
Non-linear frequency compression

Figure 1

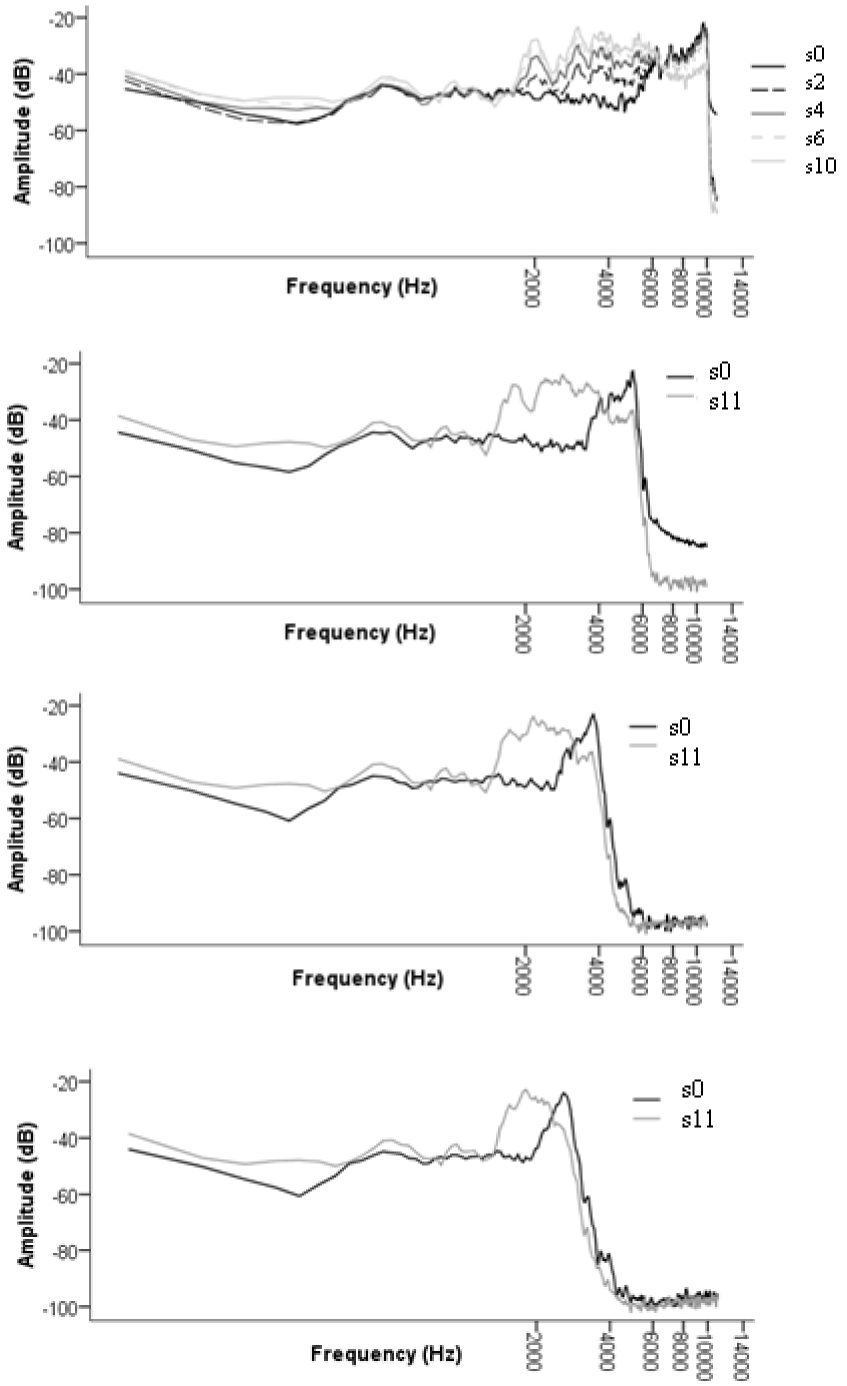
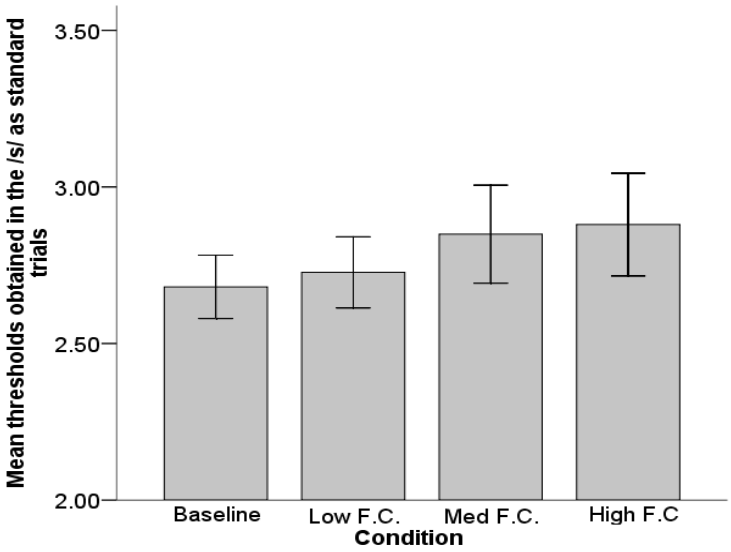
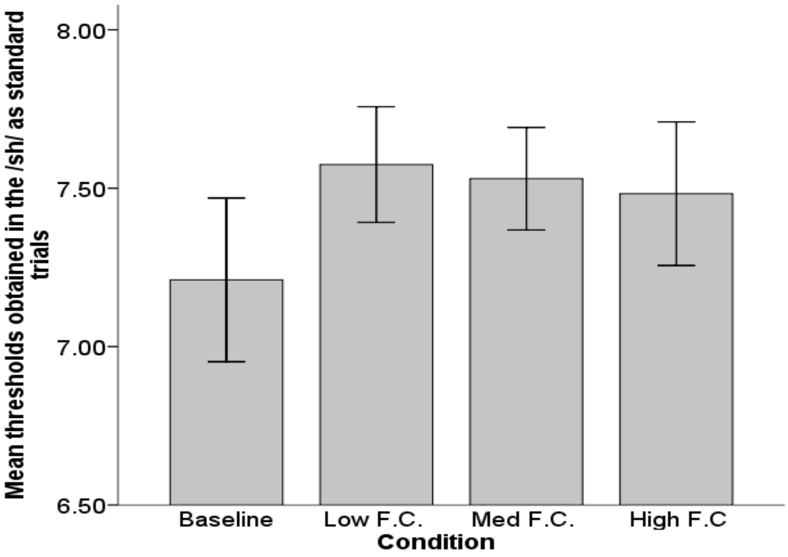

Amplitude (dB)
-20
-40
-60
-80
-100
Frequency (Hz)
2000
4000
6000
8000
10000
14000
s0
s2
s4
s6
s10
s11

Figure 2


Mean thresholds obtained in the /s/ as standard trials
3.50
3.00
2.50
2.00
Baseline
Low F.C.
Med F.C.
High F.C
Condition


Mean thresholds obtained in the /sh/ as standard trials
8.00
7.50
7.00
6.50
Baseline
Low F.C.
Med F.C.
High F.C
Condition

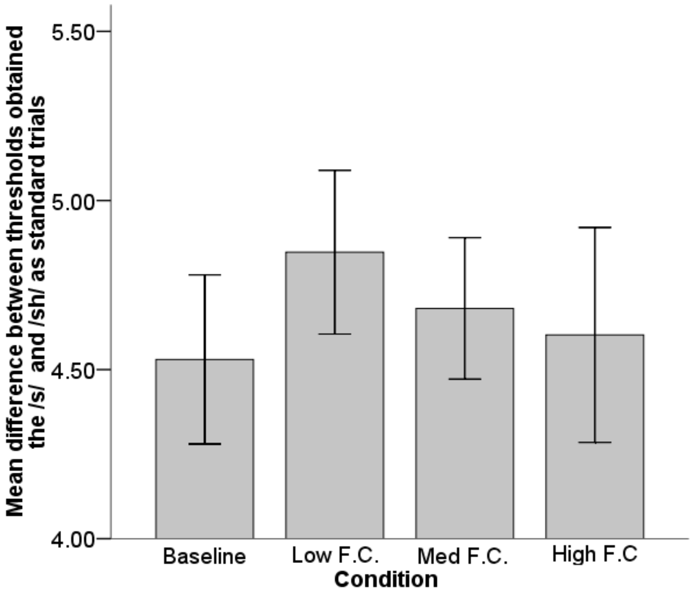

Mean difference between thresholds obtained the /s/ and /sh/ as standard trials
5.50
5.00
4.50
4.00
Baseline
Low F.C.
Med F.C.
High F.C
Condition

Figure 3

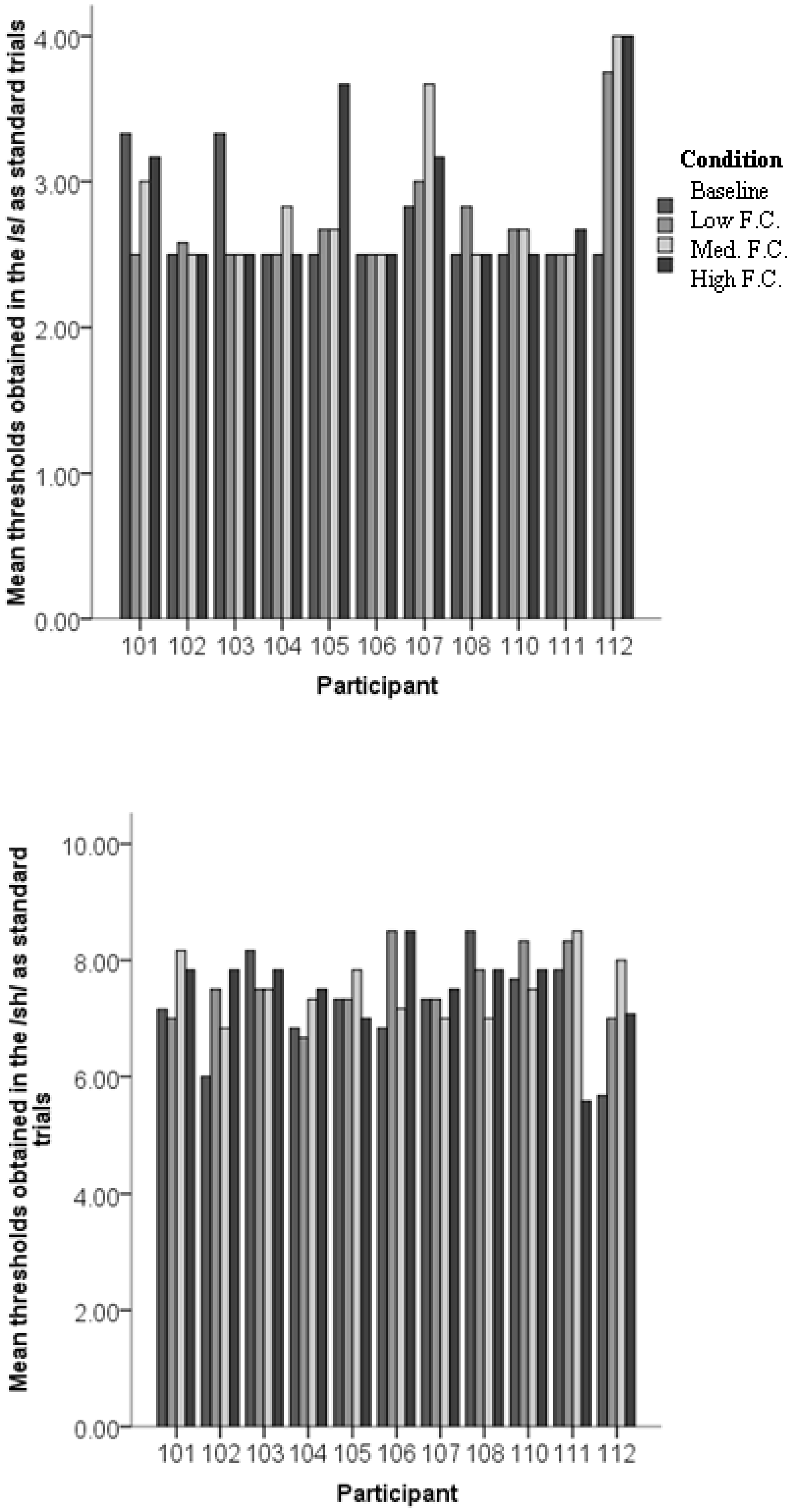

Mean thresholds obtained in the /s/ as standard trials
0.00
1.00
2.00
3.00
4.00
101 102 103 104 105 106 107 108 110 111 112
Participant
Condition
Baseline
Low F.C.
Med. F.C.
High F.C.
Mean thresholds obtained in the /sh/ as standard trials
0.00
2.00
4.00
6.00
8.00
10.00
101 102 103 104 105 106 107 108 110 111 112
Participant

Figure 4

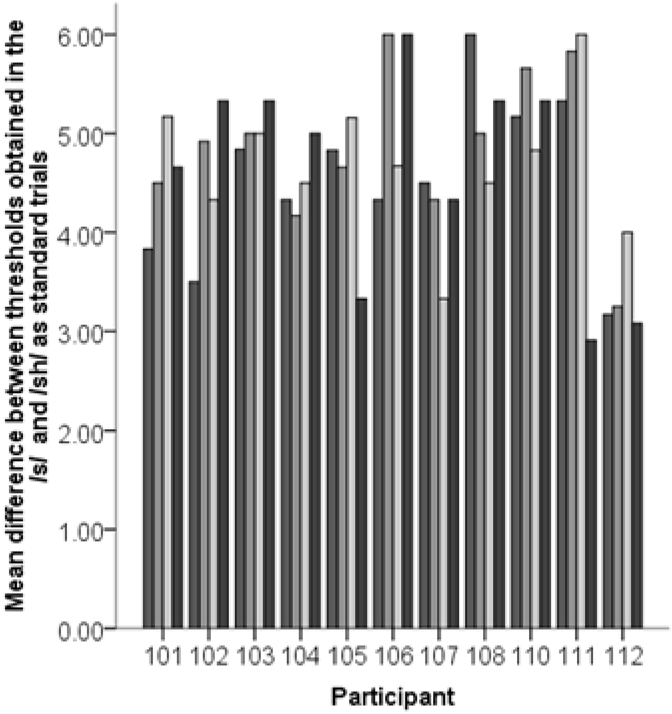


Figure 4 continued

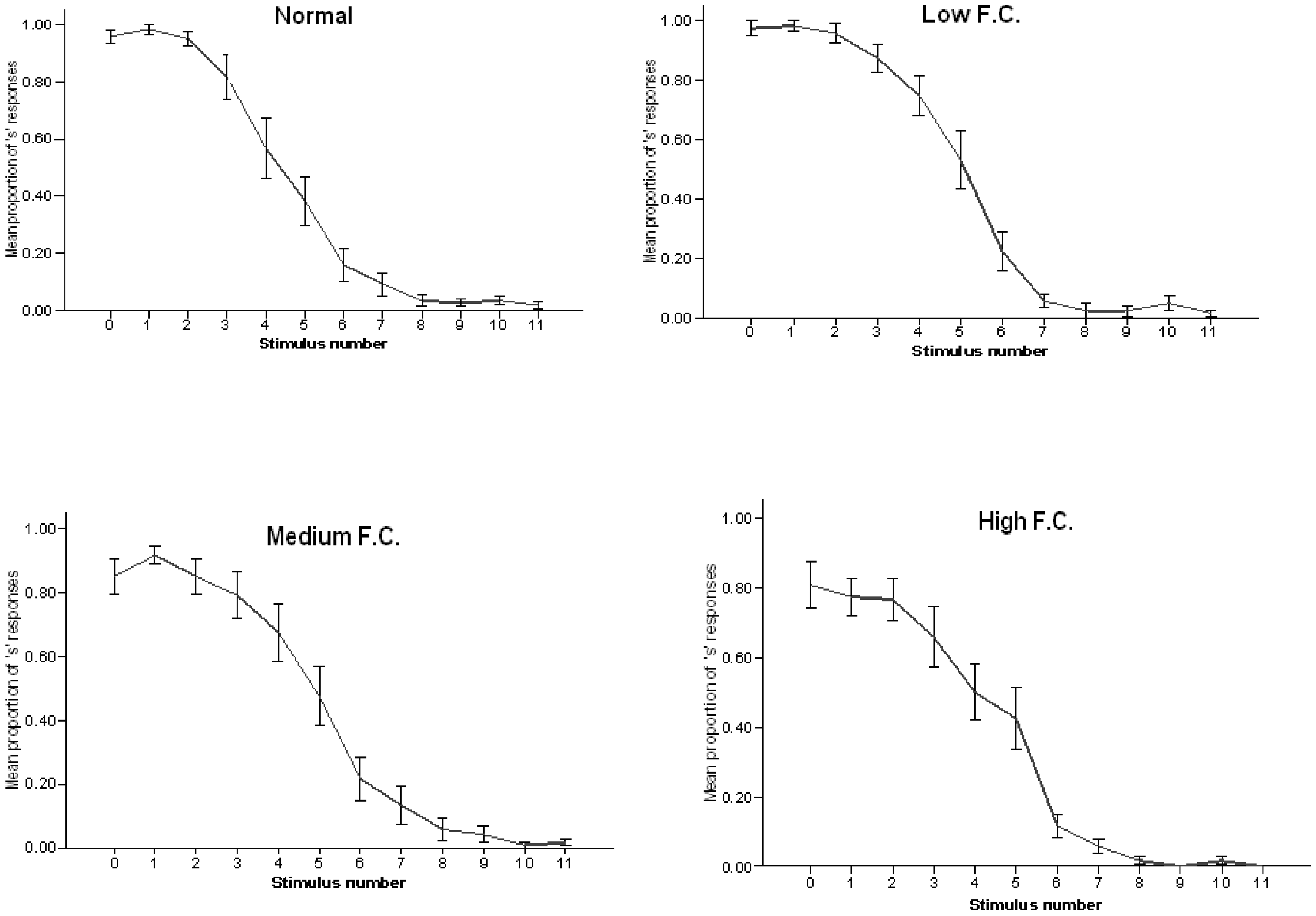

Normal
Low F.C.
Medium F.C.
High F.C.
Mean proportion of 's' responses
1.00
0.80
0.60
0.40
0.20
0.00
0 1 2 3 4 5 6 7 8 9 10 11
Stimulus number

Figure 5

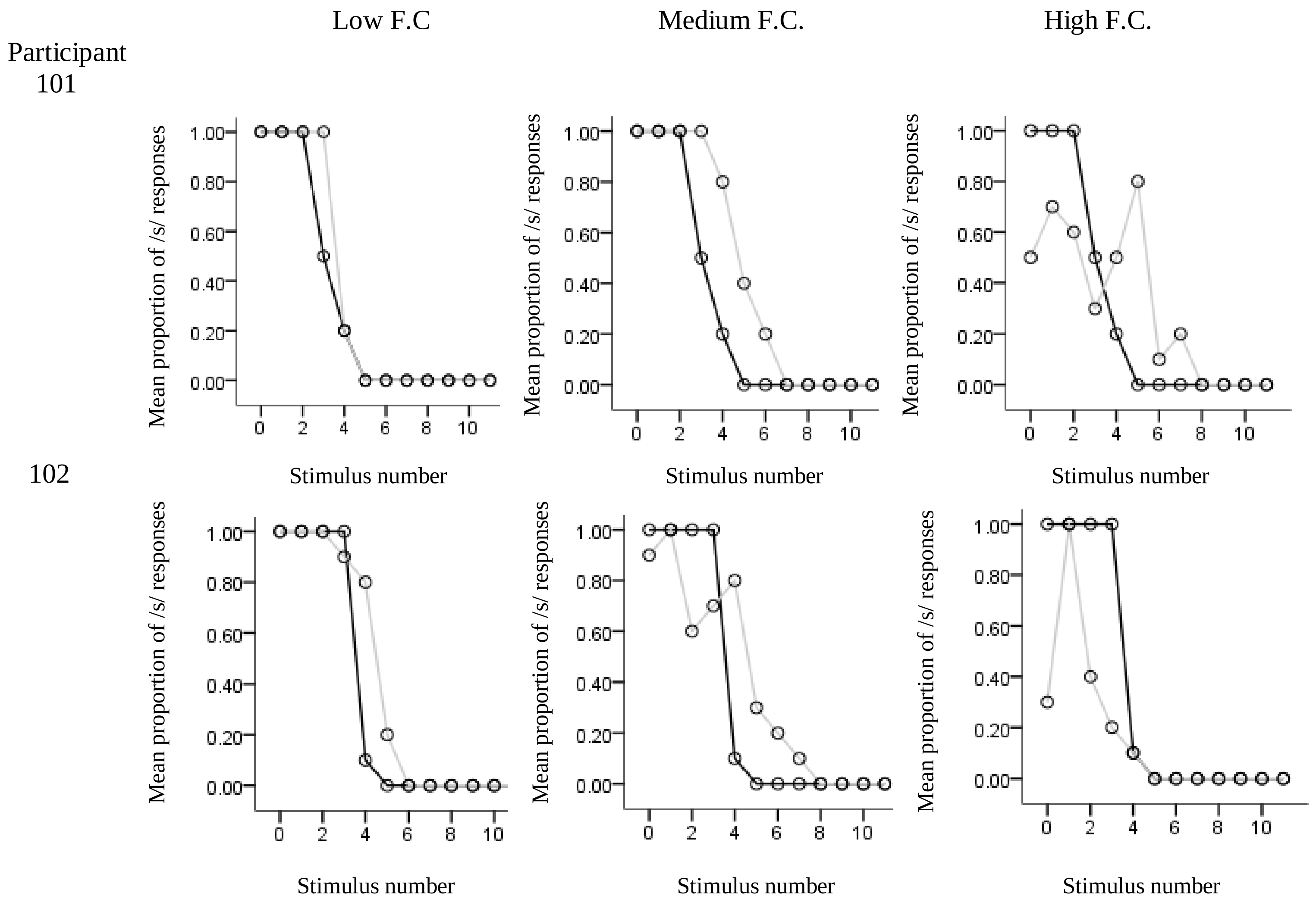

Low F.C
Medium F.C.
High F.C.
Participant
101
102
Mean proportion of /s/ responses
1.00
0.80
0.60
0.40
0.20
0.00
0
2
4
6
8
10
Stimulus number

Figure 6

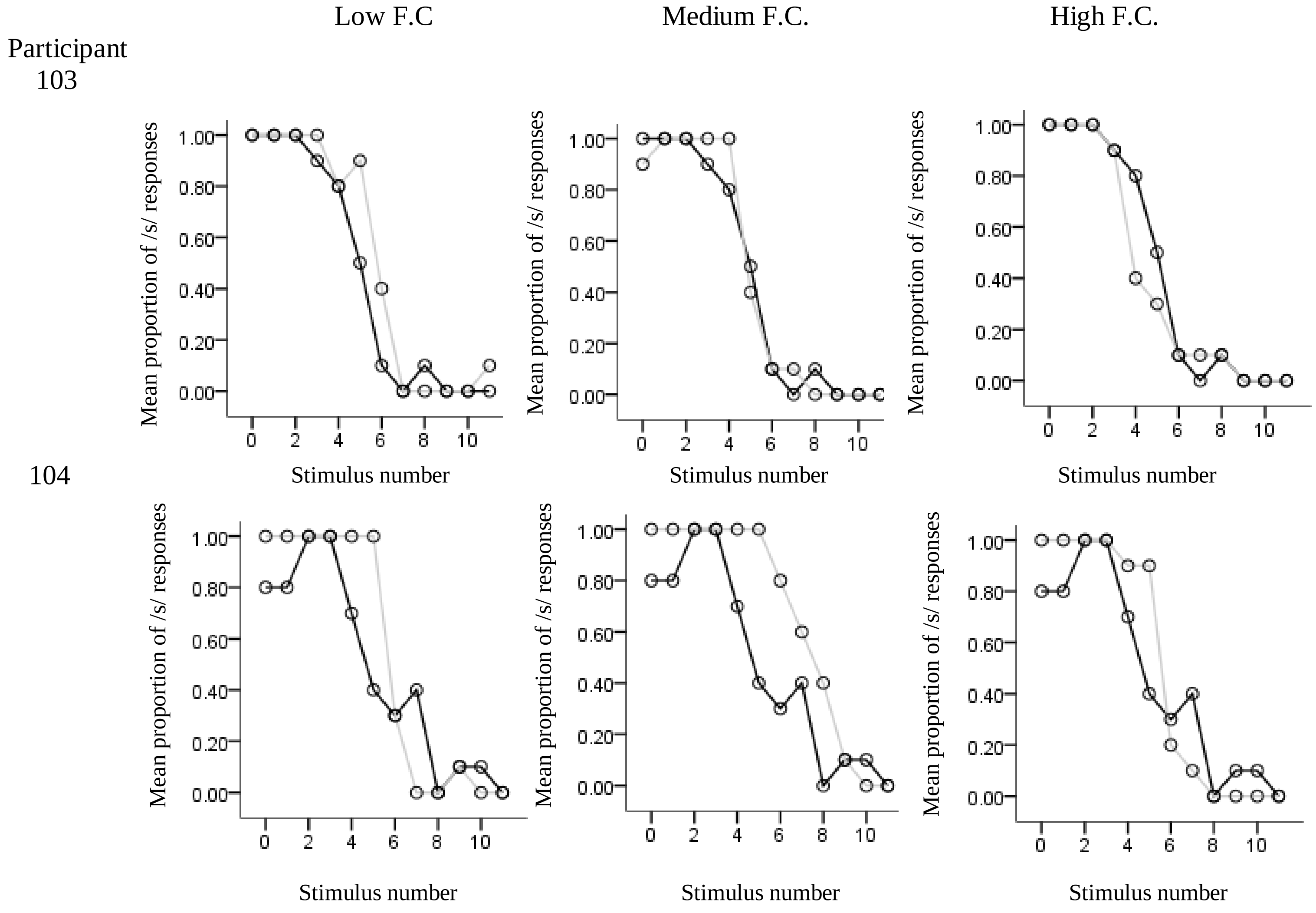


Figure 6 continued

Low F.C Medium F.C. High F.C.

Participant
105

106

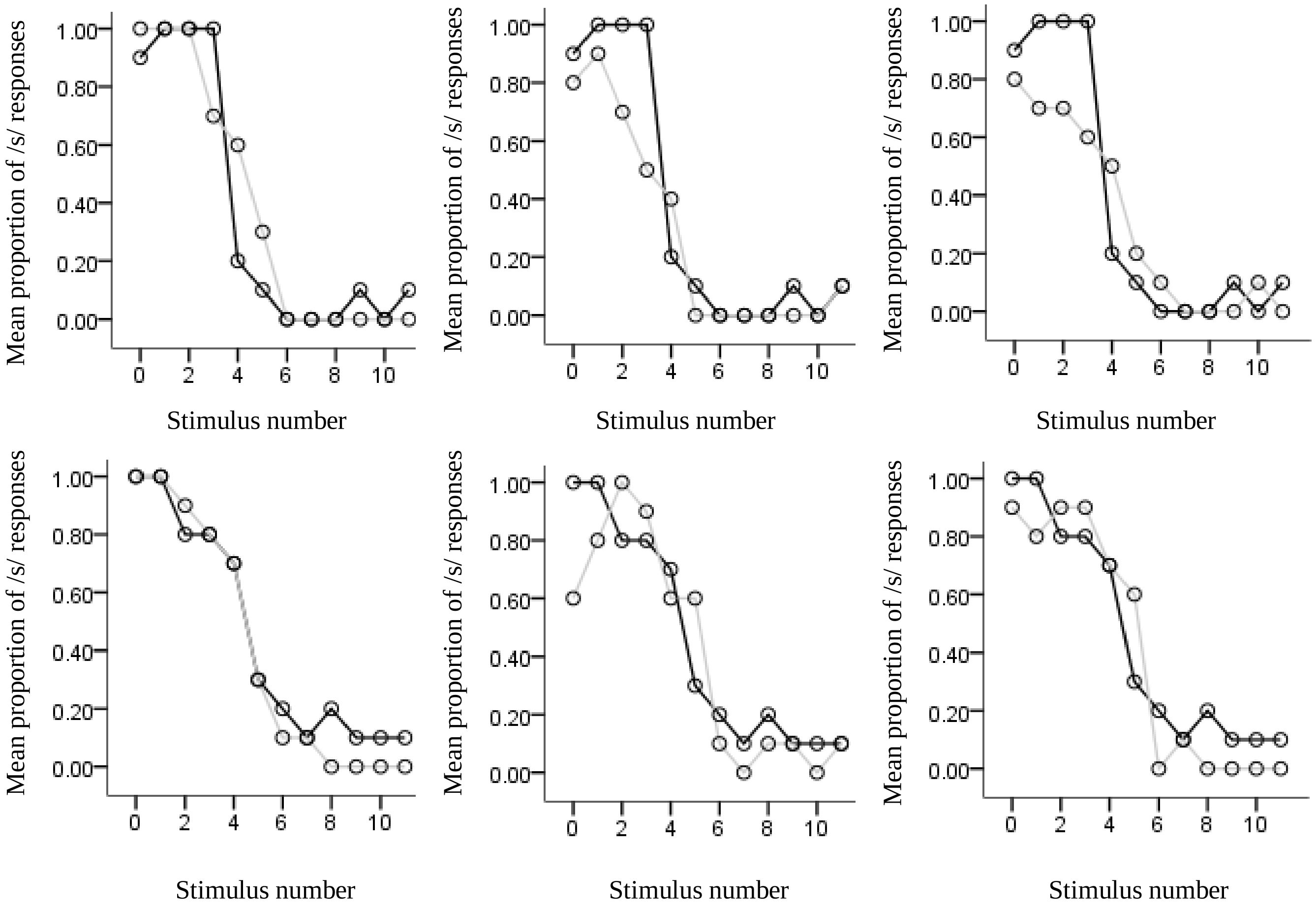


Figure 6 continued

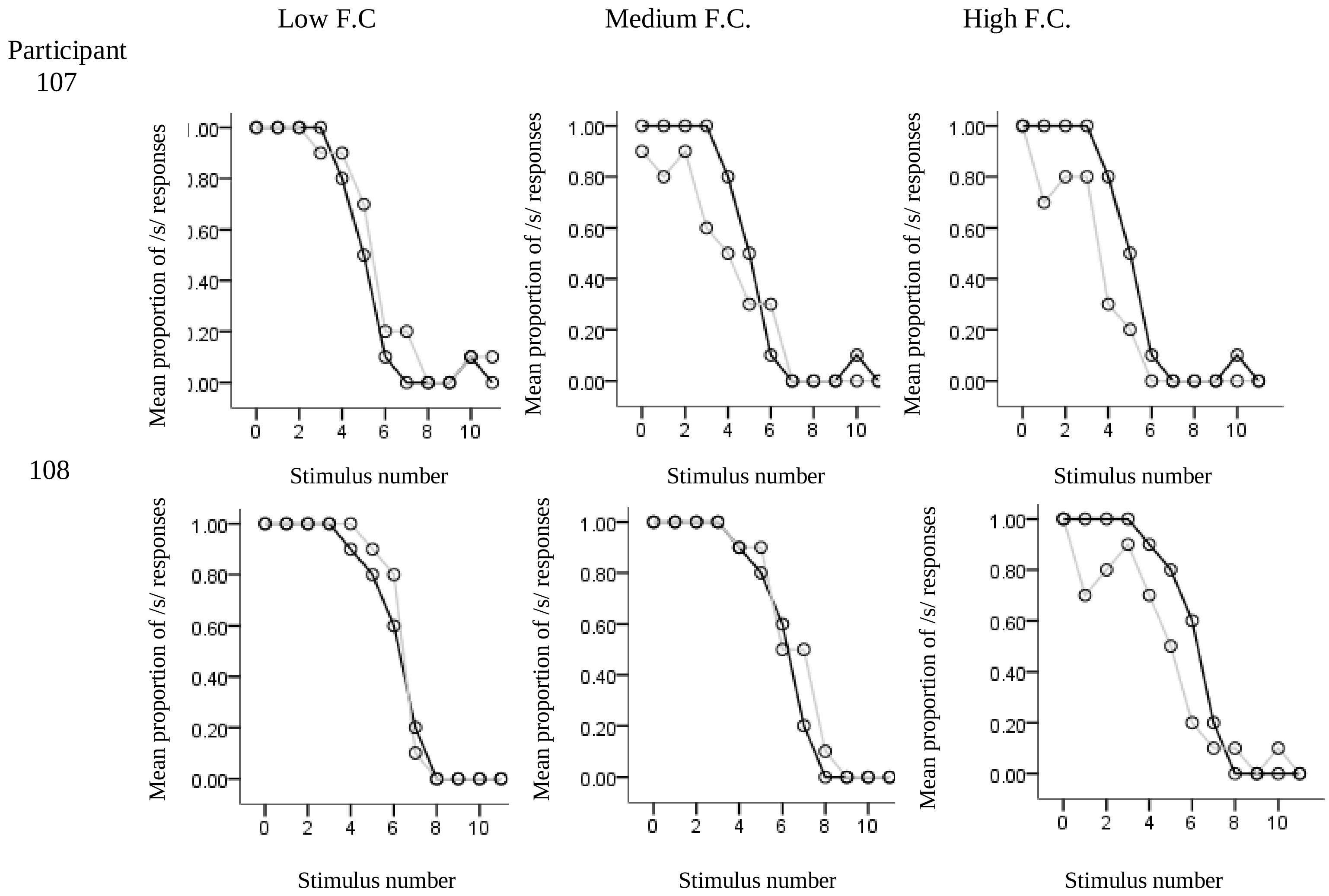


Figure 6 continued

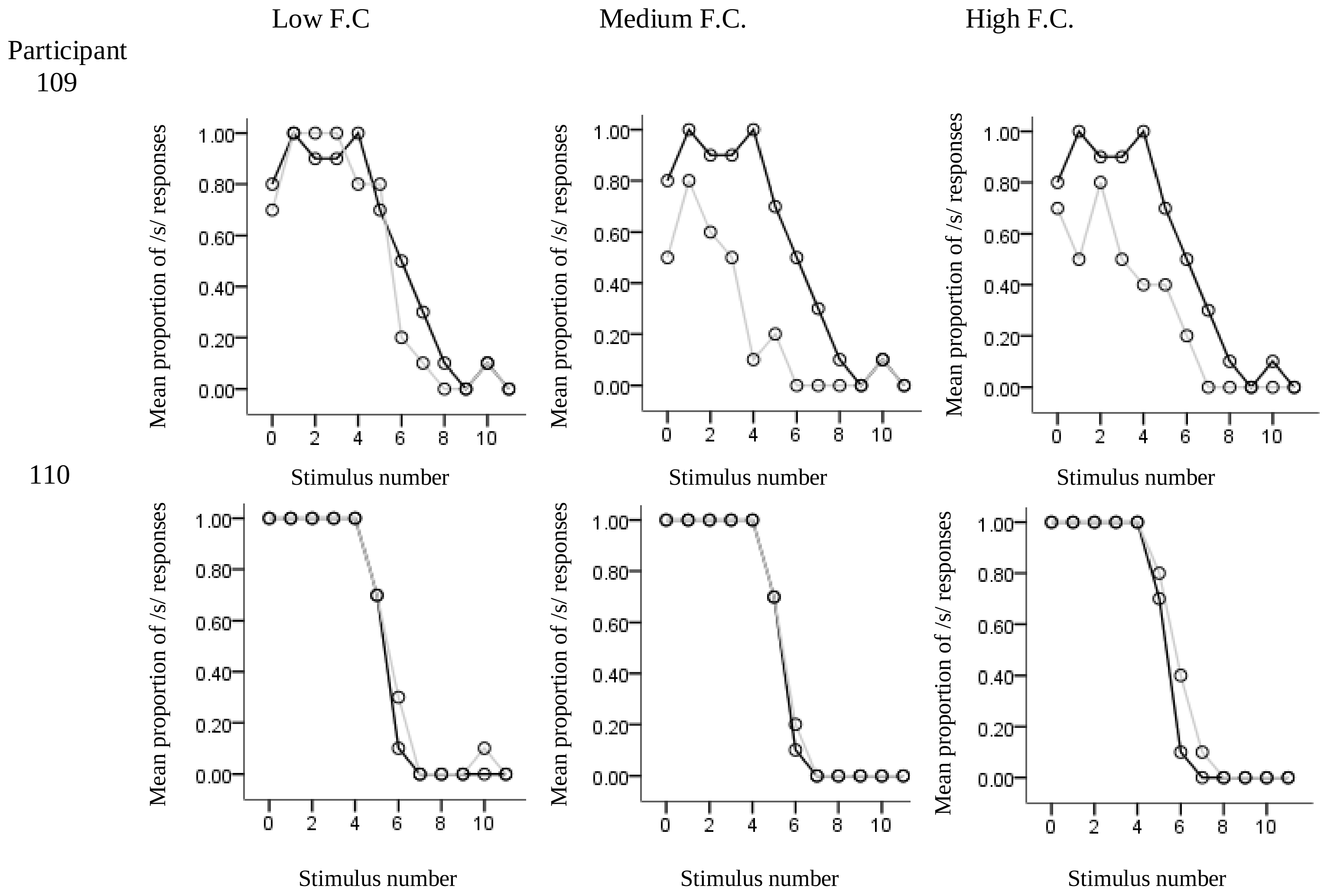
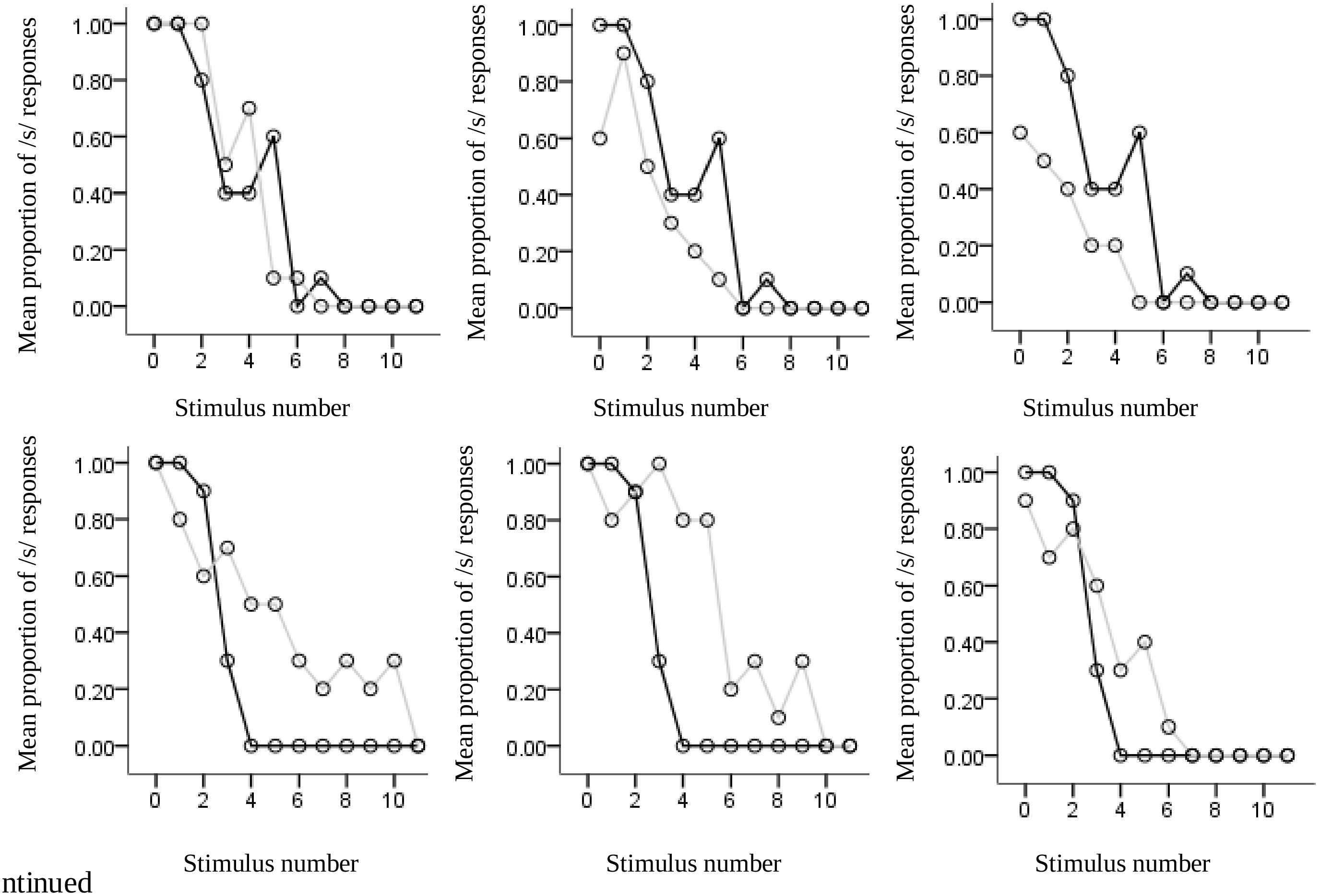


Figure 6 continued

Low F.C Medium F.C. High F.C.

Participant
111



112

Figure 6 continued

CHAPTER 5

INTERNATIONAL JOURNAL OF AUDIOLOGY MANUSCRIPT

DOES COGNITIVE FUNCTION PREDICT FREQUENCY COMPRESSED SPEECH RECOGNITION IN LISTENERS WITH NORMAL HEARING?

Does cognitive function predict frequency compressed speech recognition in listeners with normal hearing?

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Key words

Frequency Compression

Cognition

Speech in Noise

Trail Making Test

Reading Span Test

Abbreviations

TMT-A/B = Trail Making Test A/B

RST = Reading Span Test

FC = Frequency Compression

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ABSTRACT

Objective: The aim was to investigate the relationship between cognitive ability and frequency compressed speech recognition in listeners with normal hearing. *Design:* Speech in noise recognition was measured using Institute of Electrical and Electronic Engineers sentences presented over earphones at 65 dB SPL and a range of signal-to-noise ratios. There were three conditions: unprocessed, and at frequency compression ratios of 2:1 and 3:1 (cut-off frequency, 1.6 kHz). Working memory and cognitive ability were measured using the Reading Span Test and the Trail Making Test, respectively. *Study Sample:* Participants were 15 young normal hearing adults. *Results:* There was a statistically significant reduction in mean speech recognition from around 80% when unprocessed to 40% for 2:1 compression and 30% for 3:1 compression. There was a statistically significant relationship between speech recognition and cognition for the unprocessed condition but not for the frequency compressed conditions. *Conclusions:* The relationship between cognitive functioning and recognition of frequency compressed speech in noise was not statistically significant. The findings may have been different if the participants had been provided with training and/or time to 'acclimatise' to the frequency compressed conditions.

Non-linear frequency compression is a method of compressing the components of a signal, usually at the higher frequencies, into a reduced bandwidth. The intention is to restore audibility of high frequency sounds for listeners with a sensorineural hearing impairment when this has not been possible with a conventional hearing aid, due to bandwidth or usable gain limitations. Non-linear frequency compression works by compressing frequencies above a specified cut-off frequency, without altering information below the cut-off frequency. Another distinguishing feature of non-linear frequency compression is that there is no overlap between the high frequency information that has been compressed and the low and mid frequency parts of the signal that have been unaffected by non-linear frequency compression. This method of frequency lowering is currently used in a range of hearing aids manufactured by Phonak AG, Switzerland. This study aims to investigate whether cognitive functioning can predict the recognition of frequency compressed speech in noise by listeners with normal hearing.

Whilst frequency compression has been shown to provide significant benefit to some hearing impaired listeners, results have been mixed and large individual differences have been reported (for example, Simpson et al, 2005; Glista et al, 2009). Simpson et al (2005), in the first clinical study of non-linear frequency compression, provided 17 experienced hearing aid users, with moderate-to-severe sloping hearing losses, with prototype non-linear frequency compression hearing aids for a period of four-to-six weeks. At the end of the trial period, participants were asked to complete a monosyllabic word recognition task (in quiet). Participants were then asked to wear their own conventional hearing aids for a two-week period, after which, the word recognition test was repeated. The results showed that eight of the seventeen participants obtained statistically significant increases in their word recognition scores when using non-linear frequency compression aids compared to when using conventional amplification. Of the remaining participants, eight showed no significant difference in scores, whilst one participant performed significantly better with their own hearing aid than with the frequency compression device.

In a subsequent study, Simpson et al (2006) investigated the effect of frequency compression on the speech perception scores of seven listeners with steeply sloping hearing losses. Again, the non-linear frequency compression devices were worn for four-to-six weeks and testing was conducted towards the end of the trial period. In addition to a monosyllabic word recognition task, medial consonant recognition (in quiet with a male speaker) and sentence recognition in noise (with a female speaker) tests were also conducted. Results showed that there was no significant difference in mean scores, with and without frequency compression, in the speech in quiet conditions. Furthermore, group deficits of 2% in the consonant recognition task and 6% in the monosyllabic word recognition task were evident when frequency compression was compared to performance with conventional amplification. The results of the sentence in noise test revealed that only one participant obtained significant benefit from frequency compression (it is worth noting that only five participants took part in this part of the experiment). The results may also have been affected by the fact that three of the seven participants in this study had not used hearing aids previously, whereas all participants in the previous study (Simpson et al, 2005) were experienced hearing aid users.

The effect of non-linear frequency compression on perception was also investigated by Glista et al (2009). A total of twenty four participants (13 adults, 11 children) with a moderate-to-profound sloping high frequency hearing loss took part in the study. The participants were provided with bilateral non-linear frequency compression hearing aids and asked to wear them as often as possible in their everyday lives.

Initially, participants wore the hearing aid with the frequency compression disabled for a number of weeks (2 – 12 weeks, mean: 4.2 weeks), after which the experimental tests were administered to familiarise participants with the procedures (results were not analysed). During the second stage of the trial, the frequency compression setting was enabled and participants again wore the devices for a number of weeks (3 weeks to 1.3 years, mean: 10.8 weeks). All tests were then re-administered and performance with the frequency compression setting enabled was assessed. For the final part of the trial, the hearing aids were programmed with both the conventional and frequency compression settings and participants were able to switch between them as preferred. The final part of the trial lasted between 2 weeks and 5 months, following which the tests were administered again and performance with conventional processing was assessed. The results showed that 5 out of 13 adults, and 7 out of 11 children showed a significant improvement on at least one measure of speech perception when using frequency compression.

More recently, Wolfe et al (2010, 2011) have reported that the use of frequency compression led to significant improvements in the perception of some high frequency speech sounds in a group of 15 children (aged 5-13 years) with moderate hearing loss. However, only group mean scores were presented so it is not possible to determine the range in benefit from frequency compression between different listeners.

Currently, predictors of benefit from frequency compression remain elusive, although work by Glista et al (2009) suggests that age (adult versus child) and severity/configuration of hearing loss may predict performance on some speech perception tasks, with children and listeners with more severe high frequency losses obtaining the most benefit from frequency compression. However, it is possible that this reported age effect may be due to differences in the adult and paediatric prescriptions used to fit the frequency compression hearing aids: the paediatric targets recommend stronger frequency compression settings compared to adult targets. One may also infer an effect of severity and/or configuration of loss from the differing results reported in the studies by Simpson et al (2005, 2006). In the earlier study, some participants with moderately sloping losses obtained significant benefit from frequency compression whilst in the later study, none of the participants with severely sloping losses showed any benefit. Whilst these differences may be evidence of a predictive effect of hearing loss on outcome with frequency compression aids, it is possible that the results may have been influenced by the fact that all listeners in the 2005 study were experienced hearing aid users whilst three of the seven participants in the 2006 study were new hearing aid users. Furthermore, the studies used prototype frequency compression hearing aids as opposed to the commercially available aids used by Glista et al (2009).

A possible predictor of benefit from frequency compression may be cognitive ability. In a review by Akeroyd (2008), it was reported that after audiological configuration, the most significant predictor of benefit from conventional hearing aids was performance on cognitive tests; in particular, tests of working memory span. Working memory (Baddeley and Hitch, 1974) is a limited capacity system used to temporarily store and manipulate incoming information and, to an extent, to allocate attentional resources accordingly. However, to date, no study has investigated the relationship between working memory span and the perception of frequency compressed speech.

The Reading Span Test (RST) is a commonly used test of working memory span. The RST was originally developed by Daneman and Carpenter (1980) but adapted later by Rönnberg et al (1989). The test consists of two parts: i) a processing element, and ii) a storage element. Participants are presented with a sequence of sentences in blocks of 3-6. Immediately after reading each sentence, the participant must state whether the sentence made sense or not (processing component). At the end of each block, participants are asked to recall either the first or last word of every sentence in that group (storage component). The percentage of words correctly recalled is then calculated. Lunner (2003), for example, found that, after controlling for the effects of audibility and age, reading span test score was correlated with both aided and unaided recognition of speech in noise, with better performance in the RST being associated with better speech in noise scores.

A further cognitive measure that may be a candidate for predicting benefit from frequency compression is the Trail Making Test (TMT, Reitan, 1958, 1992). This test is used to measure executive control function and may be seen as an index of cognitive flexibility. In order to accurately perceive speech in noise, listeners need to be able to selectively attend to the signal and ignore the competing noise, a task that requires cognitive skills measured by the TMT. The test has two parts known as the TMT-A and the TMT-B. In both cases, the participants' task is to join 25 dots in a specified sequence. In the TMT-A, the dots are joined in numerical order. In the TMT-B, the dots are joined in a sequence alternating between numerical and alphabetical (for example, 1-A-2-B etc). It has been shown that performance on the TMT may predict the ability of listeners with a hearing loss to perceive speech in a novel accent (Adank and Janse, 2010), with those with better scores on the TMT obtaining higher speech perception scores. As frequency compression alters the spectral and temporal relationship between speech components, perception of speech processed in this way may require similar skills to those needed to perceive speech in a novel accent.

The aim of the present study was to investigate the relationship between performance in the Reading Span and Trail Making tests and recognition of frequency compressed speech in noise in listeners with normal hearing. It was hypothesised that participants with better scores in the cognitive tests would perform better on the speech in noise task in all conditions. The results of the study will be used to inform the design of future research using listeners with sensorineural hearing loss.

METHOD

Participants

A sample of 15 participants (8F and 7M), with self-reported normal hearing, was recruited to the study. Participants were aged between 18 and 50 years with a mean age of 26 years. Ethical approval was obtained from the University of Manchester, School of Psychological Sciences Research Ethics Committee.

Procedure

Reading Span Test

A computerised version of the Reading Span Test (RST) (Rönnberg et al, 1989) was administered. The RST consists of a sequence of sentences (such as 'the horse trotted nicely') in blocks of 3-6 sentences. Sentences were presented to the participant, word by word, on a computer screen at the rate of one word every 800 msec. Immediately after reading each sentence, the participant must state whether it made sense giving a yes-no response (processing component). At the end of each block, participants were asked to recall either the first or last word of every sentence in that group (storage component). The order in which participants were asked to recall either first or last words of each sentence was randomised. In the first trial, three sentences were presented. In each subsequent trial the number of sentences presented was increased by one, up to six sentences in the final trial. The presentation of each sentence was separated by a 1750 msec gap. The test took approximately ten minutes to complete. Upon completion of the test, the percentage of words correctly recalled was then calculated. This method of scoring has been shown to be more reliable than alternative techniques such as scoring based on the highest set in which participants correctly recalled the majority of words (Friedman and Miyake, 2005).

Traditionally, only the scores from the storage component of working memory span tests are analysed; however, according to Unsworth et al (2009), scores on the processing element of working memory span tasks contribute substantial unique variance when predicting higher order cognition. Therefore, in addition to analysing the percentage of words correctly recalled, the percentage of errors in the processing element of the RST (that is, whether or not the sentences made sense) was also calculated.

Trail Making Tests A and B

The TMT A and B are paper and pencil based tasks (see Reitan 1958, 1992). The participants' task was to join together a series of points on a sheet of paper in the correct order without allowing their pencil to leave the page.

In the TMT-A, the points are labelled from 1-25, the task being to join the points in the correct ascending numerical order. In the TMT-B, the points are labelled 1-12 and A-L and the participants' task was to join the points in the correct alphabetical and numerical order, alternating between the two (for example, 1-A-2-B-3-C and so on). Prior to completing the TMT tests, the participants were given a sample task on which to practice. Performance on the task was assessed by measuring the total time taken to complete each task. If the participant made a mistake, the experimenter pointed out their error and asked the participant to correct it. Errors were penalised only in that they increased the time taken to complete the task. Participants were aware that the time taken to complete the task was the outcome measure of interest.

Sentence in noise test

The stimuli were Institute of Electrical and Electronics Engineers (IEEE) sentences (Rothauser et al, 1968) spoken by a female talker with a standard English accent. IEEE sentences were selected due to the relative lack of contextual information provided in these sentence lists (for example, 'fly by night and you waste little time'). The stimuli were presented in a background of multitalker (20 speakers) babble (Auditec, St Louis, USA) at various SNRs (detailed below).

Stimuli were played on a laptop computer and presented bilaterally using Sennheiser HD 215 headphones. A total of six lists were presented in one of three conditions (two lists per condition): no frequency compression, frequency compression with a cut-off frequency of 1.6 kHz and a compression ratio of 2:1, and frequency compression with a cut-off frequency of 1.6 kHz and a compression ratio of 3:1. The settings were selected to provide medium and high levels of compression with the relatively low cut-off frequency chosen to combat predicted ceiling effects due to the use of listeners with normal hearing. Stimuli were processed by Phonak AG, using custom software to apply frequency compression using the same algorithm applied in their range of hearing aids (see Simpson et al, 2005 and the patent registered to Phonak, 2009 for technical details of the algorithm employed). The allocation of sentence lists to each condition was counterbalanced, as was the order of testing. Within each list, all sentences were presented at 65 dB SPL, and the level of the noise varied in 3 dB steps from +12 to -15 dB in a fixed order (in ascending order of difficulty), similar to the method recommended by Wilson et al (2007). The participants' task was to repeat each sentence back to the experimenter and the total percentage of keywords (5 per sentence) correctly recognized in each condition was calculated.

RESULTS

Results are reported for 14 participants only, as the data from one participant fell outside the normal range for most cognitive measures. After checking the data were normally distributed, results were summarised using mean and standard deviation and analysed using parametric statistics.

The effect of frequency compression on sentence in noise test scores

Figure 1 shows the group mean percentage correct scores on the sentence–in-noise test in each of the three signal processing conditions. A clear pattern of decreasing mean scores with increasing frequency compression is evident. The results of a one-factor repeated-measures ANOVA test confirm a significant effect of speech processing condition on mean number of keywords correctly identified (F[2,26] = 422.04, p<.001) (Mauchly's test n.s). Post hoc pairwise comparisons with a Bonferroni correction revealed significant differences in performance between each of the three conditions.

Figure 1 here

The relationship between RST and sentence in noise test scores

The mean percentage correct score on the RST was 47.4 (1 SD ± 12.44), whilst the group mean error rate was 4.37 (1 SD ±2.87).

Figure 2 here

Figure 2 shows scatter plots of the relationship between speech in noise score and percentage correct (left panel) and error rate (right panel) in the RST. The y-axes show the same range but different absolute values to enable direct comparison. Upon inspection of the left panel of Figure 2, the only condition in which a correlation between speech in noise and RST percentage correct scores appears to be present is in the unprocessed condition. Pearson's correlation coefficient was calculated to examine the relationship between scores on the Reading Span Test and performance on the sentence in noise test for each of the three conditions. A borderline significant positive correlation (indicating that better performance on the RST corresponds to better speech in noise scores) was observed in the unprocessed condition only with a correlation coefficient of 0.45, p (one tailed) = 0.045. The correlation coefficients for the two frequency compression conditions failed to reach significance: FC 2:1, r= 0.20, p (one tailed) = 0.25; FC 3:1, r= 0.11, p (one tailed) = 0.36.

The scatter plots in the right panel of Figure 3 show the relationship between the percentage of errors made in the RST and performance in the speech in noise test in each of the three signal processing conditions. Inspection of the scatter plots suggest a negative trend between the two variables and the unprocessed condition, with the relationship becoming less clear with increasing frequency compression. This correlation was significant in the unprocessed condition only, with a correlation coefficient of -0.70, p (one tailed) = 0.003. Again, the correlation coefficients for the two frequency compression conditions were non-significant at -0.37, p (one tailed) = 0.10 (FC 2:1) and -0.10, p (one tailed) = 0.38 (FC 3:1).

The relationship between TMT and sentence in noise test scores

The mean score for performance on the TMT-A was 19 seconds (1 SD ±2.90) whilst the mean score for performance on the TMT-B was 39.3 seconds (1 SD ±9.39).

Figure 3 here

The panels in the left column of Figure 3 shows the relationship between TMT-A and sentence in noise scores. The scatter plots show no clear relationship between the two measures in any of the three signal processing conditions. No significant correlations were observed between scores on the TMT-A and performance in the speech in noise task for any of the three signal processing conditions with correlation coefficients of 0.11 (no frequency compression), p (one tailed) = 0.35, 0.20 (FC 2:1) p (one tailed) = 0.24 and -0.16, p (one tailed) = 0.30 (FC 3:1), respectively.

The panels in the right hand column of Figure 3 show the relationship between TMT-B and speech in noise scores. The scatter plots suggest a negative relationship between the two variables in the unprocessed condition only. Scores on the Trail Making Test B were significantly correlated with performance in the speech in noise test in the unprocessed condition only with a correlation coefficient of -0.45, p (one tailed) =0.054, indicating that lower (and therefore, better) TMT-B scores correspond to better speech in noise perception. The correlation coefficients for the two frequency compression conditions were non significant at -0.06, p (one tailed) = 0.41 (FC 2:1) and -0.04, p (one tailed) =0.45 (FC 3:1) respectively.

The relationship between RST and TMT-B scores

The analyses above revealed that TMT-B scores and both outcome measures obtained from the RST were significantly correlated with performance in the speech in noise task (for the unprocessed condition only). Therefore, the relationship between these three measures was also investigated. The resulting scatter plots are displayed in Figure 4.

Figure 4 here

Upon inspection of the data, RST error rate and TMT-B scores appear to be positively related while a negative trend appears to be present between TMT-B and RST percentage correct scores and also between RST percentage correct and RST percentage error scores. The analysis revealed that scores on the TMT-B were significantly positively correlated with RST percentage error rate with a correlation coefficient of 0.57, p (one tailed) = 0.017 and significantly negatively correlated with RST percentage correct scores with a correlation coefficient of -0.46, p (one tailed) = 0.048. The relationship between RST error rate and percentage correct scores was found to be non significant with a correlation coefficient of -0.41, p (one tailed) = 0.070. These correlations suggest that individuals who perform well on one of these measures tend also to perform well in the other tests.

DISCUSSION

The results show poorer mean speech recognition performance in the frequency compressed conditions of the sentence in noise task. Speech perception in noise scores are correlated with scores in the TMT-B and percentage errors in the RST in the unprocessed condition only, with listeners that performed well in the cognitive tests performing well in the speech in noise test. No correlation between cognitive ability and performance in the speech in noise task was observed for either of the frequency compression conditions.

The effect of frequency compression on sentence in noise perception

The fact that performance was poorer in the frequency compressed conditions is unsurprising. Specifically, the results show that performance in the unprocessed condition was best, with performance deteriorating as the compression ratio was increased. This effect is likely due to the use of listeners with normal hearing in the study. The fact that the listeners did not have a high frequency hearing loss means that they did not gain access to any additional information when frequency compression was applied to the stimuli. In essence, frequency compression simply added distortion to the stimuli. It is expected that this pattern of results would be different had the tests been conducted using a sample of participants with a sensorineural loss when high frequency audibility would be restored after processing.

The relationship between cognitive function and the perception of unprocessed speech

The perception of non-processed speech was significantly correlated with performance in three of the four cognitive measures investigated, the TMT-A being the exception. It is possible that the TMT-A was simply too easy for the sample of young adults used in the study. This may not be the case for older listeners. Furthermore, secondary analyses revealed that scores on the TMT-B were significantly related to scores on both measures of the RST. The correlation was positive with regards to the RST error rate and negative with regards to the RST percentage correct. This was to be expected as higher scores in the TMT-B and RST error rate equate to poorer performance in the task whereas higher RST percentage correct equate to better performance in the test. This pattern of results suggests that there is some overlap between the processes abilities measured on the RST and TMT-B.

The scores show that both measures of the RST were more closely related to performance on the TMT-B than they were to each other. It may be that, in addition to assessing working memory capacity, the RST is also providing a measure of executive control and/or task switching ability due to the dual-task nature of the procedure. This idea has been previously suggested by Engle (2002) who argued that a greater working memory capacity results from better attentional control, rather than a larger working memory store. Therefore, high scores on a working memory task suggest better control of attentional resources focus on the target stimuli and avoids distracting information.

This concept seems particularly relevant in this case given that performance in a speech in noise test is, in essence, a direct measurement of the participants' ability to focus effectively on the most useful parts of the signal (for example, by effectively using gaps in the noise to identify parts of the signal) whilst diverting attention from the competing background noise. Therefore, where previous studies have shown a significant relationship between performance in a working memory task and speech in noise perception (see Akeroyd, 2008 for a review), this may be due to the executive control processes measured by the RST as opposed to the storage processes. This may also explain the lack of relationship between performance in the TMT-A and the speech in noise test observed in this study, as the TMT-A is easier, and thus places less strain on executive control mechanisms.

The relationship between cognitive function and the perception of frequency compressed speech

The results of the study provide no evidence of a relationship between performance on the specific cognitive tests used and the perception of frequency compressed speech in noise. It should be noted, however, that this conclusion applies only to situations in which the listener has no previous experience of exposure to frequency compressed speech. Furthermore, this conclusion may only apply to listeners with normal hearing. It may be that for these listeners, the degradation to the signal introduced by frequency compression may have been so severe, relative to normal speech, that even listeners who performed well in the cognitive tasks were unable to effectively use the remaining cues to recognise the sentences. This may not be the case with hearing impaired listeners, for whom frequency compression may improve the signal rather than degrade it.

As frequency compression was new to listeners in this study, it is possible that it was difficult for participants to utilise the speech cues without allowing for perceptual learning of the novel speech sounds that results from the application of frequency compression. If, due to the signal processing applied, much of the contextual information was essentially unavailable to the listener, the lack of a relationship between cognitive ability and speech in noise recognition, may seem logical. If this explanation is correct, we would expect these measures to show a correlation after the listener has been given the opportunity to acclimatise to frequency compression, and has thus regained usable access to the speech cues present in the signal. It is possible, however, that this conclusion may apply only to listeners with normal hearing.

It may also be the case that performance in cognitive tests predicts how well listeners are able to adapt to frequency compression, either in terms of overall benefit or perhaps regarding the speed of adaptation. This stands to reason as both working memory and executive functioning play an important role in learning (for example, Baddeley and Hitch, 1974)

Implications for future research

In addition to investigating the relationship between cognitive functioning and post-acclimatisation scores on the outcome measures, the effect of cognitive performance on the speed of adaptation should also be investigated. A deeper understanding of this process would enable clinicians to better provide appropriate support to individual listeners based on their learning needs. This support may take the form of delivering interventions to improve the speed of acclimatisation or simply directing patients' expectations of what degree of benefit to expect from their hearing aids.

It may also be interesting to investigate this question using a sample of listeners with normal hearing as this would enable the researcher to minimise possible confounds caused by degree and severity of hearing loss, which may camouflage potentially significant effects. Ultimately, however, research in these areas should focus on using a hearing-impaired population, for whom frequency compression devices were developed.

A further area that would benefit from additional research is the investigation of the relationship between RST and TMT-B scores. Whilst research has shown that working memory can be a significant predictor of speech in noise scores (see Akeroyd, 2008 for a review), working memory span tasks are likely to be too long to be used routinely in a clinical setting. The TMT-B, however, takes a few minutes to administer and requires no special equipment or software. If it can be shown that the utility of using working memory span tests in this way relates to their capacity to measure executive function or attentional mechanisms, rather than storage processes, tests such as the TMT-B may prove to be useful in a clinical audiology setting.

Conclusions

There was a statistically significant relationship between speech recognition and most of the cognitive measures for the unprocessed condition but not for the frequency compressed conditions. The findings may have been different if the participants had been provided with training and/or allowed to acclimatise to the frequency compressed conditions. Furthermore, it is possible that hearing impaired listeners will demonstrate a different pattern of results.

ACKNOWLEDGEMENTS

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Figure 1. Mean speech recognition in noise for each of the three signal processing conditions (FC = frequency compression). Error bars show ±1 standard error.

Figure 2. Scatter plots showing the relationship between percentage correct score (left column) and error rate (right column) on the Reading Span test and percentage of keywords correctly identified in the speech in noise test in each of the three conditions: upper panel = no frequency compression; middle panel = compression ratio of 2:1; lower panel = compression ratio of 3:1. The y-axes show the same range but different absolute values to enable direct comparison.

Figure 3. Scatter plots showing the relationship between TMT-A (left column) and TMT-B (right column) scores and the percentage of keywords correctly identified in the speech in noise test in each of the three conditions: upper panel = no frequency compression; middle panel = compression ratio of 2:1; lower panel = compression ratio of 3:1. The y-axes again show the same range but different absolute values to enable direct comparison.

Figure 4. Scatter plots showing the relationship between error rate on the RST and TMT-B scores (upper panel), RST percentage correct and TMT-B scores (middle panel) and RST percentage correct and RST error rates (lower panel).

Figure 1

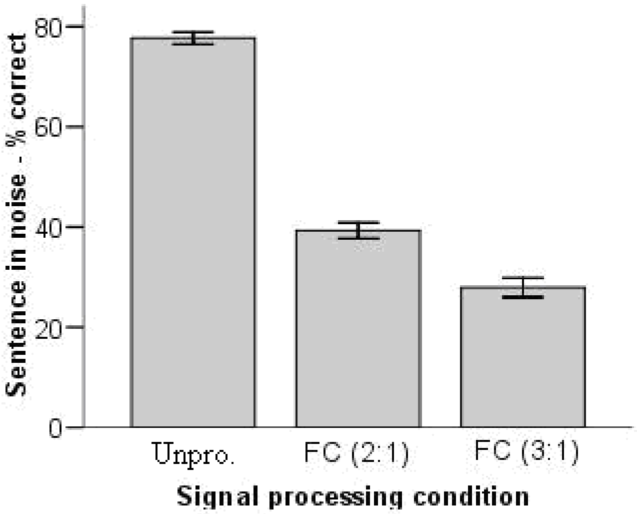

Sentence in noise - % correct
80
60
40
20
0
Unpro.
FC (2:1)
FC (3:1)
Signal processing condition

Figure 2.

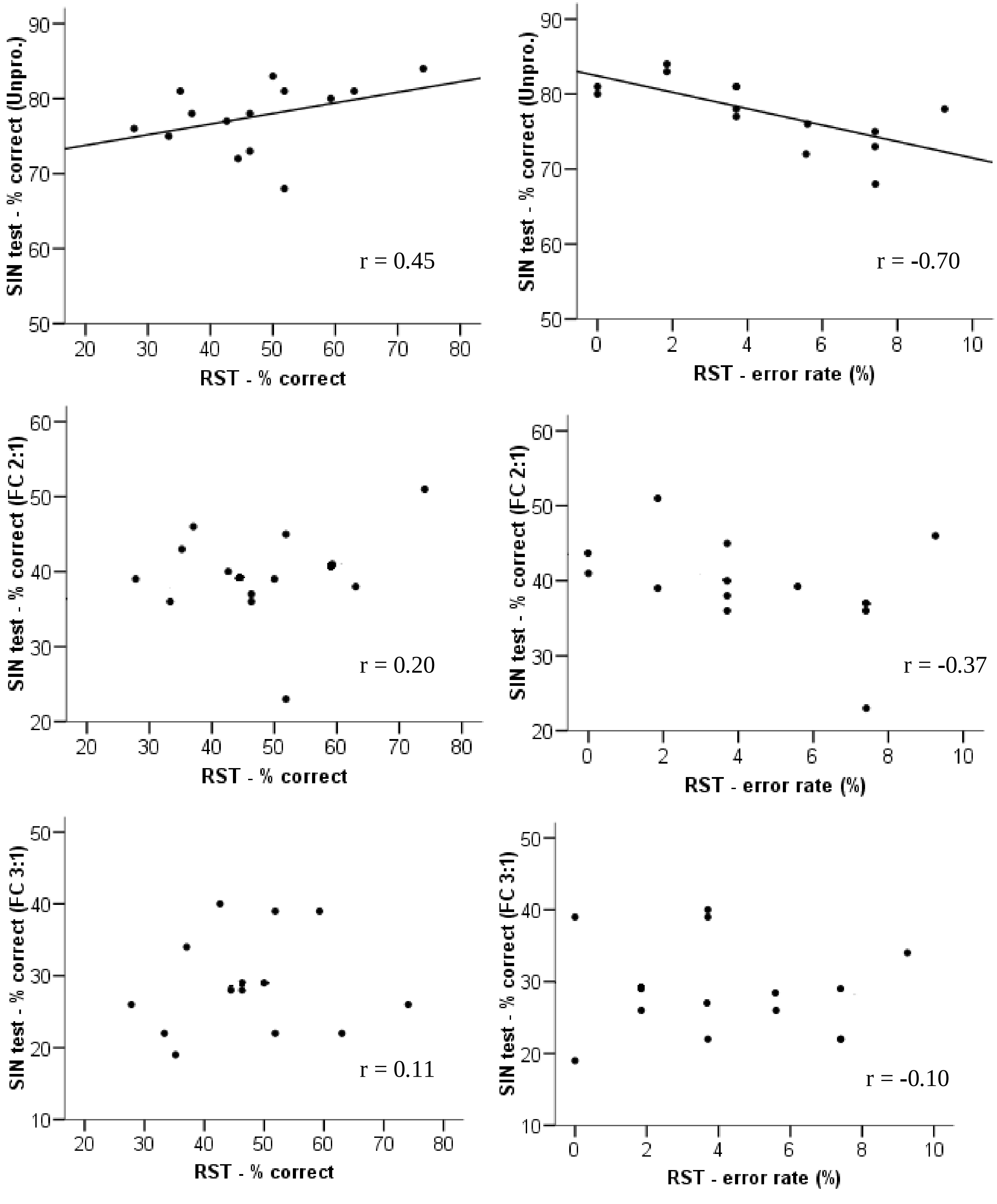

SIN test - % correct (Unpro.)
RST - % correct
r = 0.45
SIN test - % correct (Unpro.)
RST - error rate (%)
r = -0.70
SIN test - % correct (FC 2:1)
RST - % correct
r = 0.20
SIN test - % correct (FC 2:1)
RST - error rate (%)
r = -0.37
SIN test - % correct (FC 3:1)
RST - % correct
r = 0.11
SIN test - % correct (FC 3:1)
RST - error rate (%)
r = -0.10

Figure 3.

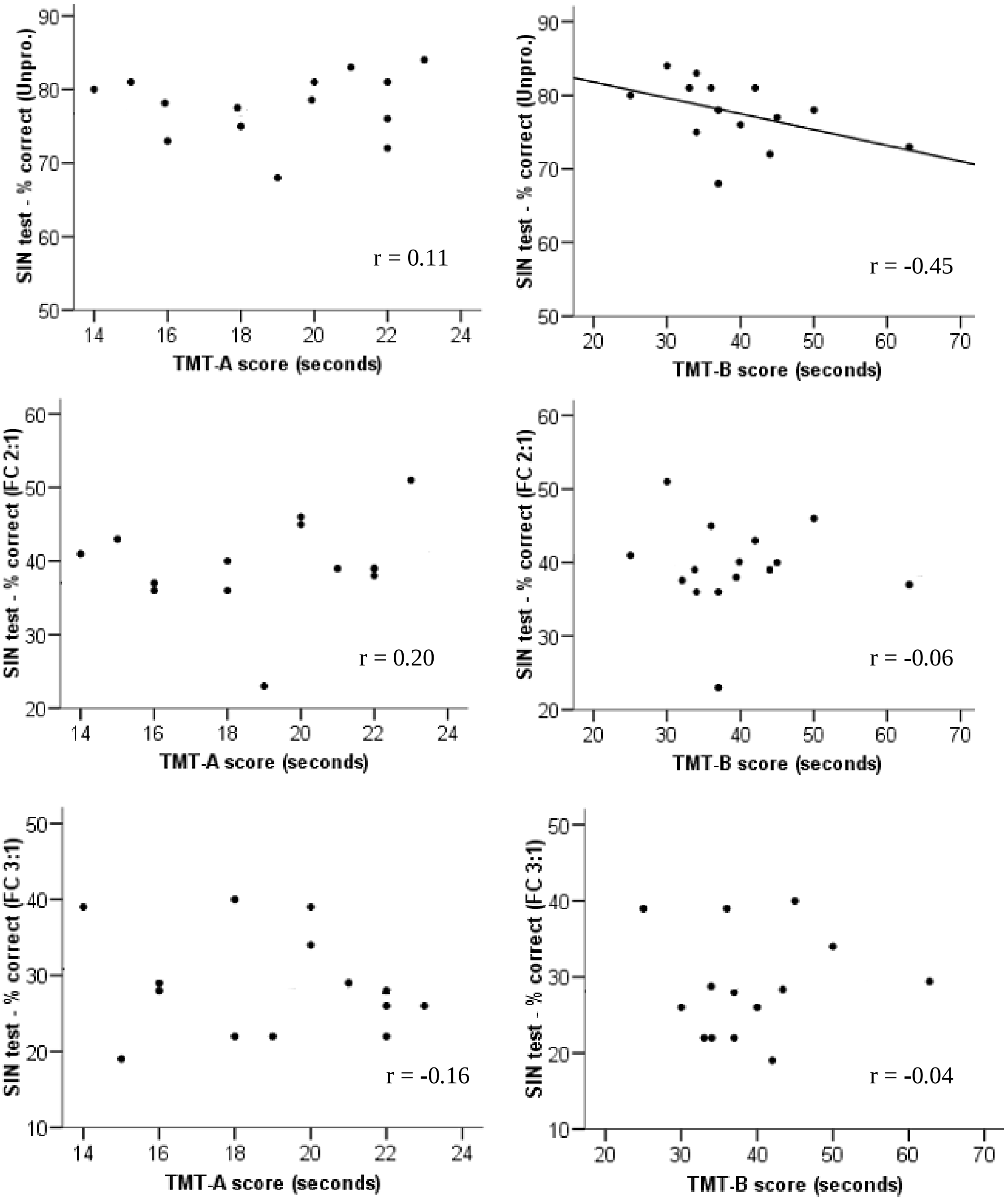
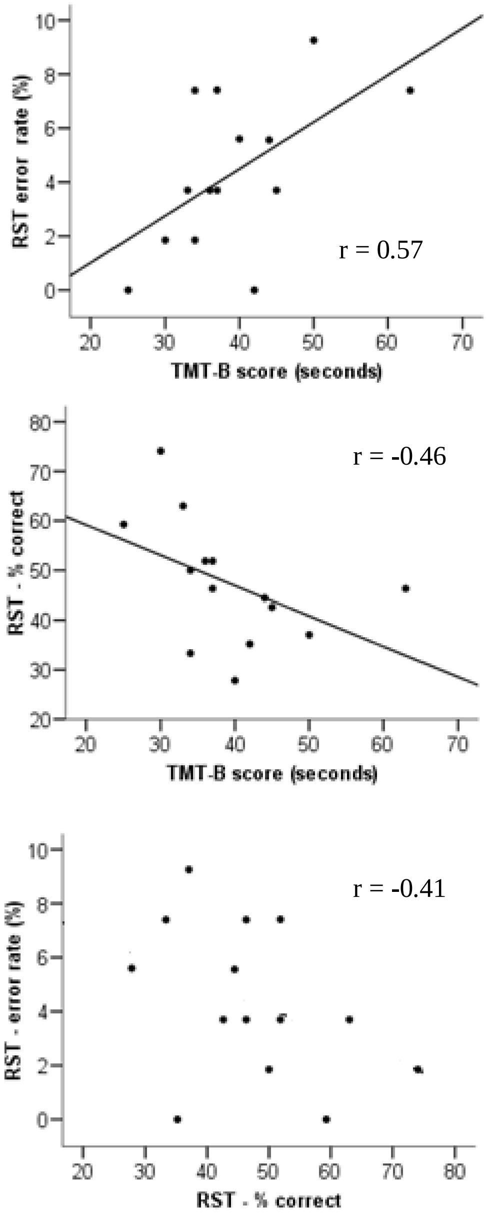

SIN test - % correct (Unpro.)
TMT-A score (seconds)
r = 0.11
SIN test - % correct (Unpro.)
TMT-B score (seconds)
r = -0.45
SIN test - % correct (FC 2:1)
TMT-A score (seconds)
r = 0.20
SIN test - % correct (FC 2:1)
TMT-B score (seconds)
r = -0.06
SIN test - % correct (FC 3:1)
TMT-A score (seconds)
r = -0.16
SIN test - % correct (FC 3:1)
TMT-B score (seconds)
r = -0.04
90
80
70
60
50
40
30
20
10
14
16
18
20
22
24
20
30
40
50
60
70

Figure 4.


RST error rate (%)
10
8
6
4
2
0
20
30
40
50
60
70
TMT-B score (seconds)
r = 0.57
RST - % correct
80
70
60
50
40
30
20
TMT-B score (seconds)
r = -0.46
RST - error rate (%)
RST - % correct
r = -0.41

CHAPTER 6

INTERNATIONAL JOURNAL OF AUDIOLOGY MANUSCRIPT

BENEFIT AND PREDICTORS OF OUTCOME FROM FREQUENCY COMPRESSION HEARING AID USE

Additional material relating to this chapter is presented in Appendix 2.

Benefit and predictors of outcome from frequency compression hearing aid use

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Key words

Frequency Compression

Acclimatisation

Speech Perception

Cognition

Sensorineural Hearing Loss

Predictors of benefit

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ABSTRACT

Objective: The aim of the study was to investigate whether frequency compression hearing aids provide additional benefit to that conferred by conventional amplification. Changes over time to speech perception were also assessed , as were predictors of outcome. *Design:* Participants wore the same hearing aid with frequency compression enabled and disabled for a total of six weeks in each condition. Tests of speech recognition (in both quiet and in noise) were administered alongside two self report questionnaires. Performance in the outcome measures was compared across the two signal processing conditions and at different time points following FC being enabled. Cognitive and audiological measurements were obtained and assessed as possible predictors of FC outcome. *Study Sample:* 12 elderly (aged 65-84 years old) experienced hearing aid users with moderate to severe high frequency hearing loss took part in the study. *Results:* At a group level, frequency compression resulted in significantly higher scores in all of the administered speech tests. There was no significant effect of signal processing condition on either of the self report outcomes. Changes over time were limited only to high frequency phoneme perception. The results suggest that both cognitive and audiological factors can be predictive of speech in noise recognition without FC, but only audiological factors are significantly correlated with additional benefit from FC. The amount of benefit obtained from frequency compression varied between individuals. *Conclusions:* Frequency compression may lead to significant improvements in speech perception outcomes in both quiet and noise for many individuals.

According to Davis (2001), almost 50% of the British population over the age of 70 years have a hearing impairment, with sensorineural hearing losses accounting for the majority of cases. Sensorineural hearing impairments are associated with increased hearing thresholds, typically more marked at the high frequencies. High frequency information is important for the perception of many consonants and for the perception of speech in noise. Conventional hearing aids are often unable to amplify high frequency sounds sufficiently to make them audible for the hearing aid user. This may be because of bandwidth limitations of the hearing aids or due to the occurrence of acoustic feedback.

Alternative signal processing strategies have therefore been developed in order to help make high frequencies audible for more hearing aid users. One such strategy is non-linear frequency compression (NLFC). NLFC is a method of altering the input signal such that frequencies above a given cut-off frequency are compressed into a reduced bandwidth (and amplified), resulting in the information being presented at a lower frequency. As the processing is non-linear, more compression is provided at the highest frequencies. Information below the cut-off frequency is amplified as normal and the compressed and non-compressed portions of the signal do not overlap. NLFC is available in a range of hearing aids manufactured by Phonak AG (Switzerland).

Previous clinical studies of NLFC investigating benefit have produced mixed results with some listeners obtaining significant benefit from NLFC and others showing no difference in speech perception scores with and without NLFC (see for example, Simpson et al, 2005, 2006; Glista et al, 2009). Therefore, the primary aim of the present study was to investigate the degree of additional benefit provided by NLFC compared to that provided by conventional amplification in experienced adult hearing aid users.

The first clinical study to investigate NLFC hearing aids was conducted by Simpson et al (2005). In this study, 17 adults with moderate-to-severe sloping hearing losses were fitted with prototype NLFC devices for four to six weeks. After this time, monosyllabic word recognition in quiet was assessed with both the NLFC hearing aids and the participants' own conventional hearing devices. The results showed that eight participants performed significantly better with NLFC, eight showed no difference and one participant performed significantly worse with NLFC. A subsequent experiment, with a subset of the original participants, confirmed that these changes were not the result of possible amplification differences between the participants' own hearing aids and the NLFC devices. An analysis at the group level showed that frequency compression significantly improved detection of fricative and affricate consonants (with a group mean improvement of approximately 11%) without impairing the perception of vowels and mid frequency consonants.

A second study conducted by Simpson at al. (2006) investigated the effect of frequency compression on the perception of seven participants with steeply sloping high frequency losses. Again, the experimental devices were worn for four to six weeks and tested was conducted towards the end of the trial period. In addition to the monosyllabic word recognition task, medial consonant recognition (both in quiet and with a male speaker) and sentence recognition in noise (with a female speaker) tests were also conducted. Results showed that there was no significant difference in group scores with and without frequency transposition in either of the tests of speech in quiet, however frequency compression led to group deficits in performance of 2% in the consonant recognition task and 6 % in the monosyllabic word recognition task.. Confusion matrices were analysed and indicated that the processing scheme seemed to lead to increased confusions between /s/ and /ʃ/ suggesting that the increased perception of some phonemes may come at the expense of others. It is possible, however, that a period of training, focussing on the discrimination of consonants (that appear to be confused in frequency compressed speech) may increase speech perception scores in participants that appeared to obtain overall benefit from the frequency compression device. The results may also have been affected by the fact that three of the seven participants in this study had not used hearing aids previously, whereas all participants in the previous study (Simpson et al, 2005) were experienced hearing aid users.

The results of the sentence in noise test revealed that only one participant obtained significant benefit (of 6 dB) from frequency compression (it is worth noting that only five participants took part in this facet of the experiment). Subjective opinion was also assessed using the Abbreviated Profile of Hearing Aid Benefit (APHAB, Cox and Alexander, 1995), the results of which showed that only one participant preferred the frequency compression aid. This person did not actually obtain any objective benefit from the device (at least on the tests administered).

The effect of NLFC on perception has also been investigated by Glista et al (2009). A total of 24 participants (13 adults, 11 children) with moderate to profound high frequency hearing losses were provided with NLFC hearing aids and asked to wear them as much as possible in their everyday lives. Performance on a number of speech perception tests in quiet, including detection of /s/ and /ʃ/ and a series of phoneme recognition tasks was assessed. In order to compare performance with conventional processing to that with frequency compression enabled, the trial was split into three parts. Initially participants wore the hearing aids with NLFC disabled (for 2-12 weeks, mean 4.17 weeks), after which the experimental tests were administered to familiarise participants with the procedures (results are not reported).

During the second stage of the trial, the frequency compression setting was enabled and participants again wore the devices for a number of weeks (3 weeks to 1.3 years, mean: 10.75 weeks). All tests were then re-administered and performance with the frequency compression setting enabled was assessed. For the final part of the trial, the hearing aids were programmed with both the conventional and frequency compression settings and participants were able to switch between them as preferred. The final part of the trial lasted between 2 weeks and 5 months, following which the tests were administered again and performance with conventional processing was assessed.

The results showed that group scores in the consonant and plural recognition tasks were significantly higher when frequency compression was enabled than with conventional processing only, whilst vowel recognition was not significantly affected by the processing strategy. The individual results of the adult participants revealed that one participant showed a significant increase in consonant recognition, four demonstrated a significant increase in plural recognition and one participant showed a significant decrease in vowel recognition when frequency compression was enabled. It is likely that the decrease in vowel perception scores observed in the aforementioned participant was due to the very low cut-off frequency used in their case (1.5 kHz). At a group level, frequency compression led to improvements in the order of 5 RAU (rationalised arcsine units) in the consonant recognition task and 10 RAU in the plural recognition task. Frequency compression led to a small decrease (of 3 RAU) in performance in the vowel recognition task. An inspection of the individual results of the child participants indicated that seven demonstrated a significant increase in plural recognition and five showed significantly improved consonant recognition scores when frequency compression was enabled. At a group level, frequency compression led to improvements in performance of 5 RAU in the consonant recognition task, 20 RAU in the plural recognition task and 1 RAU in the vowel recognition task.

Group scores in the speech detection test revealed that the mean threshold at which the stimulus could be detected fifty percent of the time was significantly lower (i.e. better) when frequency compression was enabled than when conventional processing alone was used. The mean threshold for the detection of /s/ was found to be significantly lower than the threshold for /ʃ/. Individual results revealed that ten participants received a significant benefit from frequency compression, whilst two participants performed significantly better with the conventional processing strategy.

Self reported preferences were also obtained, revealing that two of the adult participants favoured the frequency compression setting along with seven of the child participants. Only three participants overall preferred the conventional setting, the remainder showing no preference for either processing strategy.

There are, however, a number of methodological issues which may influence the interpretation of these results. Much of the benefit reported is limited to improvement in the speech sound detection and the plural recognition tasks. One would expect thresholds in the speech sound detection test to be lower with frequency compression. This is due to the fact that the high frequency energy that dominates /s/ and /ʃ/ sounds is compressed into a lower frequency region, in which it is easier to restore audibility. This is due, in part, to the configuration of the participants' hearing loss and also due to technical limitations of hearing aids (in that they are unable to provide significant amplification at very high frequencies). It should be noted that the ability to detect sounds is not the same as being able to discriminate between them or identify them correctly. This may affect the interpretation of the results of the plural recognition task. In this test, the participant was presented with a word in either its singular or plural form and asked to determine which it was. Again, one may argue that the ability to determine that the word was plural may simply reflect that they were able to detect an additional phoneme, not that they were able to correctly recognize it.

Another issue of interest is the discrepancy between the results of Simpson et al (2006) and Glista et al (2009). Simpson et al (2006) found no benefit of frequency compression to participants with a steeply sloping hearing loss. However, Glista et al (2009) found that participants with such a loss were the most likely to receive benefit from a frequency compression hearing aid. There are a number of possible reasons for this difference in findings. One explanation is that the discrepancy may be due to differences in the hearing aids used in the two studies, those used by Glista et al (2009) being more technologically advanced than those used by Simpson et al (2006). The difference may also have been related to the outcome measures used or to the duration of time that the frequency compression aid was used, which was much longer in the later study. Another factor in which the studies differed was in their methods of determining the frequency compression settings. Specifically, when fitting the hearing aid, Glista et al (2009) ensured that participants were able to correctly identify /s/ and /ʃ/ when frequency compression was enabled. If the participant was unable to identify these phonemes correctly, it was assumed that the frequency compression setting was too high and the compression ratio was reduced accordingly.

More recently, Wolfe et al (2010, 2011) have reported that the use of frequency compression led to significant improvements in the perception of some high frequency speech sounds in a group of 15 children (aged 5-13 years) with moderate hearing loss. However, only group mean scores are presented so it is not possible to determine the degree of variation in benefit from frequency compression between different listeners, an issue that potentially affects the clinical application of the findings.

Taken together, the results of the clinical trials mentioned above demonstrate that frequency compression may provide a significant perceptual benefit to some listeners. The purpose of the present study is to further investigate whether, following a period of acclimatisation, NLFC leads to improvements in speech perception and self report outcome measures in experienced adult hearing aid users.

Auditory acclimatisation (or perceptual learning) was defined by Arlinger et al (1996, ps87) as ‘a systematic change in auditory performance with time, linked to a change in the acoustic information available to the listener. It involves an improvement over time that cannot be attributed purely to task, procedural or training effects.’ In order to assess benefit from hearing devices, it is necessary to have an understanding of the time course and magnitude of auditory acclimatisation, along with the degree of individual variation in this process. Some of the earliest studies to investigate the topic of acclimatisation to amplification were conducted by Gatehouse and colleagues in the late 1980s and early 1990s and focussed on monaurally aided adult listeners with bilateral sensorineural hearing loss (see Munro, 2008, for a review of this topic). Gatehouse (1989) measured unaided speech recognition in noise in both the participants' aided and unaided ears. The results showed that when sounds were presented at 95 dB SPL, performance with the normally aided ear was best, however, at a presentation level of 65 dB SPL optimal performance was obtained with the normally unaided ear. Gatehouse suggested that this provided evidence of the ears having adapted to the presentation level to which they had been accustomed to receiving. Subsequent studies investigating intensity discrimination (Robinson and Gatehouse, 1995; 1996) and speech perception scores (Munro and Lutman, 2003) in monaurally aided adult listeners have provided further evidence of differential changes in performance between the aided and unaided ears, consistent with the effect of amplification. The aim of the present study was to investigate auditory acclimatisation to frequency compression hearing aids.

Acclimatisation in the case of binaurally fitted hearing aids was investigated by Philibert et al (2005). In this study of new hearing aid users, unaided performance on an intensity discrimination and a loudness scaling task was measured at four stages (pre fitting, and one, three and six months post fitting). The results showed that the acclimatisation effect was greatest for stimuli that were either high in frequency or intensity. That is, changes were observed only in relation to the stimuli that were most affected by amplification.

Whilst the results of the aforementioned studies are all consistent with perceptual learning, some studies have failed to find any significant evidence for this effect. Saunders and Cienkowski (1997) tested 24 new binaural hearing aid users on speech perception in backgrounds of both quiet and noise. Participants were tested on the day of fitting and 30, 60 and 90 days post fitting. A group of 24 experienced binaural hearing aid users were tested at the same intervals and served as a control group. The results showed evidence of small improvements in the performance of both groups and on both tests. These improvements did not reach statistical significance and more listeners showed no evidence of change over time in performance than did. However, the lack of evidence of acclimatisation observed in this study may relate to the fact that the test stimuli used were presented at a comfortable listening level and performance on the tests administered did not rely heavily on high frequency information. Thus, the authors note that it is possible that acclimatisation did occur, but for high frequency information only.

To date, there has been little research into how different signal processing strategies affect the acclimatisation process. Previous studies investigating the effect of NLFC on the speech perception scores of adult listeners have always provided an acclimatisation period (of at least 3 weeks) prior to testing. However, baseline tests were not conducted (see for example: Simpson et al, 2005, 2006; Glista et al, 2009). Thus, whilst it has been assumed that experienced hearing aid users require additional time to acclimatise to NLFC, there is currently no empirical evidence to support this idea.

Whilst, acclimatisation to frequency compression hearing aids in adult listeners has not yet been investigated, there has been some research of acclimatisation to frequency compression hearing aids in paediatric hearing aid users. Wolfe et al (2010) provided fifteen children, aged 5-13 years old, with moderate to moderately-severe hearing losses, with bilateral frequency compression hearing aids. A within-subjects design was employed, in which the children wore the hearing aids with and without frequency compression enabled for six weeks in each condition (the order was counterbalanced). After each six week period, aided thresholds and performance on a number of speech tests were assessed.

Speech perception in quiet was assessed using the University of Western Ontario (UWO) plural test (Glista et al, 2009) and the Phonak logatom test (Boretzki and Kegel, 2009). The UWO plural test is an open set word recognition test consisting of 15 words in both their singular and plural forms spoken by a female talker (for example, ‘ant’ and ‘ants’). The test allows for the assessment of how well a listener can hear the high frequency information required to perceive the presence of a /s/ or /z/ at the end of a word. The Phonak logatom test is an adaptive test that measures the threshold (in dB SPL) for the correct identification of a stimulus 50% of the time. The stimuli used are VCV syllables in which the vowel remains constant, whilst one of six high frequency consonants is presented. The SNR needed to obtain a criterion performance of 50% on the Bamford-Kowal-Bench (BKB, Bench et al, 1979) sentences was measured.

The group mean results showed that aided thresholds for high frequency speech and pure tone stimuli were significantly reduced (and therefore, better) when frequency compression was enabled. Performance on the UWO plural test was also significantly better, with a group mean increase in performance of 16%, when frequency compression was enabled compared to when using conventional processing alone. Frequency compression also led to significantly reduced thresholds for two of the six stimuli tested in the Phonak Logatom test (/asa/ and /ada/). However, frequency compression had no significant effect on scores in the BKB-SIN test, with frequency compression leading to an SNR advantage of only 0.7 dB.

Participants were then re-tested on all speech measures after 6 months of using frequency compression hearing aids. The results of this portion of the study are presented in Wolfe et al (2011). Neither the aided thresholds nor scores on the UWO test obtained after 6 months of using frequency compression hearing aids differed significantly from those obtained after 6 weeks of frequency compression hearing aid use. Thresholds for one of the VCV stimuli used in the Phonak logatom test (/ada/) were significantly lower after 6 months of frequency compression use than after 6 weeks of wearing frequency compression hearing aids. Whilst scores on the BKB-SIN test did not differ significantly between 6 weeks and 6 months of frequency compression use (with an improvement of only 0.8 dB), the scores after 6 months were significantly better than those obtained after 6 weeks of hearing aid use with frequency compression disabled. This was also the case with one of the stimuli (/ata/) from the Phonak logatom test.

The results of Wolfe et al (2010, 2011) provide some evidence of acclimatisation to frequency compressed speech, albeit limited. It is important to note that baseline measures were not obtained immediately after fitting so it is impossible to ascertain from the data how much acclimatisation may have taken place within the initial six weeks of use. Previous research of acclimatisation to conventional hearing aids has shown that significant changes may take place in the initial six weeks post fitting (Gatehouse, 1992). A further issue that may influence the validity of these results stems from the fact that there was no control group for the measurements taken after 6 months of frequency compression use. It is possible, therefore, that the differences in scores may be due to maturational effects (see for example, Mahon and Crutchley, 2006, for details of age related changes in receptive vocabulary) or to acclimatisation to other features of the hearing aids, rather than to frequency compression specifically. In particular, maturational effects may have influenced scores on the BKB-SIN as the stimuli used contain large amounts of contextual information, which a child may be better able to use as they develop and their receptive vocabulary improves. Furthermore, no individual data are presented, so the level of individual differences in the magnitude of acclimatisation to frequency compression cannot be assessed. The amount of individual variation in acclimatisation has important implications for clinical practice. Thus, in addition to investigating acclimatisation to frequency compression hearing aids, the present study will also attempt to identify possible predictors of benefit from frequency compression.

Individual differences play a significant role in determining the success of a hearing aid fitting, be that in terms of speech perception scores, hearing aid usage or satisfaction (see for example, Humes, 2007). Determining the specific nature of the individual differences that relate to, and may be predictive of, hearing aid outcome has been the subject of much research. As such, a number of factors have been investigated as possible predictors of hearing aid outcome. These factors can be broadly split into 3 categories: audiological, cognitive and psycho-social. A further factor that is often associated with hearing aid outcome is age. It is probable that the contribution of age to hearing aid outcome can be explained by its relationship with cognitive, psycho-social and audiological factors. As such, age as a predictor will be discussed in relation to these factors rather than as an independent contributor of variance in hearing aid outcome. The aim of the present study was to investigate whether cognitive and audiological factors can be used to predict benefit from frequency compression devices in experienced adult hearing aid users.

Psycho-social factors affecting hearing aid outcome may include sex/gender (Cox, Alexander and Gray, 1999), personality traits (Gatehouse, 1994; Saunders and Cienkowski, 1996), social support and education (Garstecki and Erler, 1998). Much of the research conducted into psychosocial factors has focussed on their role in predicting hearing aid uptake, adherence and satisfaction. Whilst it is important to understand why some people choose to seek, and to continue, treatment for their hearing problems whilst others do not, this is not the focus of the current study. As such, only audiological and cognitive predictors of speech perception following amplification will be discussed further.

The contribution of audiological factors as a predictor of speech perception outcomes following amplification is normally limited to a discussion of hearing thresholds. However, a number of other variables may also fall within this category. Specifically, duration of deafness (or auditory deprivation), previous hearing aid use, or the presence of cochlear dead regions.

Unsurprisingly, most studies seeking to explain individual differences in aided speech perception have identified differences in hearing thresholds as the main source of variance (see for example, Humes, 2007; Tun and Wingfield, 1999). However, the influence of hearing thresholds on speech perception outcome seems to be affected by the type of speech test administered. Specifically, audiometric thresholds (with higher thresholds being predictive of poorer performance) tend to account for more variance in relatively easy tasks (such as identifying words in a quiet background) than for more complex tests, such as sentence in noise recognition, (Humes, 2007). This is supported by the finding that predictions of the speech in noise recognition scores of older adults, based on audiometric factors, normally predict levels of performance greater than those observed, whilst speech in quiet predictions are, as a rule, much more accurate (Hargus and Gordon-Salant, 1995).

Thus, once a task becomes more demanding, the influence of audibility on performance is diminished and the influence of cognitive factors become more pronounced. This seems reasonable given that in order to perceive any sound, the signal must first be detected by the ear, transferred successfully to the brain and then interpreted using cognitive skills. If the signal is relatively intact upon reaching the brain (and not degraded to begin with), fewer cognitive resources will be needed to decipher the signal. If, however, the signal is degraded in some way, be it via a noisy background, an impaired auditory system or a hearing aid processor, more cognitive resources will be required to make sense of the degraded signal.

One way of investigating the influence of cognition on speech perception is to investigate the amount of benefit obtained by the provision of contextual cues. There is evidence to show that older listeners, with or without hearing loss, continue to gain benefit from contextual information, particularly when speech is degraded in some way (Pichora-Fuller, 2008; Aydelott et al, 2011). In some cases, older listeners get more benefit than younger listeners from contextual information (Pichora-Fuller et al, 1995).

It has been suggested that the increased reliance of older listeners on contextual information to understand degraded speech, may be a compensatory response to an age related decline in perceptual abilities (Schneider et al, 2002; Aydelott et al, 2011).

In order to make use of contextual information or degraded perceptual cues, one must have the capacity to allocate sufficient cognitive resources to the task at hand. This process is likely to involve a number of specific cognitive abilities, but seems to be most accurately indexed using complex working memory span tests. Working memory (Baddeley and Hitch, 1974) is a limited capacity system used to temporarily store and manipulate incoming information and, to an extent, to allocate attentional resources accordingly. Working memory span tasks such as the reading span test (Daneman and Carpenter, 1980; Rönnberg et al, 1989) consist of two parts: a processing element, and a storage element. In the reading span test, participants are presented with a sequence of sentences in blocks of 3-6. Immediately after reading each sentence, the participant must state whether the sentence made sense or not (processing component). At the end of each block, participants are asked to recall either the first or last word of every sentence in that group (storage component). The percentage of words correctly recalled is then calculated. In a review of studies linking cognition and speech in noise perception, measures of working memory span were found to be the most reliable predictor of test performance once the influence of audibility had been accounted for (Akeroyd, 2008). Lunner (2003), for example, found that, after controlling for the effects of audibility and age, reading span test score was correlated with both aided and unaided recognition of speech in noise.

Whilst it is generally agreed that cognitive factors are more predictive of speech perception performance when the stimulus is degraded in some way, there is some evidence to suggest that the degree to which working memory span predicts speech recognition may be dependent on the degree to which the stimuli differs from phonological representations stored in the long term memory, rather than simply the degradation itself. Rönnberg and colleagues (2003, 2008) proposed a working memory model for ease of language understanding. The model suggests that as long as listening conditions are favourable, speech stimuli are implicitly processed and compared to representations stored in the long term memory. If listening conditions are compromised in some way, be it via noise, hearing loss or hearing aid processing, a mismatch may occur between the stimuli being presented and the representation stored in the long term memory. The model suggests that when such a mismatch occurs, explicit storage and processing resources are required and listening becomes more effortful (Rudner and Rönnberg, 2008). The reading span test provides an index of the explicit processing and storage capacities available to the listener. Therefore, in situations where a degraded signal has led to a mismatch between phonological representations in the long term memory and the percept of the degraded stimulus, it is predicted that working memory capacity will correlate with speech perception.

Rudner et al (2008) found that in a sample of 102 experienced hearing aid users, working memory span scores did indeed show greater correlation with aided speech in noise perception scores in situations where a mismatch between speech representations in the long term memory and the speech stimuli was created. The mismatch was created either by altering the compression release time characteristics of the listeners' hearing aids such that the input signal differed from the sound the listener would normally receive. When listeners were tested with a novel compression release time (mismatch condition), speech scores were more highly correlated with reading span test scores than when they were tested using the compression release time to which they were accustomed (match condition), with listeners with higher reading span test scores performing better in the mismatch condition than those with lower scores.

These results are of particular interest as they demonstrate that the characteristics of the signal processing strategy used in hearing aids can affect the relationship between cognition and speech in noise perception. Lunner (2003) also suggested that it is important to note that the hearing aid processing method may in itself be cognitively demanding. This is in agreement with the results reported by Gatehouse et al (2006) and Cox and Xu (2010) who showed that listeners with greater cognitive skills were more likely to benefit from fast acting compression than those with poorer cognitive performance. The implication from the mismatch theory is that the more the hearing aid processing causes the signal to differ from the representation stored in the long term memory, the greater the predictive role of cognition will be.

One method of signal processing that may increase the likelihood of mismatches occurring relative to conventional amplification is non-linear frequency compression (NLFC). Currently, predictors of benefit from frequency compression remain elusive, although work by Glista et al (2009) suggests that age (although only considered as a dichotomous variable: adult versus child) and severity/configuration of hearing loss may predict performance on some, but not all, speech perception tasks. The results suggested that children and listeners with poorer high frequency thresholds were most likely to benefit from NLFC. However, it is possible that this reported age effect may be due to differences in the adult and paediatric prescriptions used to fit the frequency compression hearing aids (the paediatric targets recommended stronger frequency compression settings when compared to the adult targets). One may also infer an effect of severity and/or configuration of loss from the differing results reported in the studies by Simpson et al (2005, 2006). In the earlier study, some participants with moderately sloping losses obtained significant benefit from frequency compression whilst in the later study, none of the participants with severely sloping losses showed any benefit. Whilst these differences may be evidence of a predictive effect of hearing loss on outcome with frequency compression aids, it is possible that these differences were influenced by the fact that all listeners in the 2005 study were experienced hearing aid users whilst three of the seven participants in the 2006 study were new hearing aid users. Furthermore, the studies used prototype frequency compression hearing aids as opposed to the commercially available aids used by Glista et al (2009).

Thus, the final aim of the current study was to investigate the extent to which audiometric and cognitive factors predict both speech perception scores with conventional amplification and additional benefit from NLFC in experienced adult hearing aid users.

METHOD

Participants

A total of 12 listeners (9 male, 3 female) with bilateral sensorineural hearing loss took part in the study. Based on the experience of the authors, a clinically significant difference over time was estimated to be an improvement in mean performance of 5% (1 sd ±5). A minimum of 10 participants were required for a statistical power of >80% on a 2-tailed paired statistical test at a significance level of 5%. 12 participants were recruited to allow for attrition. Listeners were aged between 65 and 84 years old (mean = 74 years old) and were experienced hearing aid users. Details of the selection criteria employed are presented in Table 1. One participant (002) was not a native English speaker, however had been resident in the UK for 15 years. As the analyses focus on benefit from frequency compression, as opposed to mean scores, this participant was accepted onto the study on the basis that their level of English language proficiency was unlikely to change over the course of the trial. Details of each participants hearing loss and relevant history are provided in Table 2.

Participants were recruited from a local audiology clinic (n=3), a participant database held in the Audiology department at the University of Manchester (n=5) and via word of mouth (n=4).

Table 1 here

Auditory screening consisting of otoscopy, pure tone audiometry (both air and bone conduction thresholds were measured) and tympanometry was conducted. The Threshold Equalising Noise (TEN) test was also administered in order to identify potential dead regions (this did not affect inclusion in the trial). Participants were not paid to take part in the study, however, travel expenses were reimbursed. Ethical approval was granted by Greater Manchester West Research Ethics Committee on behalf of the NHS (Approval code: 10/H1014/44).

Table 2 here

Procedure

Hearing Aid Fitting and Verification

Participants were fitted bilaterally with Phonak Naida V SP hearing aids. The Naida V SP is a fully programmable, 16 channel behind-the-ear hearing instrument that is suitable for moderate-to-severe hearing impairment. The hearing aids have a maximum output of 140 dB SPL and a maximum gain of 75 dB, both measured in a 2-cc coupler. The hearing aids were programmed to match the NAL-NL2 prescription targets (Keidser et al, 2011, advance copy used in the present study). The settings were then verified using real ear insertion gain (REIG) measurements taken using an Aurical Plus (Type 2A, GN Otometrics) measurement system along with Noah 3 software (Hearing

Instrument Manufacturers' Software Association). All measurements were made with the frequency compression setting disabled. The hearing aid settings were verified using modulated speech-type noise at 50, 65 and 80 dB SPL. Once the hearing aid response had been matched as closely as possible to the target values, subjective listening checks were carried out. Further alterations were then made to the hearing aid settings if required. Table 3 shows the group mean targets and match achieved (after fine tuning).

Table 3 here

Once the initial gain settings were finalised, frequency compression was enabled. This signal processing method works by applying non-linear frequency compression to frequencies above a given cut-off point. Frequency compression is not applied to sounds lower in frequency than the cut-off point. The gain provided by the hearing aid is unaffected by the use of frequency compression. Further technical details of the algorithm can be found in Simpson et al (2005) and in the registered patent (Phonak, 2009). Using the Phonak fitting software (iPFG, 2.6), it is only possible to alter the cut-off point and compression ratio together. The fitting software provides a recommended frequency compression setting, based on the manufacturer's guidelines. However, it was felt in many cases that this setting was not strong enough to allow the listener to obtain any benefit from frequency compression, as the changes made by frequency compression would have remained inaudible to the listeners. Therefore, in all cases bar one (where the listener preferred the recommended setting), the frequency compression setting enabled was stronger than the recommended setting (reflected in a lower cut off frequency and higher compression ratio). In order to ensure than the frequency compression setting was appropriate, a number of criteria were assessed. The frequency compression setting that allowed the audibility of the highest frequencies whilst maintaining a cut-off frequency of >2 kHz (in order not to adversely affect sound quality) was selected. Participants were then asked to discriminate between recordings of /s/ and /ʃ/ spoken by a female talker using a same-different procedure. If the participant was unable to consistently discriminate between these stimuli, or reported problems with the sound quality (for example, a 'lisping' quality), a weaker frequency compression setting (reflected in a higher cut off frequency and lower compression ratio) was applied. The selected frequency compression settings are shown in Table 2, along with details of the setting recommended by the manufacturer.

Automatic program selection and noise reduction features were disabled for the duration of the study, as were the manual volume controls. Participants were provided with an additional program, in which noise reduction features were enabled and instructed to use this program only in situations in which the noise was so intrusive as to make them consider removing the hearing aids. This setting was identical to the original program in every other way. Hearing aid usage was monitored throughout the trial using the data logging feature of the hearing aids. All participants wore the devices for an average of at least 8 hours per day throughout the trial. Usage of the noise reduction program was monitored throughout the trial. If the data logging facility of the hearing aid indicated that this program had been used more than 10% of the time, participants were asked whether they were having difficulty with the hearing aids and reminded of the importance of using the first setting as much as possible. This happened on two occasions. No major difficulties were reported and use of the noise reduction setting decreased to acceptable levels in both cases.

The frequency compression setting was then disabled and participants wore the hearing aids at home for one week. Any alterations to the hearing aid settings were made at this appointment. Three participants requested reductions in the low frequency gain of between 2 and 6 dB. No further alterations were made later in the trial.

Real ear insertion gain measurements were repeated at one session in the middle of the trial and again at the final testing session in order to check that the hearing aids were functioning consistently. The group mean REIG measurements obtained at the initial and final testing sessions can be seen in Table 3 along with the prescribed targets. The measurements obtained in the middle of the trial are not presented as data from 3 participants are missing.

In order to minimise the influence of placebo effects, participants were not told whether frequency compression was enabled or disabled at any point in the trial. Most participants were unable to immediately notice any difference between the two settings, thus making it unlikely that they would have been able to guess which signal processing condition they were in. It is possible that later in the trial, the signal processing condition may have been more easily recognised, due to noticeable differences in perception, however, no participant reported being aware of which condition they were being exposed to. Recruitment materials specified that listeners may or may not benefit from frequency compression, a fact highlighted by the experimenter at the initial testing session.

Study Design

The trial took approximately 18 weeks to complete and was split into four parts. A schematic showing the timeline of the trial and details of each testing session can be seen in Table 4. A single group design was used. Prior to fitting the frequency compression hearing aids, there were 3 sessions comprising of the initial screening tests and familiarisation with the speech tests.

Table 4 here

After fitting the hearing aids, an A-B-A design was used. All participants wore the hearing aids with frequency compression disabled first (for a mean duration of 3.63 weeks, SD = 0.81), then enabled (for a mean duration of 6.57 weeks, SD = 0.95) then disabled again (for a mean duration of 3.95 weeks, SD = 2.75). Thus, the participants wore the devices at home for approximately six to seven weeks with each setting. According to Gatehouse (1992), at least six weeks are required to acclimatise to a new hearing aid setting. Participants completed a number of speech tests and questionnaires with frequency compression disabled (after the first 3 weeks of use again at the end of the trial having the worn the devices with frequency compression disabled for an additional 3 weeks) and with frequency compression enabled (after 6 weeks of wearing the hearing aids with frequency compression enabled). In order to compare the benefit obtained with and without frequency compression, the mean of the two sets of scores obtained without frequency compression were compared to performance with frequency compression enabled. Participants also completed speech tests and questionnaires at 3 additional sessions that took place at 0, 1 and 3 weeks after frequency compression was enabled in order to investigate the effect of acclimatisation to NLFC.

All testing was conducted in a quiet room, acoustically representative of a normal living room (with reverberation times of <0.3 s measured in octave intervals from 0.125 to 8 kHz). Nonsense syllable recognition tests in both quiet and noise were administered so as to reduce the influence of contextual cues on performance. A sentence in noise test was also administered to give an indication of speech perception performance in a context similar to that experienced in real life. Reported presentation levels were measured (using a CEL 254 digital impulse sound level metre) at one metre in front of the loudspeaker (at zero degrees azimuth), at the approximate head height of a listener. Measurements are based on the average level of the sentence material and the level of a reference tone provided as part of the nonsense syllable test package. Presentation levels were rechecked at various points throughout the trial to ensure consistency. Head position was monitored visually during testing sessions. The opportunity was taken to gather preliminary self-report data (Glasgow Hearing Aid Benefit Profile and Speech, Spatial and Qualities of Hearing Scale) in order to identify possible trends on which to base future research. Participants also completed the Reading Span Test (RST) and the Trail Making Tests (TMT) A and B on two occasions, once at the first testing session and once at the penultimate testing session. Further details of the tests administered are provided below.

VCV recognition in quiet

Stimuli consisted of 20 nonsense syllables in /i/ - consonant - /i/ context (for example, /iki/) spoken by a female talker. The stimuli were taken from the IHR VCV test package (Faulkner, 1998; IHR Products, Nottingham).

Stimuli were presented via a loudspeaker situated one metre in front of the listener at zero degrees azimuth. The level at which the stimuli were presented was set individually for each listener (between 55 and 70 dB SPL) to minimise the risk of floor and/or ceiling effects occurring. The level was set at the point at which participants achieved mean scores of between 65 and 88% correct without frequency compression enabled. One participant achieved scores above this level (91%) and three participants were only able to achieve scores below this range even at a presentation level of 70 dB SPL (48%, 54% and 63% respectively). The level was kept constant between test sessions. Each test run consisted of one practice block and four test blocks of 20 presentations each (one presentation of each VCV token). Participants were given a response sheet with a matrix showing each of the 20 possible consonants. Participants pointed to the sound corresponding to the speech stimulus they heard. Responses were then recorded on the computer by the experimenter. Whilst it is possible that this method could have been affected by unconscious bias, every care was taken to try and ensure that this was not the case.

As frequency compression affects only the frequency range above the selected cut-off point, it is expected that changes over time or relative to performance without NLFC, will be primarily restricted to high frequency consonants such as fricatives and affricates and to place of articulation contrasts which tend to rely on high frequency formant transitions (see Fry, 1979 and Miller and Nicely, 1955 for further details of speech acoustics.)

High frequency VCV recognition in quiet

Stimuli consisted of a total of 20 speech tokens in the format vowel-consonant-vowel. 8 syllables, the identification of which relies on high frequency information, were presented in both /a/ - consonant - /a/ and /u/ - consonant - /u/ formats. The stimuli were taken from the IHR VCV test package (Faulkner, 1998; IHR Products, Nottingham).

The procedure used was identical to that described under the ‘VCV in quiet recognition’ subheading and the same presentation levels were used. This test was only completed on two occasions rather than three (after 6 weeks experience with frequency compression and after the final 3 weeks experience with frequency compression disabled).

VCV recognition in noise

Stimuli consisted of 20 nonsense syllables in /i/ - consonant - /i/ context spoken by a female talker. The stimuli were presented in a background of multi-talker babble noise (20 speakers). The stimuli were taken from the IHR VCV test package (Faulkner, 1998; IHR Products, Nottingham).

The procedure was almost identical to that described under the ‘VCV in quiet recognition’ subheading. The level of presentation varied between participants but was consistent the level used for in VCV in quiet task for each listener. The speech to noise ratio (SNR) was also determined on an individual basis to prevent ceiling or floor effects (and varied from +2 to -2 SNR, with the exception of one participant, 008, who was tested with an SNR of +10 due to floor effects). An SNR that resulted in a 10-20% decrease in score when compared to performance on the VCV in quiet test was selected.

Sentence in Noise recognition

Lists of IEEE sentences (Rothauser et al, 1969) spoken by a female talker were presented in a background of 20 talker babble noise (Auditec, St Louis, USA). The stimuli were again presented via a loudspeaker situated at head height one metre in front of the listener at zero degrees azimuth. The presentation level of the sentences remained constant throughout each list but the level of the noise varied from +15 to -12 dB in a fixed order, similar to the method recommended by Wilson et al (2007). Sentences were presented at 55 dB SPL for all participants except one (participant 008) who was unable to complete the task at this level. For this listener, sentences were presented at 65 dB SPL.

The participants’ task was to repeat each sentence back to the experimenter and the percentage of keywords (5 per sentence) correctly recalled was calculated. Three sentence lists were administered on each occasion of testing.

Glasgow Hearing Aid Benefit Profile

The Glasgow Hearing Aid Benefit Profile (GHABP; Gatehouse, 1999) is a self report questionnaire assessing six dimensions consisting of initial disability, initial handicap, hearing aid use, hearing aid benefit, residual disability and satisfaction. Each dimension is assessed in relation to four pre specified listening situations (if they occur in the participant’s life and cause them difficulty) with the option of including up to four additional listening situations specified by the respondent. The participant responds using a five point scale. In this case, only responses relating to three of the four pre-specified listening situations were measured (hearing aid use was excluded as participants were asked to wear their hearing aids as much as possible throughout the duration of the trial). This decision was made as both individual and group differences in scores were assessed, thus it was felt that consistency both between and within participants should be maximised. The decision to use the GHABP as opposed to the Glasgow Hearing Aid Difference Profile was in order to minimise the influence of confusions being made in memory of the different hearing aid settings. The GHABP has been used, with success to examine topics such as patterns of benefit in linear and nonlinear hearing aid fittings (Gatehouse et al, 2006), the effect of counselling on perceived hearing aid benefit (Kemker and Holmes, 2004) and on acclimatisation to the fitting of monaural hearing aids (Munro and Lutman, 2004).

The first two dimensions, initial disability and initial handicap, are normally used to assess the respondents perceived hearing problems prior to hearing aid fitting. However, in this instance, these scales were used to assess perceived hearing difficulties experienced with the participants' own hearing aid(s). Disability refers to the types and degrees of listening difficulty the respondent is experiencing whilst handicap denotes the perceived impact of these difficulties on the participants' everyday life (Gatehouse, 1999).

The final four dimensions relate to experiences post hearing aid fitting, or in this case, post fitting the study hearing aids. Hearing aid use indexes the proportion of time the respondent wears their hearing aids when required. The benefit dimension refers to the perceived difference in hearing ability pre and post hearing aid fitting, or between different hearing aid fittings. Residual disability assesses the hearing difficulties that remain following hearing aid fitting whilst the satisfaction is thought to capture facets of a hearing aid fitting extending beyond audition, for example comfort and cosmetic factors (Gatehouse, 1999).

The GHABP was administered by the experimenter as a structured interview. Ratings for the final three dimensions were obtained at four intervals, giving two measures with frequency compression disabled (after three and six weeks of use with this setting) and two measures with frequency compression enabled (at one and six weeks post fitting). Ratings for the two initial dimensions, based on participants' experiences with their own hearing aids, were obtained at the first instance of administering the questionnaire, that is at three weeks post fitting of the study hearing aids. Responses were then scored out of a maximum of 100 for each dimension. The overall mean score for each version of the test was also calculated.

Speech, Spatial and Qualities of Hearing Scale

The Speech, Spatial and Qualities of Hearing (SSQ) Scale (Gatehouse and Noble, 2004) is a self report measure consisting of three subscales. The three subscales relate to speech perception, spatial hearing and quality of sound. Each subscale is comprised of a series of listening situations which the respondent marks out of 10, where a score of 10 indicates complete ability and a score of zero indicates minimal ability (Noble and Gatehouse, 2006). A total of 50 listening situations are rated. The SSQ has been used to investigate the relationship between perceived disability and asymmetrical hearing loss (Noble and Gatehouse, 2004), the use of adaptive directional microphones (Blamey, Fiket and Steele, 2006), unilateral versus bilateral hearing aid fittings (Noble and Gatehouse, 2006) and binaural hearing and dynamic listening (Gatehouse and Akeroyd, 2006). Many of these studies have analysed the results either at the level of individual test items or by using different subscales to those that will be used in the present study, thus it is difficult to compare the results. However, Blamey, Fiket and Steele (2006) used the same subscales as will be used in the current study (namely, speech, spatial and qualities subscales) finding differences of between 2 and 5% between conditions (based on the type of microphone used in the listeners' hearing devices).

The SSQ was administered in the form of a structured interview. The decision to administer the questionnaire in this way was based upon research indicating that this method of administration results in the highest test-rest reliability when compared to self administration of the scale (Singh and Pichora Fuller, 2010)**.** The SSQ was administered on the same four occasions as the GHABP. Mean scores for each subscale, as well as the overall mean score, were calculated.

Familiarisation Sessions

Prior to fitting the study hearing aids, the participants attended two familiarisation sessions in which they were introduced to the speech tests to be used throughout the study. Participants completed repeated runs of the VCV in quiet and in noise tests along with the sentence in noise test whilst wearing their own hearing aids. The IEEE sentence lists used in the familiarisation sessions were different to those used in later test sessions. Practice on the VCV in quiet and in noise tests was done with stimuli in an

/a/ context spoken by a female talker. Thus the test was exactly the same procedurally however used different stimuli to the version of the test used in later test sessions. The reason for not using exactly the same stimuli in both the familiarisation and testing sessions was that it was felt that the amplification provided by the participants own hearing aids would be more similar to the amplification given in the no frequency compression condition of the study hearing aid. Thus, it was felt that were participants trained with exactly the same stimuli as used in the test sessions, this may bias the results in favour of the no frequency compression condition. However, at the end of each familiarisation session, VCV in quiet and in noise tests were completed with stimuli in an /i/ context. This was to help inform the experimenter of the appropriate level/ SNR to try after fitting the study hearing aids. Participants completed between 8 and 11 complete runs of the VCV tests and between 6 and 12 sentence lists. At the end of the two sessions, the final consecutive scores had to be within 5% of each other. If this was not the case, further familiarisation tests would have been administered. This was not necessary for any participant.

Active Listening Task

In addition to attending testing sessions, participants were asked to spend one hour a week listening to an audio book whilst at the same time following the text. A choice of three books was provided. Participants were asked to do this as an aide to help them acclimatise to their new hearing devices. In particular, as frequency compression may alter the nature of certain high frequency sounds, it was felt that it may be beneficial for participants to be able to see text of the sounds they were hearing in order to make them aware of any phonemic confusions they may have been making. Participants were provided with audio equipment where required and asked to keep a diary detailing the time they spent listening to the audiobook. All participants completed this task with little variation in the amount of time spent doing it.

Reading Span Test

The Reading Span Test (Daneman and Carpenter, 1980; Rönnberg et al, 1989) consists of a sequence of sentences in blocks of 3-6. Sentences were presented to the participant word by word on a computer screen at the rate of one word every 800 msec. Immediately after reading each sentence, the participant must state whether the sentence made sense giving a yes-no response (processing component). At the end of each block, participants were asked to recall either the first or last word of every sentence in that group (storage component). The order in which participants were asked to recall either first or last words of each sentence was randomised. In the first trial, three sentences were presented. In each subsequent trial the number of sentences presented was increased by one, up to six sentences in the final trial. The presentation of each sentence was separated by a 1750 msec gap. The test took approximately ten minutes to complete. Upon completion of the test, the percentage of words correctly recalled was then calculated. This method of scoring has been shown to be more reliable than alternative techniques such as scoring based on the highest set in which participants correctly recalled the majority of words (Friedman and Miyake, 2005).

Traditionally, only the scores from the storage component of working memory span tests are analysed; however, according to Unsworth et al (2009), scores on the processing element of working memory span tasks contribute substantial unique variance when trying to predict higher order cognition. Therefore, in addition to analysing the percentage of words correctly recalled, the percentage of errors in the processing element of the RST (that is, whether or not the sentences made sense) was also calculated.

The reading span test has been used to predict unaided and aided speech recognition in noise (Lunner, 2003), the effect of novel signal processing techniques on speech recognition (Rudner et al, 2008; Foo et al, 2007) and the ability to describe the effects of a signal processing scheme (Lunner, 2003). The results of these studies suggest that, once the effect of hearing threshold has been accounted for, individuals with better RST scores tend to achieve higher speech recognition scores and are better able to use fast-compression and to describe the effects of the signal processing scheme than are those with poorer RST scores.

Trail Making Test

The Trail Making Tests A and B (TMT-A/B, Reitan, 1958, 1992) are paper and pencil based tasks. The TMT was included in the study as it has been shown that performance on the TMT may predict the ability of listeners with a hearing loss to perceive speech in a novel accent (Adank and Janse, 2010). As frequency compression alters the spectral relationship between speech components, perception of speech processed in this way may require similar skills to those needed to perceive speech in a novel accent.

The participants' task was to join together a series of points on a sheet of paper in the correct order without allowing their pencil to leave the page. In the TMT-A, the points are labelled from 1-25, the task being to join the points in the correct numerical order. In the TMT-B, the points are labelled 1-12 and A-L and the participants' task was to join the points in the correct alphabetical and numerical order, alternating between the two (for example, 1-A-2-B-3-C and so on). Prior to completing the TMT tests, the participants were given a sample task on which to practice.

Performance on the task was assessed by measuring the total time taken to complete each task. If the participant made a mistake, the experimenter pointed out their error and asked the participant to correct it. Errors were penalised only in that they increased the time taken to complete the task. Participants were aware that the time taken to complete the task was the outcome measure of interest.

RESULTS

In order to investigate the effect of acclimatisation on performance and of benefit from NLFC in the administered tests, a series of analyses were carried out. At a group level, the effect of session number on performance (FC0 x FC6, where FC0 refers to tests administered immediately after NLFC was enabled and FC6 refers to testing conducted after 6 weeks of NLFC use) and of benefit from frequency compression (FC6 x the mean score from the two NoFC testing sessions) were examined using a series of paired samples t-tests Prior to conducting these analyses, data were checked to ensure that the assumptions of normality were met. Examination of skewness and kurtosis indicated that all data satisfied this assumption. In addition, confusion matrices were generated using the results obtained in the nonsense syllable tests. The confusion matrices were then analysed using Sequential Information Analysis (SINFA, Miller and Nicely, 1955; Wang and Bilger, 1973). This method allows for the examination of how much information relating to specific features of consonant articulation is transmitted in each condition. Table 5 shows the feature allocation matrix on which the analysis is based. The analysis was conducted using Feature Information Xer (FIX) software (Johnson, Department of Phonetics and Linguistics, UCL). Further statistical tests could not be performed as it was not possible, using this analysis software, to obtain any measure of the level of variance in the data.

VCV Recognition in Quiet

Acckimatisation

An inspection of the group means (displayed in Figure 1) shows that performance at FC6 was slightly higher than that at FC0 with a mean percentage correct of 80.5 (SD = 14.60) at FC6 compared to 78.5 (SD = 14.60) at FC0 The results of a paired samples t-test confirm that there is no significant effect of session number on performance (t[23] = -1.44, p = 0.163).

Figure 1 here

The individual data (presented in Figure 1) show that 7 participants performed better at FC6 than at FC0, 5 participants scored within 1.5% of their FC0 score at FC6 and no participants performed more poorly at FC6 than at FC0.

Figure 2 here

Figure 2 shows confusion matrices displaying the responses (raw scores out of 48) obtained at FC0, FC6 and a difference matrix showing the number of responses obtained at FC6 minus those obtained at FC0. Thus, in the difference matrix, a positive number indicates an increase in responses over time, whilst a negative number indicates a decrease in responses over time. Scores along the diagonal (highlighted in bold) are percentage correct scores whilst the other scores refer to the percentage of errors made. Inspection of the data reveals large improvements (over 10%) in the correct identification of /f/ and /θ/ and an accompanying decrease in the proportion of times that these phonemes were confused for /s/. A decrease in the proportion of times that /tʃ/ was confused for /t/ is also evident.

The results of the SINFA are shown in the bar chart presented in Figure 3. Inspection of the data indicates that there is no difference between the amount of information transmitted relating to any of the articulatory features under examination, with the exception of place of articulation, in which there was a 2% increase in the amount of information transmitted at FC6 relative to the NoFC condition.

Figure 3 here

Benefit from NLFC

An inspection of the group means (displayed in Figure 4) shows that mean percentage correct with FC enabled (80.5, SD = 14.60) was higher than No FC (73.6,SD = 14.21). The results of a paired samples t-test confirm that there was a significant effect of signal processing strategy on performance (t[23] = -2.87, p = 0.001).

Figure 4 here

The individual data (presented in Figure 4) show that 7 participants performed better with FC enabled than without FC, 3 participants obtained similar results (with a difference of less than 1.5%, this value having been arbitrarily selected) with both signal processing strategies and 2 participants performed more poorly with FC than with No FC.

Figure 5 here

Figure 5 shows confusion matrices displaying the number of responses obtained without FC (raw scores out of 98) and a difference matrix showing the responses obtained at FC6 minus those obtained without FC (in order to create the difference matrix, the FC6 scores were doubled to make them comparable with the NoFC scores, which were based on twice the number of testing sessions; see Figure 2 for the confusion matrix showing responses at FC6). Thus, a positive number indicates an increase in responses when frequency compression was enabled, whilst a negative number indicates a decrease in responses when FC was used. Scores along the diagonal (highlighted in bold) are percentage correct scores whilst the other scores refer to the percentage of errors made. Inspection of the data reveals large improvements (over 10%) in the correct identification of /s/ and /z/ and an accompanying decrease in the proportion of times that /s/ was mistaken for /f/ and /θ/ and that /z/ was mistaken for /v/. The percentage of times that /θ/ was confused with /f/ also decreased when frequency compression was enabled.

The results of the SINFA (displayed in Figure 3) indicate that there is no difference in the amount of information transmitted in the FC6 and NoFC conditions in relation to any articulatory feature with the exception of place of articulation, in which there was a 5% increase at FC6 relative to the NoFC condition.

High frequency VCV recognition in quiet

Benefit from NLFC

An inspection of the group means (shown in Figure 6) indicate that performance with FC enabled was better than that with No FC with a mean percentage correct of 83.3 (SD = 18.54) with FC enabled compared to 78.4 (SD = 19.82) with FC disabled. The results of a paired samples t-test confirm that there is a significant effect of signal processing strategy on performance (t[47] = -5.87, p = 0.001).

Figure 6 here

The individual data (shown in Figure 6) indicate that 8 participants performed better with FC enabled than without FC, 4 participants obtained similar results (with a difference of less than 1.5%) with both signal processing strategies and no participants performed more poorly with FC than with No FC.

VCV Recognition in Noise

Acclimatisation

An inspection of the group means (shown in Figure 7) shows that performance at FC6 was better than that at FC0 with a mean percentage correct of 70.2 (SD = 15.71) at FC6 compared to 68.7 (SD = 14.71) at FC0. The results of a paired samples t-test indicate that there is a significant effect of session number on performance (t[23] = -2.14, p = 0.044).

Figure 7 here

The individual data (presented in Figure 7) show that 5 participants performed better at FC6 than at FC0, 7 participants scored within 1.5% of their FC0 score at FC6 and no participants performed more poorly at FC6 than at FC0.

Figure 8 here

Figure 8 shows confusion matrices displaying the responses (raw scores out of 48) obtained at FC0, FC6 and a difference matrix showing the number of responses obtained at FC6 minus those obtained at FC0. Inspection of the data reveals large improvements (over 10%) in the correct identification of /n/, /l/ and /θ/ and an accompanying decrease in the proportion of times that /θ/ and /f/ were confused for /s/. In addition, a decrease in the proportion of times that /tʃ/ was confused for /t/ is also evident. The proportion of times that /l/ was mistaken for /m/ also decreased over time. However, an increase in confusions between /m/ and /n/ over time is apparent.

The bar chart displayed in Figure 9 shows the group mean SINFA results. An inspection of the graph suggests that marginally more information relating to frication, manner, place and sonorance at FC6 relative to FC0. It should be noted that this effect was only very small, in the order of 1-2% only.

Figure 9 here

Benefit from NLFC

An inspection of the group means (shown in Figure 10) shows that performance in the FC condition was better than that in the No FC condition with mean percentage correct scores of 70.2 (SD = 15.71) and 61 (SD = 13.63), respectively. The results of a paired samples t-test indicate that the effect of signal processing strategy on performance was significant (t[23] = -5.37, p< 0.001).

Figure 10 here

The individual data (presented in Figure 10) show that 9 participants performed better with FC enabled than without it and 2 participants performed more poorly with FC when compared to their performance in the No FC condition.

Figure 11 here

Figure 11 shows confusion matrices displaying the number of responses (raw scores out of 96) obtained without FC and a difference matrix showing the responses obtained at FC6 minus those obtained without FC (as with the data obtained in the VCVQ tests, scores obtained at FC6 were doubled to allow for the creation of a meaningful difference matrix; see Figure 8 for the confusion matrix showing responses at FC6). Inspection of the data reveals large improvements (over 10%) in the correct identification of /d/, /z/, /k/, /s/ and /v/ and a large decrease in confusions between /r/ and /w/, /z/ and /v/, /k/ and /p/, /s/ and /f/ and /s/ and /θ/ when frequency compression was enabled. However, the use of frequency compression also resulted in an increase in confusions between /m/ and /n/.

The results of the SINFA, displayed in Figure 9, show small improvements (in the order of 1-2%) in the amount of information transmitted relating to the articulatory features of frication, manner and sonorance at FC6 relative to the NoFC condition. A larger improvement (of 6%) is evident for the transmission of place of articulation information at FC6 when compared to the NoFC condition.

Sentence in Noise Recognition

Acclimatisation

An inspection of the group mean percentage correct scores (presented in Figure 12) show that scores obtained at FC6 were very similar to those obtained at FC0 with mean scores of 56.5 (SD = 12.67) and 55.2 (SD = 14.43). The results of paired samples t-test indicate that there was no significant effect of session number on performance (t[35] = 0.82, p = 0.415).

Figure 12 here

An inspection of the individual results (presented in Figure 10) show that 5 participants obtained better scores at FC6 than at FC0, 2 participants scored within 1.5% of their FC0 scores at FC6 and 5 participants performed worse at FC6 than at FC0.

Benefit from NLFC

The group mean results, presented in Figure 13, indicate that performance with FC enabled was better than that with FC disabled with mean percentage correct scores of 56.5 (SD = 12.67) and 49.7 (SD = 16.89) respectively. The results of a paired samples t-test confirm the significance of these results (t[35] = -4.42, p <0.001)
At an individual level, 10 participants performed better in the FC condition than in the No FC condition, 1 participant obtained similar scores (less than 1.5% difference) in both conditions and 1 participant performed more poorly when FC was enabled than when it was disabled.

Figure 13 here

Glasgow Hearing Aid Benefit Profile

Table 6 shows the group and individual mean scores obtained in 4 of the 5 subscales of the GHABP. The subscales relating to initial disability and handicap relate to the participants' experience without the use of a hearing aid and will, therefore, not be analysed further. Scores on the final 3 subscales, relating to residual disability, hearing aid benefit and hearing aid satisfaction were obtained with and without FC. The group mean scores were slightly higher in the FC condition than in the NoFC condition in the Hearing Aid Benefit and Satisfaction subscales. Scores on the Residual Disability subscale were very similar in the FC and no FC conditions. A series of paired samples t-tests indicated that none of these group differences in ratings given in the two conditions reached statistical significance (Hearing Aid Benefit: t[11] = 0.20, p = 0.849; Satisfaction: t[11] = 0.76, p = 0.465; Residual Disability: t[11] = -0.29, p = 0.775).

Table 6 here

Speech, Spatial and Qualities of Hearing Scale

Table 7 shows the group and individual mean scores obtained in the SSQ. The overall means are presented along with mean scores for each of the 3 subscales of the questionnaire, obtained in both the FC and No FC conditions.

An inspection of the mean overall scores (presented in Table 7) indicate that, at a group level, there is very little difference between scores given in the No FC and FC conditions. The results of a paired samples t-test confirm that this difference in score is not significant (t[11] = -0.29, p = 0.778). Scores in each of the three subscales also vary little between the two conditions with no evidence of statistically significant differences between the conditions in any of the subscales (Speech: t[11] = 0.02, p = 0.985; Spatial: t[11] = -1.40, p = 0.188; Qualities: t[11] = 1.65, p = 0.126).

Table 7 here

Predictors of benefit

Pearson's correlation coefficient was calculated to investigate the relationship between possible predictors of benefit from frequency compression and scores on the sentence recognition in noise (SIN) test. Predictors were correlated with both the mean percentage correct SIN score without FC and with the additional benefit obtained from frequency compression after 6 weeks use (mean SIN % correct at FC6 – mean SIN % correct without FC). Potential audiological predictors included mean high frequency pure tone threshold (mean of thresholds at 2,4,6 and 8 kHz) in the better ear (HFPTA) and the presence of dead regions (DRs). The influence of HFPTA was partialled out for all subsequent correlations, thus the scatterplots presented are partial correlation plots. The axes of the oartial correlation plots display the residuals of each variable when correlated with the controlled for variable (in this case, HFPTA), thus the axes do not show the raw scores. The presence of DRs was coded as a dichotomous variable (where 0 = no DRs and 1 = one or more DRs in at least one ear), therefore a point biserial correlation analysis was conducted. Possible cognitive predictors included mean percentage correct on the RST, mean percentage error rate on the RST, mean TMT-A score and mean TMT-B score. Despite the multiple correlations, a Bonferroni correction was not applied as it was felt that the increase in the risk of a Type 2 error occurring outweighed the potential benefits of reducing the risk of a Type 1 error (see Cabin and Mitchell, 2000, for a discussion of when to use the Bonferroni correction).

Audiological Predictors

HFPTA

Inspection of the scatterplots shown in the left hand column of Figure 14 indicate a strong negative correlation between HFPTA and mean SIN scores without FC (upper panel) and a strong positive correlation with benefit obtained from FC (lower panel). Therefore, participants with poorer hearing thresholds at the high frequencies performed more poorly on the SIN test and obtained greater benefit from FC. These correlations are both statistically significant, albeit borderline in relation to benefit from FC (No FC: r = -0.92, p <0.001; benefit from FC: r = 0.59, p = 0.045).

Figure 14 here

Presence of DRs

The scatterplots shown in the right hand column of Figure 14 suggest that there is no strong relationship between the presence of DRs and performance in the SIN test either with (lower panel) or without (upper panel) FC. The analysis confirmed that these correlations are not statistically significant (No FC: r = -0.03, p = 0.925; benefit from FC: r = 0.13, p = 0.705).

Cognitive Predictors

RST: % Correct

An inspection of the scatterplots presented in the left hand column of Figure 15 suggest a positive relationship between RST % correct scores and performance in the SIN test without FC (upper panel). This suggests that participants who obtain higher scores in the RST also obtain higher scores in the SIN test. However, there is no evidence of a relationship between RST % correct and benefit obtained from FC (lower panel). The results of the statistical analyses show that neither of these correlations reaches statistical significance (No FC: r = 0.53, p = 0.094; benefit from FC: r = -0.17, p = 0.625).

Figure 15 here

RST: % Errors

The scatterplots displayed in the right hand column of Figure 15 indicate a strong negative correlation between RST error rate and SIN scores without FC (upper panel) and a weak positive correlation with SIN scores with FC (lower panel). This suggests that participants who make more errors in the RST perform more poorly in the SIN test, yet obtain more benefit from FC, than those who make fewer errors in the RST. The results of the statistical analyses indicate that only the correlation between RST error rate and SIN without FC is borderline statistically significant (No FC: r = -0.60, p = 0.050; benefit from FC: r = 0.34, p = 0.306).

TMT-A

The scatterplots shown in the left hand column of Figure 16 indicate a strong negative relationship between TMT-A scores and performance in the SIN test without FC. This suggests that participants who obtain higher (and therefore worse) TMT-A scores perform more poorly in the SIN test than those who obtain lower (and therefore better) TMT-A scores. No clear evidence of a relationship between TMT-A score and benefit obtained from FC is apparent in the scatterplot presented in the lower panel of the left hand column of Figure 13. The results of the statistical analyses confirm that only the correlation between TMT-A scores and performance in the SIN test without FC is statistically significant (No FC: r = -0.69, p = 0.018; benefit from FC: r = 0.28, p = 0.413).

Figure 16 here

TMT-B

The scatterplots displayed in the right hand column of Figure 16 indicate a strong negative relationship between TMT-B scores and performance in the SIN test without FC (upper panel) with no clear evidence of a strong relationship between TMT-B scores and benefit obtained from FC (lower panel). This suggests that participants who obtain higher (and therefore poorer) scores on the TMT-B perform more badly in the SIN test but obtain similar levels of benefit from FC to those who perform well on the TMT-B. The results of the statistical analysis indicate that only the correlation between TMT-B scores and performance in the SIN test without FC is statistically significant (No FC: $r = -0.67$, $p = 0.026$; benefit from FC: $R = 0.06$, $P = 0.851$).

DISCUSSION

The findings of the study show that at a group level, participants obtained significant benefit from frequency compression on all of the speech tests administered. However, scores on the SSQ and GHABP did not reflect this improvement, with similar ratings being given in both the FC and No FC conditions. In agreement with the findings of previous studies of frequency compression (Simpson et al, 2005; Glista et al, 2009), the degree of benefit obtained from FC varied between individuals. In addition, the findings provide limited evidence of acclimatisation to frequency compressed speech. Whilst, with the exception of the VCVN test, there was no significant effect of time on overall mean performance in the speech tests administered, large changes can be seen in the pattern of consonant confusions made.

The results of the study indicate that, based on the factors investigated, benefit from frequency compression to speech in noise recognition can best be predicted by the severity of high frequency hearing loss. Measures of cognitive functioning are predictive of speech in noise recognition without frequency compression, however, there is no relationship between cognitive function and benefit derived from frequency compression. This pattern of results is similar to those observed in a study investigating the role of cognition as a predictor of frequency compressed speech recognition in listeners with normal hearing (Ellis and Munro, submitted).

Acclimatisation to frequency compression

The results of the consonant recognition in quiet test show a large increase over time in the correct identification of /f/ and /θ/, and a corresponding decrease in the percentage of times these phonemes were mistaken for /s/. These stimuli all contain the majority of their spectral energy in the high frequencies thus it is unsurprising that change over time is evident. It is likely that listeners have been used to hearing very degraded versions of these consonants, therefore, the results suggest that they needed time to relearn how to correctly label these novel sounds. This pattern was also observed in results of the consonant recognition in noise test, along with further improvements in the correct identification of /n/ and /l/. These improvements were accompanied by an increase in confusions between /m/ and /n/ with a corresponding decrease in the number of times that /m/ was mistaken for /l/. This change in the pattern of confusions between lower frequency consonants is likely to be as a result of frequency compression affecting high frequency formant transition necessary for the discrimination of these stimuli. It is important to note that whilst the pattern of confusions may have altered over time, there is no evidence of a large decrease over time in the correct identification of any phoneme, either in the VCVQ or VCVN tests.

There is no evidence of an increase over time in confusions between /s/ and /ʃ/ in either task. Previous research has indicated that frequency compression may result in an increase in confusions between these two phonemes (Simpson et al, 2006) and thus the lack of acclimatisation effect seen here may be viewed as surprising. However, the results of the present study show that the mislabelling of /s/ as /ʃ/ occurred only 10.4% (in the VCVQ test) and 8.3% (in the VCVN test) of the time immediately after frequency compression was enabled. Therefore, whilst changes in the rate of these confusions did occur (down to 6.3% and 4.2% in the VCVQ and VCVN after 6 weeks experience of FC), these changes were relatively small. The results of the SINFA indicated only small differences in the amount of information transmitted at FC0 when compared to FC6. This is in line with the group mean percentage correct scores, in both the VCVQ and VCVN tests, which show only small differences in performance at FC6 and FC0.

This difference between the results of Simpson et al (2006) and the present study is likely to be related to differences in the fitting strategy employed. In the current study, unlike in the study reported by Simpson et al (2006), one of the criteria used to assess the suitability of the frequency compression settings was to ensure that the listener was able to discriminate between /s/ and /ʃ/ (similar to the criteria suggested by Glista et al, 2009), therefore the relative lack of confusion between these phonemes, observed in the results of the speech tests, is perhaps unsurprising. However, it seems that this method of determining the frequency compression settings did not eliminate consonant confusions, but simply altered their nature. Specifically, the results of the current study show a large increase over time in the correct identification of /f/ and /θ/, and a subsequent decrease in the percentage of times these phonemes were mistaken for /s/. The results of Simpson et al (2006) show that few listeners in their study showed evidence of making these confusions. There are two possible explanations for this. The first is that the measurements taken in Simpson et al’s (2006) study were obtained 4-6 weeks after fitting of the FC device. Therefore, participants may have made these confusions initially but learned to correct these errors over time, consistent with the results of this study. The second reason may be related to the aforementioned differences in the strategy used to select the frequency compression setting. Recent work conducted by Hamilton et al (2011) on listeners with normal hearing suggests that strong frequency compression settings lead to confusions between /s/ and /ʃ/ whilst weaker settings lead to confusions between /θ/ and /s/. Again, this would be consistent with the current findings. Further research investigating how best to use phonemic confusion data in the selection of frequency compression settings is required.

It could be argued that the changes over time observed in the consonant confusion data are evidence of procedural learning rather than acclimatisation to frequency compression. If this was the case, one would expect to see larger changes over time on performance in the consonant recognition tasks when compared to the sentence in noise task. This is due to the fact that stimuli in the consonant recognition tasks were identical at all sessions, whilst the sentence material varied. However, there was no evidence of changes over time in overall mean performance on any of the tests administered. Furthermore, the changes in the pattern of confusions made in the consonant recognition task are primarily restricted to high frequency consonants, where the effect of frequency compression would be most evident. Had there been evidence of acclimatisation in mean performance in any of the speech tests, scores with frequency compression would have been compared to scores without frequency compression, obtained at the end of the trial. This would have allowed for the separation of procedural learning and acclimatisation to frequency compression.

It is important to note that the current findings apply only to experienced hearing aid users with moderate-to-severe high frequency hearing loss. Therefore, whilst evidence of acclimatisation to frequency compression in this population appears to be limited to high frequency consonants only, this is likely to be related to the fact that, for these listeners, only the high frequency information has been altered relative to the conventional hearing aids to which they are accustomed. Thus, the results of the study pertain only to additional acclimatisation to frequency compression. It is expected that acclimatisation would have a much greater effect on the perception of new hearing aid users as they would have to adapt to all aspects of the signal processing, rather than just frequency compression as was the case in the current study.

Other issues that may affect the generalisability of the results include the fact that it is possible that high levels of variability in performance in the speech tests masked changes over time that would be clinically, if not statistically, significant. Further research, using larger numbers of stimuli, is needed to investigate this issue. It may also be the case that factors other than speech recognition are influenced by acclimatisation. It may be interesting for future research to focus on investigating changes over time to listening effort. It is also possible that a greater effect of acclimatisation would have been seen if stimuli had been presented at a lower level, thus making the tests more difficult. However, whether an understanding of acclimatisation to very low level (and thus unlike most listening situations) would be clinically useful is debatable. Furthermore, the findings of the study relate only to acclimatisation taking place in the initial 6 weeks after frequency compression is enabled. Research by Wolfe et al (2011) suggests that additional, albeit limited, changes may take place later than this. Specifically, improvements in the recognition of the phonemes /s/ and /d/ (reflected in lower thresholds needed to identify these stimuli correctly) occurred between 6 weeks and 6 months of frequency compression hearing aid use. These results were obtained in a paediatric population, thus further research is needed to track long term changes in adult users of frequency compression devices.

Benefit from frequency compression

Consonant recognition scores, in both quiet and in noise, improved significantly with the use of frequency compression. An examination of the confusion matrices shows that the majority of these improvements were restricted to changes in the pattern of recognition of high frequency stimuli. Specifically, large improvements are seen in the perception of stimuli that contain the majority of their energy in high frequency regions (such as /s/ and /z/) and decreases in confusions between stimuli that are discriminated between on the basis of high frequency formant transitions (such as /d/ - /g/ and /r/ - /w/). This is consistent with the results obtained in previous studies of frequency compression (Simpson et al, 2005; Glista et al, 2009, Wolfe et al, 2010) and is to be expected given that the changes introduced by frequency compression are specific to the high frequencies. The results also indicate that changes in the pattern of consonant recognition are more wide ranging when the stimuli are presented in a background of noise than when they are presented in quiet. The largest changes, in both the VCVN and VCVQ results, were seen with regards to confusions between /v/ and /z/. The phoneme /z/ contains more energy than /v/ in the frequency range above 3kHz, their lower frequency spectral composition being very similar. Thus, the improvements in correct identification of /z/ and the accompanying decrease in confusions with /v/ may indicate that NLFC provided listeners with high frequency information that they did not have access to with conventional amplification. There has been no previous research on the effect of frequency compression on the perception of consonants in noise, and thus no comparisons can be drawn. The observation that frequency compression seems to provide greater benefit in more difficult listening conditions is likely to be related to the fact that listeners performed more poorly in this task than on the VCV in quiet test, leaving more room for improvement with frequency compression. It also demonstrates that this method of frequency lowering does not lead to adverse effects in noisy situations. Furthermore, there is no evidence of an increase in confusions between /s/ and /ʃ/ as observed by Simpson et al (2006). This is likely to be related to difference in how the frequency compression settings were selected, with the ability to discriminate between /s/ and /ʃ/ being one of the criteria used to judge the suitability of a frequency compression setting in the present study.

The results of the SINFA showed small improvements in the transmission of frication, manner and sonorance in the VCVN test at FC6 when compared to the NoFC condition. The majority of the improvement was seen in the transmission of place of articulation information, in both the VCVN and VCVQ tests. These results are similar to those reported by Simpson et al (2005), however, a larger difference in frication information transmitted is evident in that study when compared to the results of the current study. These differences may be due to slight differences in the NLFC algorithm/settings used or to slight differences in the method of analysis. It may also have been the case that ceiling effects (relating to the transmission of specific articulatory features rather than to overall performance) may have affected the results of the current study. The fact that place information improved in both studies is unsurprising, given that NLFC affects only the high frequencies, in which place of articulation information is concentrated.

This results of the sentence recognition in noise test again showed a significant benefit of frequency compression at a group level. This finding is at odds with the results reported by Wolfe et al (2010) who also measured sentence in noise recognition after 6 weeks experience of frequency compression hearing aid use but found no evidence of significant improvements with frequency compression when compared to scores obtained with conventional amplification. This difference in findings is likely to be related to the nature of the sentence lists used. Wolfe et al (2010) used BKB sentence lists which contain more contextual information than the IEEE sentences used in the present study. It seems reasonable to assume that the additional acoustic information provided by frequency compression would provide greater benefit in situations where only limited contextual information is available. In such situations, listeners would be less able to use cognitive resources to compensate for a distorted signal. Future research is needed to investigate the interaction between contextual information and benefit from frequency compression. It is also possible that the difference in findings relates to variations in participant characteristics between the studies. The participants in Wolfe et al’s (2010) study were children and had less severe high frequency losses that the listeners in the present study. Again, more research, using participants with different configurations of hearing loss, is needed to further investigate situations in which frequency compression leads to improved speech in noise perception.

Even though frequency compression was shown to provide significant benefit to speech perception, the results of the administered questionnaires indicated that there was little difference in subjective ratings of the two signal processing methods. Furthermore, at an individual level, ratings given in the questionnaires did not correspond with the degree of benefit obtained from frequency compression in the speech tests. Again,

these findings are consistent with those reported by Simpson et al (2006). It is important to note, that whilst scores on the GHABP and SSQ did not improve significantly with frequency compression, they did not get significantly worse. However, due to the small sample size and the high level of variability in the data, it is likely that there was not sufficient statistical power to detect a significant effect. Due to the inherent variability of self report measures, a larger scale study is required to systematically examine the effect of NLFC on subjective outcome measures.
High levels of variability in the data at an individual level meant that statistical analyses could not be performed. Therefore, in order to discuss individual differences in benefit obtained from NLFC, it is suggested that listeners who achieved higher scores in the majority of speech tests (on at least 3 of the 4 tests administered) should be considered good frequency compression users. If this criterion is applied, 9 of the 12 participants showed evidence of obtaining benefit from frequency compression.

At the end of the trial, all participants chose to keep the study hearing aids and 10 participants preferred to have frequency compression enabled (including 2 of the listeners who obtained no obvious benefit from frequency compression). Of the 2 participants who chose to have the frequency compression disabled after the trial, one had no real preference (in concurrence with his speech perception scores) so decided to stick with conventional processing. The other participant did obtain higher speech perception scores with frequency compression but preferred the quality of sound when frequency compression was disabled.

It is possible that greater benefit from FC would be seen if participants were given longer to acclimatise to the hearing aids. Wolfe et al (2011) compared performance after 6 weeks and 6 months of frequency compression hearing aid use and found some evidence of continued improvements in speech perception. This research was conducted on a paediatric population and thus may not be applicable to adult hearing aid users. Further research is needed to investigate long term changes relating to frequency compression hearing aid use, on both objective and subjective outcome measures, in an adult population.

It could be argued that order effects may have influenced the results of the current study due to the use of an A-B-A design where the order in which frequency compression was enabled and disabled was not counterbalanced (A= frequency compression, B = no frequency compression). When calculating the benefit provided by frequency compression, the mean scores obtained after 3 and 6 weeks hearing aid use without frequency compression (at the end of each ‘A’ period) were compared to those obtained after 6 weeks experience of frequency compression use (at the end of the ‘B’ period). If there was a large task learning effect, one may suggest that inclusion of scores obtained at the end of the first ‘A’ period may have biased the results in favour of frequency compression. To address this issue, the results were recalculated and the scores obtained with frequency compression were compared to the final scores obtained without frequency compression. A significant benefit from frequency compression was still evident for all of the speech tests administered. Again, there was no effect of signal processing condition on ratings given in either the SSQ or the GHABP.

Predictors of benefit

The observation that high frequency pure tone average loss is predictive of benefit from frequency compression is consistent with results reported by Glista et al (2009). However, it should be noted that in the present study, this result is likely to have been disproportionately influenced by one particular case (evidenced by a Cook’s distance value of 1.49, above the cutoff of 1 recommended by Cook and Weisberg, 1982). This is not to suggest that the results are invalid, only that they should be interpreted cautiously. The findings of both the present study and that conducted by Glista et al (2009) indicate that listeners with greater high frequency losses obtain more benefit from frequency compression than those with less severe high frequency losses. This suggests that benefit from frequency compression is related to the increased audibility of high frequency sounds resulting from this signal processing method. However, the results of a study conducted by Simpson et al (2006) found no evidence of speech perception benefit from NLFC in a sample of listeners with severely sloping sensorineural losses. The inconsistency between the results of these studies suggest that more research, using a greater number of participants with a wider range of severity and configuration of loss, is required to enable greater understanding of the relationship between high frequency hearing loss and benefit from NLFC.

Once the effect of high frequency hearing loss was partialled out, the presence of dead regions did not predict sentence in noise recognition without NLFC. This is in agreement with results reported by Dillon et al (2011), who found that once the effect of hearing loss had been accounted for, dead regions had little effect on the intelligibility of conventionally amplified speech. The results of the present study also indicate that the presence of dead regions is not predictive of benefit from NLFC. However, these results should be interpreted cautiously as the analysis in the present study was based simply on whether there was evidence of at least one dead region or not. The edge frequency and width of the dead regions was not taken into account. It is perfectly plausible that these factors may need to be considered when selecting the frequency compression cut-off point. Research has suggested that providing amplification at frequencies over 70% above the edge frequency of a dead region is of limited benefit to listeners (Vickers et al, 2001). It may therefore be the case that compressing high frequency information into this region is also of limited benefit to the listener. Further research is needed to investigate this issue.

The results indicate that, once the effect of high frequency hearing loss has been partialled out, cognitive performance can be used to predict sentence in noise recognition without frequency compression. Specifically, results in the TMT-A and B tests, along with the percentage of errors made in the RST were related to performance in the speech in noise test. Listeners who obtained better scores in the cognitive tests also tended to achieve higher scores in the sentence recognition task. This finding is consistent with the results of previous studies of sentence recognition scores (see Akeroyd, 2008 for a review). However, the percentage correct obtained in the RST, ameasure that has often been shown to correlate with aided speech perception scores (see for example, Lunner, 2003), was not predictive of either performance without frequency compression or benefit obtained from it. It should be noted that a positive trend between percentage correct on the RST and sentence recognition without frequency compression is evident, however, this relationship did not reach statistical significance. The fact that this correlation did not reach significance whilst correlations with the remaining 3 cognitive measure did may be related to the cognitive processes that these tasks are indexing.

The percentage correct score on the reading span test is normally seen as a reflection of working memory span whilst the TMT-A and B are generally seen as indices of executive function and task switching abilities. One may also consider performance in the RST, particularly in respect to error rate, to be an index of executive function (see for example, Engle, 2002). Therefore the results of the current study may provide evidence that it is not working memory span, per se, but rather executive functioning, that is predictive of speech in noise recognition. This seems logical, given that the ability to efficiently perceive speech in noise depends on the capacity to focus attention on the useful parts of the signal, and away from the competing noise, an ability governed by executive function. That the TMT-A and B were shown here to be predictive of aided speech in noise recognition (albeit without frequency compression) may be of clinical interest. These tests require no special equipment and take only minutes to administer thus making them a practical option to administer in a clinical, as well as a research, setting. Additional research is needed to further investigate the relationship between executive function and speech perception. However, potentially, performance on tests such as the TMT A and B could be used to inform clinical decisions on hearing aid settings and how best to counsel hearing aid users in terms of predicted benefit from amplification.

The fact that none of the cognitive measures correlated with additional benefit derived from frequency compression on speech recognition scores may be considered in light of the working memory model of ease of language understanding proposed by Rönnberg and colleagues (2003, 2008; Rudner and Rönnberg, 2008). According to the model, cognitive resources are taxed when speech stimuli differ from representations stored in the long term memory. It may be that as changes introduced by frequency compression are concentrated only at the high frequencies, the differences between sentences that have been compressed in frequency and those that have not are not large enough to require additional cognitive resources. Furthermore, it is also possible that frequency compression actually makes speech more similar to the representations stored in the long term memory, depending on the duration and severity of hearing loss.

The finding that benefit from NLFC is not predicted by performance on cognitive tests suggests that cognitive status does not need to be considered when assessing the potential candidacy for NLFC. The clinical implication of this finding is that NLFC may provide additional benefit to that conferred by conventional amplification, even to less cognitively able patients.

Conclusions

The findings show that acclimatisation in the first 6 weeks of frequency compression use is limited to changes in the perception of certain high frequency phonemes, in particular a reduction in mislabelling /f/ and /θ/ as /s/. The effect of acclimatisation seems to be greatest in difficult listening situations (nonsense syllable recognition in noise). These changes took place without formal training. The findings apply only to experienced users of conventional hearing aids. Further research is needed to investigate long term acclimatisation to frequency compression in this population, along with additional research focussing on new hearing aid users.

The results suggest that frequency compression provides significant benefit (above that obtained from conventional amplification) to speech perception for many listeners with moderate-to-severe sensorineural hearing loss, at least on lab-based outcome measures. However, this improvement may not be reflected in subjective ratings of frequency compression. Clinicians should therefore be aware that a listener may actually be obtaining significant benefit from frequency compression even self report outcomes suggest otherwise. Ideally, speech perception outcomes should be measured with and without frequency compression in order to allow the clinician to counsel the listener effectively.

In addition, the findings of the study show that benefit from frequency compression, at least in terms of a lab-based sentence in noise task, can be predicted by the severity of high frequency hearing loss. Specifically, listeners with poorer high frequency thresholds tend to obtain more benefit from frequency compression than those with better high frequency thresholds. However, further research with a greater number of listeners is necessary to determine the generalisability of these findings. Performance on cognitive tests, whilst predictive of overall sentence in noise scores with conventional processing, is not related to benefit obtained from frequency compression. The implication of this finding is that frequency compression should be considered as a viable treatment option even for less cognitively able listeners. The results also highlight that tests of executive function may be useful in a clinical setting.

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LIST OF TABLES

Table 1

Selection criteria	Defined as:
Sensorineural hearing loss	No air-bone gap of greater than 15 db at any frequency. Moderate-to-severe high frequency loss.
Symmetrical hearing loss	No asymmetry of greater than 20 db at more than two frequencies
Previous hearing aid experience	Of at least 1 year, wearing the device(s) for at least 4 hours per day
Native speaker level fluency in English	n/a
No previous experience of frequency lowering hearing aids	n/a
No abnormalities of middle ear function	Normal tympanometric readings
No reports of significant cognitive impairment	n/a

Table 2.

Participant	Age at start of trial (years)	Duration (years) of hearing loss	Duration (years) of previous HA use*	Ear	NLFC settings applied: cut-off freq. (CR)**	NLFC settings prescribed: cut-off freq. (CR)**	Dead regions (kHz) ***	Hearing threshold at specified frequencies (dB HL)								
								250	500	1000	1500	2000	3000	4000	6000	8000
001	69	10	10 (L)	Right	3700	4500	None	5	0	20	40	45	55	50	50	70
001				Left	(2.6:1)	(2.8:1)	None	0	0	35	65	70	70	70	70	60
002	80	20	20 (B)	Right	2000	3300	3 & 4	25	15	20	50	65	90	90	85	80
002				Left	(1.8:1)	(2.1:1)	3 & 4	35	30	25	50	60	80	85	90	75
003	80	10	7 (B)	Right	3300	2800	None	20	25	35	45	55	65	80	85	80
003				Left	(2.4:1)	(2.3:1)	4	25	25	30	35	40	55	60	70	75
004	66	10	4 (R)	Right	3100	4400	None	10	30	45	65	60	60	60	65	65
004				Left	(2.4:1)	(2.7:1)	None	15	20	30	45	45	55	60	80	65
005	77	5	3 (L)	Right	3100	4400	3	20	5	20	35	40	55	45	75	70
005				Left	(2.4:1)	(2.7:1)	None	20	15	35	45	55	60	60	95	85
006	74	8	4 (R)	Right	3000	4300	None	50	60	60	55	50	55	55	75	65
006			3 (B)	Left	(2.3:1)	(2.7:1)	3	50	55	60	60	60	55	40	85	75
007	73	5	1 (L)	Right	3100	4500	None	35	45	45	45	50	50	60	55	60
007			2 (B)	Left	(2.5:1)	(2.7:1)	None	30	50	55	50	45	65	60	90	80
008	84	9	3 (R)	Right	2000	2700	3 & 4	30	40	60	60	55	80	95	105	110
008			5 (B)	Left	(1.7:1)	(1.8:1)	3 & 4	35	30	50	70	75	70	95	115	105
009	65	8	4 (R)	Right	2800	3700	None	25	35	50	55	60	60	65	85	85
009				Left	(2.4:1)	(2.3:1)	None	15	35	45	55	55	60	55	90	70
010	79	10	8 (B)	Right	2600	4100	None	40	40	45	55	45	65	75	80	90
010				Left	(2.1:1)	(2.5:1)	None	30	30	40	45	50	55	60	75	85
011	75	5	5 (L)	Right	3100	4500	None	20	20	30	30	25	35	50	55	80
011				Left	(2.5:1)	(2.8:1)	None	30	30	30	25	45	35	40	85	85
012	65	6	3 (L)	Right	2400	3400	1.5, 2(i),3 (i), 4	15	10	25	70	75	70	80	85	75
012			3 (B)	Left	(2.0:1)	(2.1:1)	2 (i), 3(i), 4	10	10	10	70	80	85	90	90	75
Mean	71.9	8.8	7.1	n/a	n/a		n/a	24.8	27.3	37.5	50.7	54.4	61.9	65.8	80.6	77.7

* (L) = left, (R) = right, (B) = bilateral ** CR = compression ratio *** i = inconclusive

Table 3.

Level (dB SPL)	Mean targets and deviation (target – match, in dB) in real ear insertion gain from target prescribed using the NAL-NL2 fitting formula.							
	250	500	1000	2000	3000	4000	6000	8000
Target (65)	3.1	2.9	11.1	19.4	22.7	25.9	26.6	26.6
	(4.5)	(4.6)	(5.6)	(4.5)	(5.4)	(5.2)	(4.7)	(4.5)
Initial fitting (65)	2.4	1.4	-2.7	-3.0	-2.0	5.1	9.8	22.5
	(4.5)	(4.0)	(4.8)	(4.7)	(7.5)	(10.4)	(6.6)	(7.8)
Initial fitting (50)	7.7	4.6	-3.3	0.7	3.8	11.2	17.4	21.6
	(7.0)	(4.8)	(3.8)	(6.4)	(8.4)	(10.4)	(6.6)	(6.6)
Initial fitting (80)	-0.7	-0.6	-3.1	-3.9	-2.8	2.8	5.3	17.4
	(1.5)	(2.0)	(3.8)	(6.0)	(6.9)	(10.3)	(6.9)	(9.5)
End of trial (65)	0.7	2.4	-2.8	-4.5	-1.0	7.7	11.0	24.2
	(3.8)	(5.7)	(5.0)	(4.2)	(5.6)	(8.7)	(8.8)	(7.7)

Table 4.

Week	Hearing aid Setting*	Session Number	Activities												
			Active listening task	Hearing screening	HA fitting/REMs	RST	TMT-A&B	Practice speech tests	VCV-Q	VCV-N	VCV-HF	SIN	GHABP	SSQ	Counselling questionnaire
1	0	1		X		X	X								
2	0														
3	0	2						X							
4	0														
5	1	3	X		X			X							
6	1	4	X					X							X
7	1		X												
8	1	5							X	X		X	X	X	
9	2	6	X						X	X		X			X
10	2	7	X						X	X		X	X	X	
11	2		X												
12	2	8	X		X				X	X		X			X
13	2		X												
14	2		X												
15	2	9							X	X	X	X			
16	1	10	X			X	X						X	X	X
17	1		X												
18	1		X												
19	1	11			X				X	X	X	X	X	X	

*Hearing aid setting: 0=own aids; 1=Naida without NLFC; 2=Naida with NLFC

Table 5.

	Stimulus									
	b	**d**	**g**	**w**	**y**	**r**	**l**	**v**	**z**	**j**
Voicing	V+	V+	V+	V+	V+	V+	V+	V+	V+	V+
Place	bilabial	alveolar	velar	bilabial	palatal	alveolar	alveolar	labiodent.	alveolar	palatal
Manner	plosive	plosive	plosive	glide	glide	glide	glide	fricative	fricative	affricate
Sonorance	N	N	N	N	N	N	N	N	N	N
Frication	N	N	N	N	N	N	N	Y	Y	N

	Stimulus									
	m	**n**	**p**	**t**	**k**	**f**	**th**	**s**	**sh**	**ch**
Voicing	V+	V+	V-	V-	V-	V-	V-	V-	V-	V-
Place	bilabial	alveolar	bilabial	alveolar	velar	labiodent.	dental	alveolar	palatal	palatal
Manner	nasal	nasal	plosive	plosive	plosive	fricative	fricative	fricative	fricative	affricate
Sonorance	Y	Y	N	N	N	N	N	N	N	N
Frication	N	N	N	N	N	Y	Y	Y	Y	Y

Table 6.

Participant	GHABP Subscale							
	Initial Disability	Handicap	Hearing Aid Benefit		Residual Disability		Satisfaction	
			FC	No FC	FC	No FC	FC	No FC
001	31.3	25	81.3	42.7	25	21.9	75	63.5
002	25	31.3	58.3	44.8	16.8	22.9	66.8	54.2
003	12.5	12.5	50	43.8	31.3	18.8	56.3	59.4
004	56.3	50	43.7	53.1	37.5	40.6	62.5	56.3
005	31.3	31.3	81.3	75	12.5	15.6	93.8	71.8
006	68.8	87.5	62.5	71.9	37.5	32.8	68.8	71.8
007	56.3	62.5	68.8	75	18.8	18.8	75	78.1
008	56.3	18.8	50	42.7	31.3	33.3	50	55.2
009	87.5	56.3	68.8	62.5	25	37.5	75	62.5
010	43.8	31.3	62.5	61.5	18.8	35.4	50	53.1
011	56.3	68.8	56.3	90.6	40.6	15.6	56.3	93.8
012	43.8	56.3	50	37.5	43.8	53.1	50	37.5
Group Mean	47.4	44.3	61.1	58.4	28.2	28.9	64.9	63.1

FC = frequency compression

Table 7.

Participant	**SSQ Subscale**						**Overall**	
	Speech		**Spatial**		**Qualities**			
	FC	**No FC**	**FC**	**No FC**	**FC**	**No FC**	**FC**	**No FC**
001	7.4	7.0	7.3	7.2	8.5	8.3	7.7	7.5
002	6.0	5.9	8.0	7.6	7.6	7.0	7.2	6.8
003	7.3	5.9	7.6	6.8	7.6	7.6	7.5	6.7
004	6.8	6.0	7.6	7.2	8.6	8.5	7.7	7.2
005	8.6	8.7	10	9.9	9.8	9.8	9.5	9.5
006	7.8	7.6	8.6	7.7	9.1	9.1	8.5	8.1
007	7.8	6.7	7	5.6	7.9	7.3	7.6	6.5
008	2.7	5.2	4.4	7.4	9.1	8.3	5.4	7.0
009	6.1	4.6	8.8	7.2	9.1	7.8	8.0	6.5
010	5.9	6.3	6.1	6.1	7.9	7.8	6.6	6.8
011	6.2	7.6	4.6	6.8	7.8	8.6	6.2	7.6
012	5.2	5.5	7.9	8.0	7.5	6.8	6.9	6.8
Group Mean	6.5	6.5	7.3	7.8	8.4	8.1	7.4	7.5

FC = frequency compression

LIST OF FIGURES

Figure 7. Bar chart showing group and individual mean scores (percentage correct) on the VCV in noise test at FC0 (paler bar) and FC6 (darker bar). Error bars show ± 1 standard error.

Figure 8. Confusion matrices showing group responses (raw scores out of 48) obtained at FC0 (first matrix), FC6 (second matrix) and the difference in the group responses obtained at FC0 and FC6 (third matrix) in the VCV in noise test. A positive value in the difference matrix indicates an increase in responses over time whilst a negative score indicates a decrease in responses over time.

Figure 9. chart showing the group mean percentage of articulatory feature information transmitted in the VCVN test at FC0, FC6 and in the NoFC condition.

Figure 10. Bar chart showing the group and individual mean scores (percentage correct) obtained in the VCV in noise test with and without frequency compression. The pale bars represent scores with frequency compression whilst the darker bars represent scores without frequency compression. Statistically significant differences are marked with an asterisk. Error bars show ± 1 standard error.

Figure 11. Confusion matrices showing group responses (raw scores out of 96) in the NoFC condition (first matrix) and the difference in the group responses obtained with and without frequency compression (second matrix) in the VCV in noise test. A positive value indicates an increase in responses with frequency compression whilst a negative score indicates a decrease in responses with frequency compression (when compared to performance without frequency compression).

Figure 12. Bar chart showing group and individual mean scores (percentage correct) on the sentence recognition in noise test at FC0 (paler bar) and FC6 (darker bar). Error bars show ± 1 standard error.

Figure 13. Bar chart showing the group and individual mean scores (percentage correct) obtained in the sentence recognition in noise test with and without frequency compression. The pale bars represent scores with frequency compression whilst the

darker bars represent scores without frequency compression. Statistically significant differences are marked with an asterisk. Error bars show ± 1 standard error.

Figure 14. Left hand column: Scatterplots showing correlations between High Frequency Pure Tone Average (HFPTA, 2,4,6 and 8 kHz) in the better ear and mean percentage correct in the sentence in noise test without frequency compression (upper panel) and with benefit obtained from frequency compression (lower panel).Right hand column: Scatterplots showing partial correlations (with HFPTA controlled for) between the presence of dead regions and the mean percentage correct in the sentence in noise test without frequency compression (upper panel) and with benefit obtained from frequency compression (lower panel).

Figure 15. Left hand column: Scatterplots showing partial correlations (with HFPTA controlled for) between the mean percentage correct obtained on the RST and the mean percentage correct in the sentence in noise test without frequency compression (upper panel) and with benefit obtained from frequency compression (lower panel). Right hand column: Scatterplots showing partial correlations (with HFPTA controlled for) between the mean percentage of errors obtained on the RST with the mean percentage correct in the sentence in noise test without frequency compression (upper panel) and with benefit obtained from frequency compression (lower panel).

Figure 16. Left hand column: Scatterplots showing partial correlations (with HFPTA controlled for) between the mean TMT-A scores and the mean percentage correct in the sentence in noise test without frequency compression (upper panel) and with benefit obtained from frequency compression (lower panel). Right hand column: Scatterplots showing partial correlations (with HFPTA controlled for) between the mean TMT-B scores with the mean percentage correct in the sentence in noise test without frequency compression (upper panel) and with benefit obtained from frequency compression (lower panel).

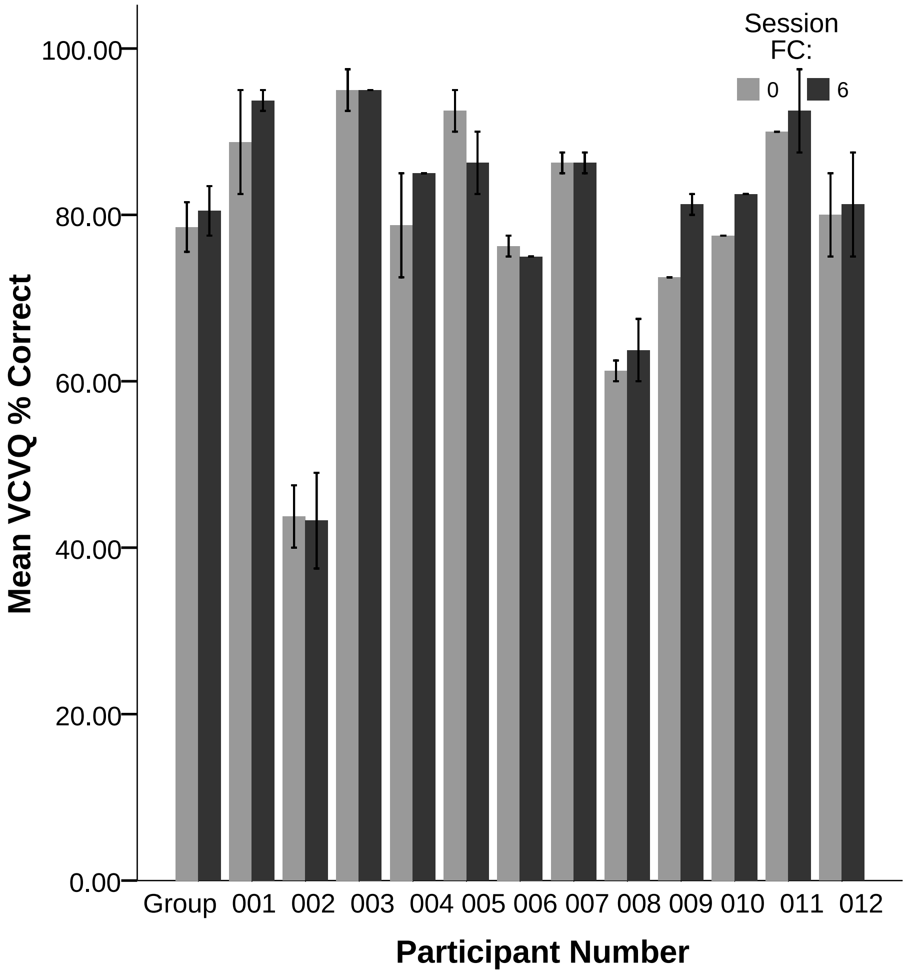
Session FC:
0
6
100.00
80.00
60.00
40.00
20.00
0.00
Mean VCVQ % Correct
Group
001
002
003
004
005
006
007
008
009
010
011
012
Participant Number

Figure 1.

		Response																		
		b	**d**	**g**	**w**	**y**	**r**	**l**	**v**	**z**	**j**	**m**	**n**	**p**	**t**	**k**	**f**	**th**	**s**	**sh**	**ch**
Stimulus	**b**	**48**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	d	1	**45**	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	g	4	9	**34**	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
	w	0	0	0	**36**	0	12	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	y	0	0	0	0	**31**	4	0	6	4	0	1	0	0	0	0	1	1	0	0	0
	r	0	0	0	8	0	**40**	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	l	0	0	0	0	0	1	**43**	1	0	0	3	0	0	0	0	0	0	0	0	0
	v	0	0	0	0	0	0	0	**47**	1	0	0	0	0	0	0	0	0	0	0	0
	z	0	1	0	0	0	0	0	7	**38**	0	0	0	0	0	0	1	1	0	0	0
	j	0	3	0	0	0	0	0	0	0	**44**	0	0	0	1	0	0	0	0	0	0
	m	0	0	0	0	0	2	4	0	0	0	**35**	7	0	0	0	0	0	0	0	0
	n	0	0	0	0	0	1	0	0	0	0	29	**18**	0	0	0	0	0	0	0	0
	p	0	0	0	0	0	0	0	0	0	0	0	0	**48**	0	0	0	0	0	0	0
	t	0	0	0	0	0	0	0	0	0	0	0	0	0	**48**	0	0	0	0	0	0
	k	0	0	0	0	0	0	0	0	0	0	0	0	1	14	**33**	0	0	0	0	0
	f	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	**19**	13	13	2	0
	th	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	5	**16**	26	0	0
	s	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	**42**	5	0
	sh	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	**47**	0
	ch	0	0	0	0	0	0	0	0	0	0	0	0	0	6	0	0	0	0	0	**42**

Figure 2

		Response																			
		b	**d**	**g**	**w**	**y**	**r**	**l**	**v**	**z**	**j**	**m**	**n**	**p**	**t**	**k**	**f**	**th**	**s**	**sh**	**ch**
Stimulus	**b**	**46**	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
	d	1	**45**	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	g	4	7	**37**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	w	0	0	0	**37**	0	10	0	1	0	0	0	0	0	0	0	0	0	0	0	0
	y	0	0	0	0	**28**	4	3	5	3	0	2	0	0	0	0	2	1	0	0	0
	r	0	0	0	6	0	**42**	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	l	0	0	0	0	0	0	**41**	0	0	0	6	1	0	0	0	0	0	0	0	0
	v	0	0	0	0	0	0	0	**44**	1	0	0	0	0	0	0	2	1	0	0	0
	z	0	1	0	0	0	0	0	7	**38**	0	0	0	0	0	0	2	0	0	0	0
	j	0	4	2	0	0	0	0	0	0	**42**	0	0	0	0	0	0	0	0	0	0
	m	0	0	0	0	0	0	1	0	0	0	**39**	8	0	0	0	0	0	0	0	0
	n	0	0	0	1	0	0	0	0	0	0	31	**16**	0	0	0	0	0	0	0	0
	p	0	0	0	0	0	0	0	0	0	0	0	0	**46**	2	0	0	0	0	0	0
	t	0	0	0	0	0	0	0	0	0	0	0	0	0	**46**	0	0	2	0	0	0
	k	0	0	0	0	0	0	0	0	0	0	0	0	1	11	**36**	0	0	0	0	0
	f	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	**27**	11	7	2	0
	th	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	5	**23**	17	2	0
	s	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	**44**	3	0
	sh	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	**47**	0
	ch	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	3	0	0	**44**

Figure 2 continued

	Response																			
Stimulus	**b**	**d**	**g**	**w**	**y**	**r**	**l**	**v**	**z**	**j**	**m**	**n**	**p**	**t**	**k**	**f**	**th**	**s**	**sh**	**ch**
b	**-2**	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
d	0	**0**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
g	0	-2	**3**	0	0	0	0	0	0	0	0	0	-1	0	0	0	0	0	0	0
w	0	0	0	**1**	0	-2	0	1	0	0	0	0	0	0	0	0	0	0	0	0
y	0	0	0	0	**-3**	0	3	-1	-1	0	1	0	0	0	0	1	0	0	0	0
r	0	0	0	-2	0	**2**	0	0	0	0	0	0	0	0	0	0	0	0	0	0
l	0	0	0	0	0	-1	**-2**	-1	0	0	3	1	0	0	0	0	0	0	0	0
v	0	0	0	0	0	0	0	**-3**	0	0	0	0	0	0	0	2	1	0	0	0
z	0	0	0	0	0	0	0	0	**0**	0	0	0	0	0	0	1	-1	0	0	0
j	0	1	2	0	0	0	0	0	0	**-2**	0	0	0	-1	0	0	0	0	0	0
m	0	0	0	0	0	-2	-3	0	0	0	**4**	1	0	0	0	0	0	0	0	0
n	0	0	0	1	0	-1	0	0	0	0	2	**-2**	0	0	0	0	0	0	0	0
p	0	0	0	0	0	0	0	0	0	0	0	0	**-2**	2	0	0	0	0	0	0
t	0	0	0	0	0	0	0	0	0	0	0	0	0	**-2**	0	0	2	0	0	0
k	0	0	0	0	0	0	0	0	0	0	0	0	0	-3	**3**	0	0	0	0	0
f	0	0	0	0	0	0	0	-1	0	0	0	0	1	0	0	**8**	-2	-6	0	0
th	0	0	0	0	0	0	0	0	0	0	0	0	-1	1	0	0	**7**	-9	2	0
s	0	0	0	0	0	0	0	0	-1	0	0	0	0	1	0	0	0	**2**	-2	0
sh	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**	0
ch	0	0	0	0	0	0	0	0	0	0	0	0	0	-5	0	0	3	0	0	**2**

Figure 2 continued

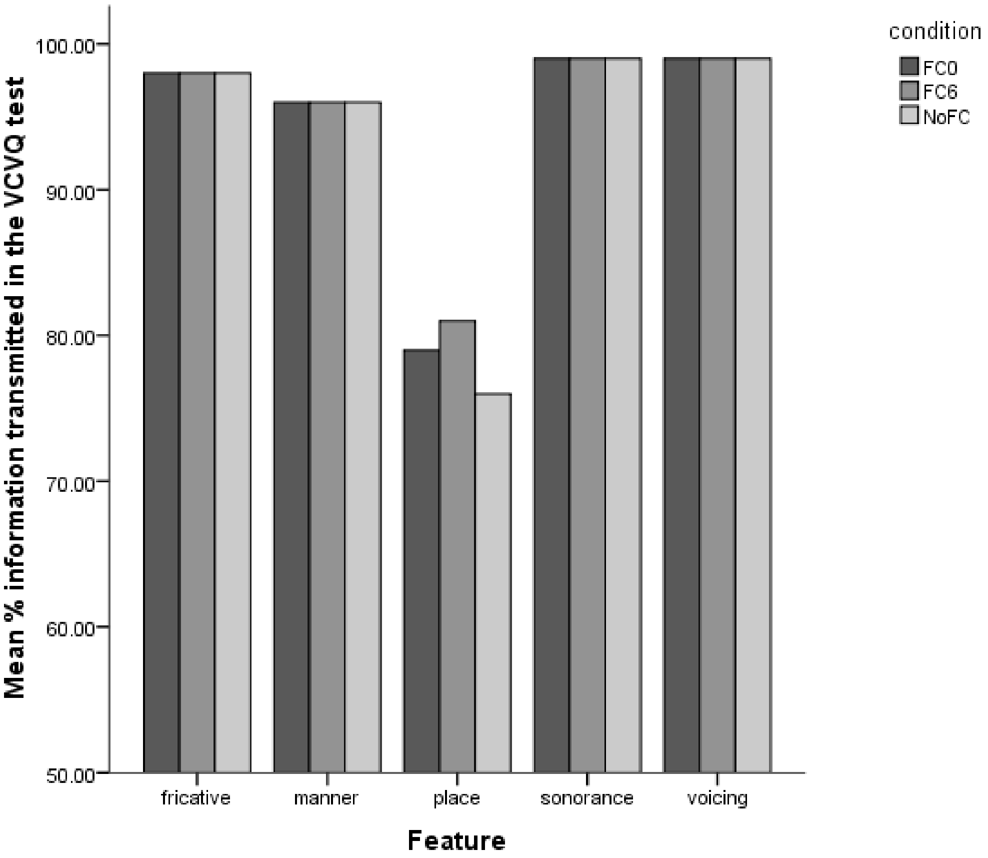
condition
FC0
FC6
NoFC
Mean % information transmitted in the VCVQ test
100.00
90.00
80.00
70.00
60.00
50.00
fricative
manner
place
sonorance
voicing
Feature

Figure 3

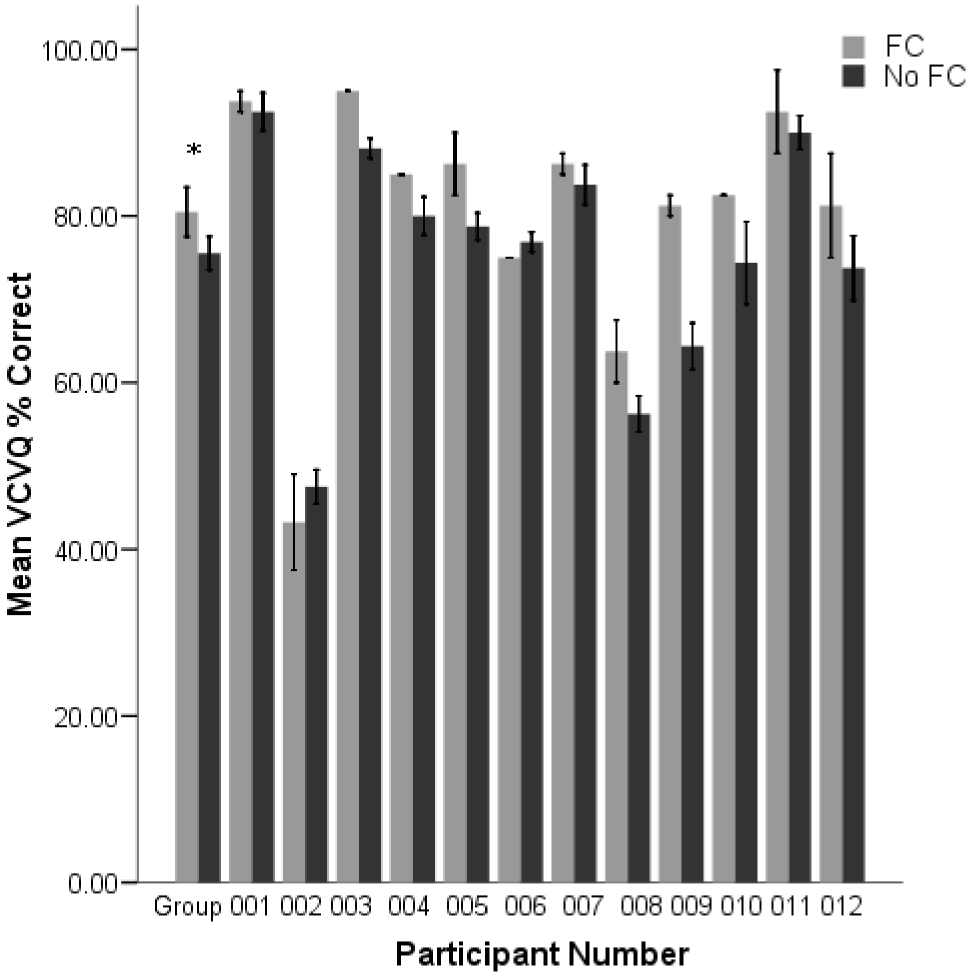
Mean VCVQ % Correct
100.00
80.00
60.00
40.00
20.00
0.00
*
FC
No FC
Group
001
002
003
004
005
006
007
008
009
010
011
012
Participant Number

Figure 4

	Response																			
Stimulus	**b**	**d**	**g**	**w**	**y**	**r**	**l**	**v**	**z**	**j**	**m**	**n**	**p**	**t**	**k**	**f**	**th**	**s**	**sh**	**ch**
b	**91**	1	0	0	0	0	0	4	0	0	0	0	0	0	0	0	0	0	0	0
d	1	**87**	8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
g	5	24	**67**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
w	0	0	0	**71**	0	24	0	0	0	0	0	0	0	0	0	1	0	0	0	0
y	0	0	0	2	**60**	4	6	7	9	0	4	0	0	0	0	3	1	0	0	0
r	0	0	0	16	0	**80**	0	0	0	0	0	0	0	0	0	0	0	0	0	0
l	0	0	0	0	0	1	**84**	1	0	0	10	0	0	0	0	0	0	0	0	0
v	0	0	0	0	0	0	0	**91**	0	0	0	0	0	1	0	2	2	0	0	0
z	0	0	0	0	0	0	0	50	**40**	0	0	0	0	0	0	3	3	0	0	0
j	0	9	4	0	0	0	0	0	0	**82**	0	0	0	1	0	0	0	0	0	0
m	0	0	0	0	0	0	2	0	0	0	**74**	20	0	0	0	0	0	0	0	0
n	0	0	0	0	0	1	0	0	0	0	59	**35**	0	0	0	1	0	0	0	0
p	0	0	0	0	0	0	0	0	0	0	0	0	**93**	1	2	0	0	0	0	0
t	0	0	0	0	0	0	0	0	0	0	0	0	1	**92**	1	0	2	0	0	0
k	0	0	0	0	0	0	0	0	0	0	0	0	5	18	**69**	0	2	0	0	2
f	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**57**	14	21	4	0
th	0	0	1	0	0	0	0	0	0	0	0	0	0	2	0	25	**41**	27	0	0
s	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	11	18	**62**	4	1
sh	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	**94**	0
ch	0	0	0	0	0	0	0	0	0	0	2	0	0	9	0	0	4	0	0	**81**

Figure 5

		Response																			
		b	**d**	**g**	**w**	**y**	**r**	**l**	**v**	**z**	**j**	**m**	**n**	**p**	**t**	**k**	**f**	**th**	**s**	**sh**	**ch**
Stimulus	**b**	**1**	1	0	0	0	0	0	-2	0	0	0	0	0	0	0	0	0	0	0	0
	d	1	**3**	-4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	g	3	-10	**7**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	w	0	0	0	**3**	0	-4	0	2	0	0	0	0	0	0	0	-1	0	0	0	0
	y	0	0	0	-2	**-4**	4	0	3	-3	0	0	0	0	0	0	1	1	0	0	0
	r	0	0	0	-4	0	**4**	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	l	0	0	0	0	0	-1	**-2**	-1	0	0	2	2	0	0	0	0	0	0	0	0
	v	0	0	0	0	0	0	0	**-3**	2	0	0	0	0	-1	0	2	0	0	0	0
	z	0	2	0	0	0	0	0	-36	**36**	0	0	0	0	0	0	1	-3	0	0	0
	j	0	-1	0	0	0	0	0	0	0	**2**	0	0	0	-1	0	0	0	0	0	0
	m	0	0	0	0	0	0	0	0	0	0	**4**	-4	0	0	0	0	0	0	0	0
	n	0	0	0	2	0	-1	0	0	0	0	3	**-3**	0	0	0	-1	0	0	0	0
	p	0	0	0	0	0	0	0	0	0	0	0	0	**-1**	3	-2	0	0	0	0	0
	t	0	0	0	0	0	0	0	0	0	0	0	0	-1	**0**	-1	0	2	0	0	0
	k	0	0	0	0	0	0	0	0	0	0	0	0	-3	4	**3**	0	-2	0	0	-2
	f	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	**-3**	8	-7	0	0
	th	0	0	-1	0	0	0	0	0	0	0	0	0	0	0	0	-15	**5**	7	4	0
	s	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	-11	-18	**26**	2	-1
	sh	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**	0
	ch	0	0	0	0	0	0	0	0	0	0	-2	0	0	-7	0	0	2	0	0	**7**

Figure 5 continued

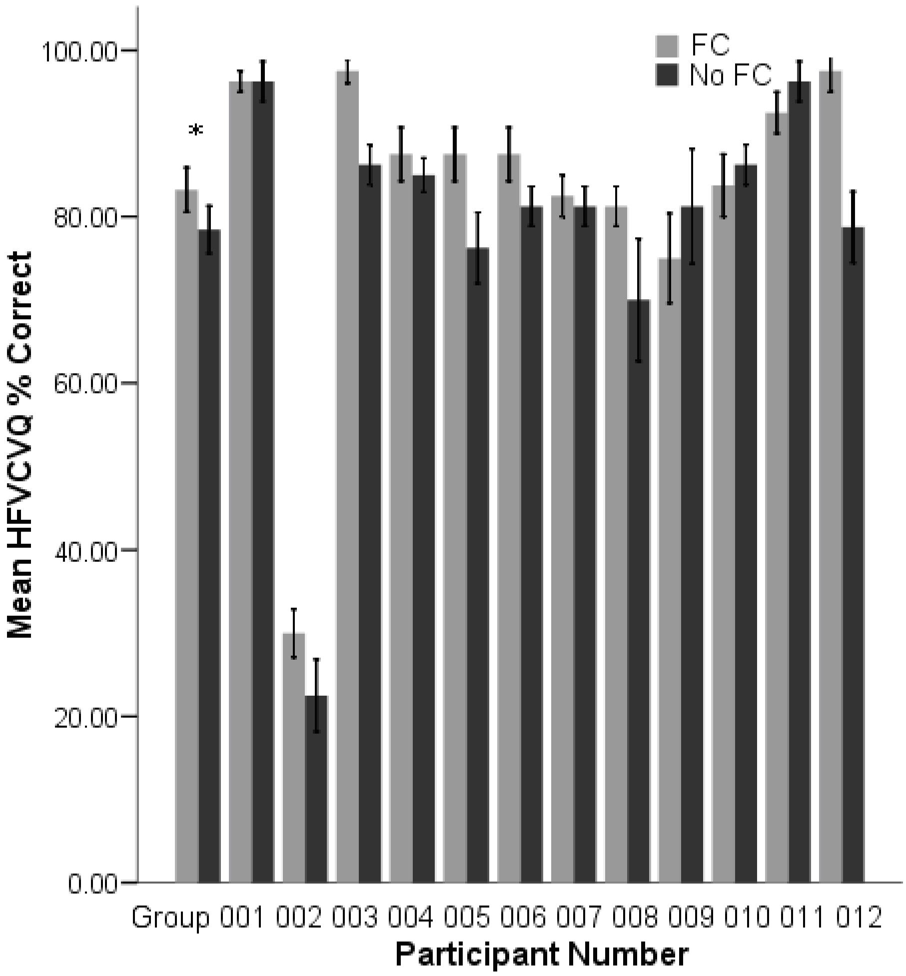
FC
No FC
*
100.00
80.00
60.00
40.00
20.00
0.00
Mean HFVCVQ % Correct
Group
001
002
003
004
005
006
007
008
009
010
011
012
Participant Number

Figure 6

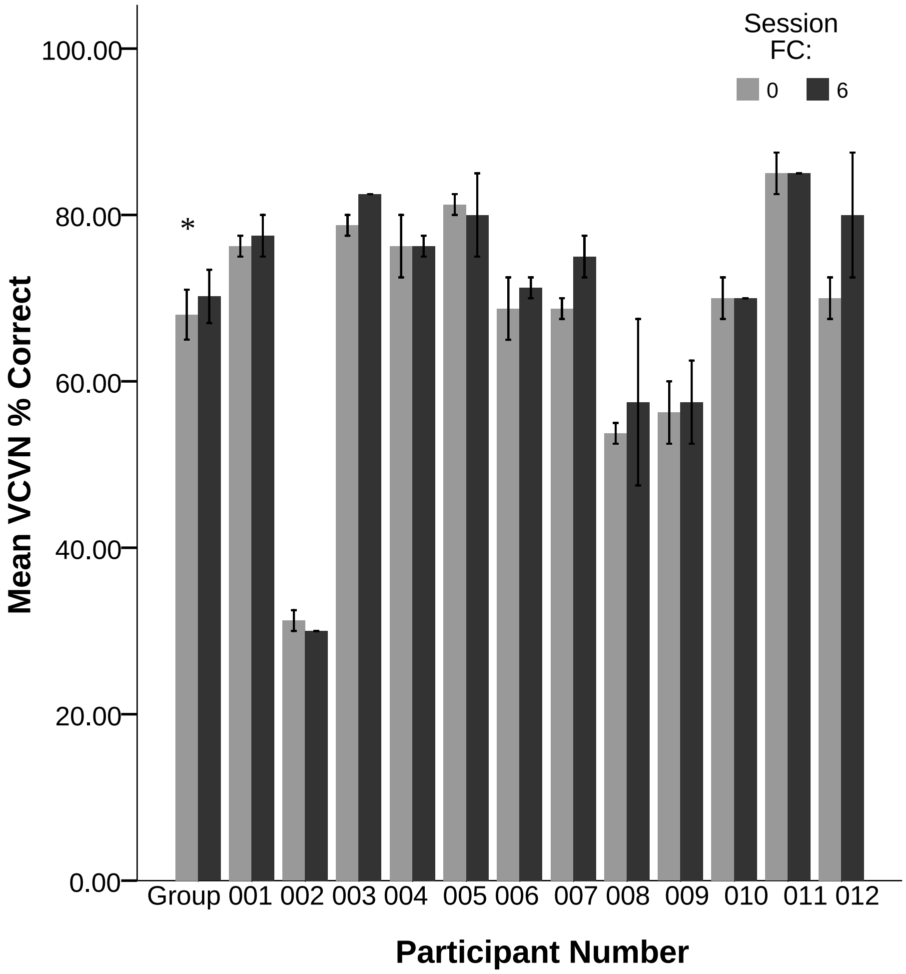
Session FC:
0
6
Mean VCVN % Correct
100.00
80.00
60.00
40.00
20.00
0.00
*
Group
001
002
003
004
005
006
007
008
009
010
011
012
Participant Number

Figure 7

		Response																			
		b	**d**	**g**	**w**	**y**	**r**	**l**	**v**	**z**	**j**	**m**	**n**	**p**	**t**	**k**	**f**	**th**	**s**	**sh**	**ch**
Stimulus	**b**	**36**	3	0	0	0	0	0	5	1	0	0	0	1	0	0	0	2	0	0	0
	d	0	**47**	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
	g	3	6	**36**	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0
	w	1	0	0	**35**	0	8	0	2	1	0	0	0	0	0	0	1	0	0	0	0
	y	1	0	0	0	**27**	5	2	5	3	0	5	0	0	0	0	0	0	0	0	0
	r	0	0	0	14	0	**27**	2	1	0	0	3	0	0	0	0	0	1	0	0	0
	l	1	0	0	0	1	1	**29**	5	0	0	11	0	0	0	0	0	0	0	0	0
	v	0	0	0	1	0	0	0	**41**	0	0	2	0	0	0	0	1	3	0	0	0
	z	1	2	0	0	0	0	0	6	**37**	0	0	0	0	0	0	1	0	1	0	0
	j	0	4	0	0	0	0	0	0	0	**43**	0	0	0	0	0	0	0	0	0	1
	m	0	0	0	0	1	5	5	0	0	0	**32**	5	0	0	0	0	0	0	0	0
	n	0	0	0	2	0	0	3	1	0	0	39	**3**	0	0	0	0	0	0	0	0
	p	0	0	0	0	0	0	0	0	0	0	0	0	**42**	3	3	0	0	0	0	0
	t	0	0	0	0	0	0	0	0	0	0	0	0	0	**44**	0	0	0	1	0	3
	k	0	0	0	0	0	0	0	0	0	0	0	0	2	10	**35**	0	0	0	0	1
	f	0	0	0	0	0	0	0	0	1	0	0	0	2	0	0	**13**	16	16	0	0
	th	0	2	0	0	0	0	0	0	0	0	0	0	0	4	0	8	**14**	20	0	0
	s	0	0	0	0	0	0	0	0	2	0	0	0	2	0	1	0	0	**39**	4	0
	sh	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	**45**	0
	ch	0	0	0	0	0	0	0	0	0	0	0	0	0	7	1	0	0	0	0	**40**

Figure 8

		Response																			
		b	**d**	**g**	**w**	**y**	**r**	**l**	**v**	**z**	**j**	**m**	**n**	**p**	**t**	**k**	**f**	**th**	**s**	**sh**	**ch**
Stimulus	**b**	**37**	1	0	0	0	0	0	8	0	0	0	0	0	0	0	0	2	0	0	0
	d	2	**44**	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	0
	g	5	9	**34**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	w	0	0	0	**33**	0	13	0	0	0	0	1	1	0	0	0	0	0	0	0	0
	y	0	0	0	1	**18**	3	5	7	5	0	7	0	0	0	0	0	1	0	0	1
	r	0	0	0	7	0	**31**	4	4	0	0	2	0	0	0	0	0	0	0	0	0
	l	1	0	0	1	0	2	**35**	4	0	0	4	0	0	0	0	1	0	0	0	0
	v	1	0	0	0	0	0	1	**42**	1	0	0	0	0	0	0	1	2	0	0	0
	z	0	0	0	2	0	0	0	4	**39**	0	0	0	0	0	0	2	0	1	0	0
	j	0	2	2	0	0	0	0	0	0	**42**	0	0	0	1	0	0	1	0	0	0
	m	0	0	0	0	0	1	3	0	0	0	**33**	11	0	0	0	0	0	0	0	0
	n	0	0	0	0	0	2	0	0	0	0	37	**9**	0	0	0	0	0	0	0	0
	p	0	0	0	0	0	0	0	1	0	0	0	0	**44**	1	1	0	1	0	0	0
	t	0	0	0	0	0	0	0	0	0	1	0	0	2	**40**	2	0	2	0	0	1
	k	0	0	0	0	0	0	0	0	0	0	0	0	1	6	**38**	0	2	0	1	0
	f	0	0	0	0	0	0	0	1	1	0	0	0	2	0	0	**16**	16	11	1	0
	th	1	0	0	0	0	0	0	0	1	0	0	0	1	2	0	7	**22**	13	1	0
	s	0	1	0	0	0	0	0	0	1	0	0	0	1	0	0	1	1	**40**	2	1
	sh	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**48**	0
	ch	0	0	0	0	0	0	0	0	0	1	0	0	0	2	2	0	2	0	0	**41**

Figure 8 continued

		Response																			
		b	**d**	**g**	**w**	**y**	**r**	**l**	**v**	**z**	**j**	**m**	**n**	**p**	**t**	**k**	**f**	**th**	**s**	**sh**	**ch**
Stimulus	**b**	**1**	-2	0	0	0	0	0	3	-1	0	0	0	-1	0	0	0	0	0	0	0
	d	2	**-3**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
	g	2	3	**-2**	0	0	0	0	0	0	0	0	0	-3	0	0	0	0	0	0	0
	w	-1	0	0	**-2**	0	5	0	-2	-1	0	1	1	0	0	0	-1	0	0	0	0
	y	-1	0	0	1	**3**	-2	3	2	2	0	2	0	0	0	0	0	1	0	0	1
	r	0	0	0	-7	0	**4**	2	3	0	0	-1	0	0	0	0	0	-1	0	0	0
	l	0	0	0	1	-1	1	**6**	-1	0	0	-7	0	0	0	0	1	0	0	0	0
	v	1	0	0	-1	0	0	1	**1**	1	0	-2	0	0	0	0	0	-1	0	0	0
	z	-1	-2	0	2	0	0	0	-2	**2**	0	0	0	0	0	0	1	0	0	0	0
	j	0	-2	2	0	0	0	0	0	0	**-1**	0	0	0	1	0	0	1	0	0	-1
	m	0	0	0	0	-1	-4	-2	0	0	0	**1**	6	0	0	0	0	0	0	0	0
	n	0	0	0	-2	0	2	-3	-1	0	0	-2	**6**	0	0	0	0	0	0	0	0
	p	0	0	0	0	0	0	0	1	0	0	0	0	**2**	-2	-2	0	1	0	0	0
	t	0	0	0	0	0	0	0	0	0	1	0	0	2	**-4**	2	0	2	-1	0	-2
	k	0	0	0	0	0	0	0	0	0	0	0	0	-1	-4	**3**	0	2	0	1	-1
	f	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	**3**	0	-5	1	0
	th	1	-2	0	0	0	0	0	0	1	0	0	0	1	-2	0	-1	**8**	-7	1	0
	s	0	1	0	0	0	0	0	0	-1	0	0	0	-1	0	-1	1	1	**1**	-2	1
	sh	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-3	**3**	0
	ch	0	0	0	0	0	0	0	0	0	1	0	0	0	-5	1	0	2	0	0	**1**

Figure 8 continued

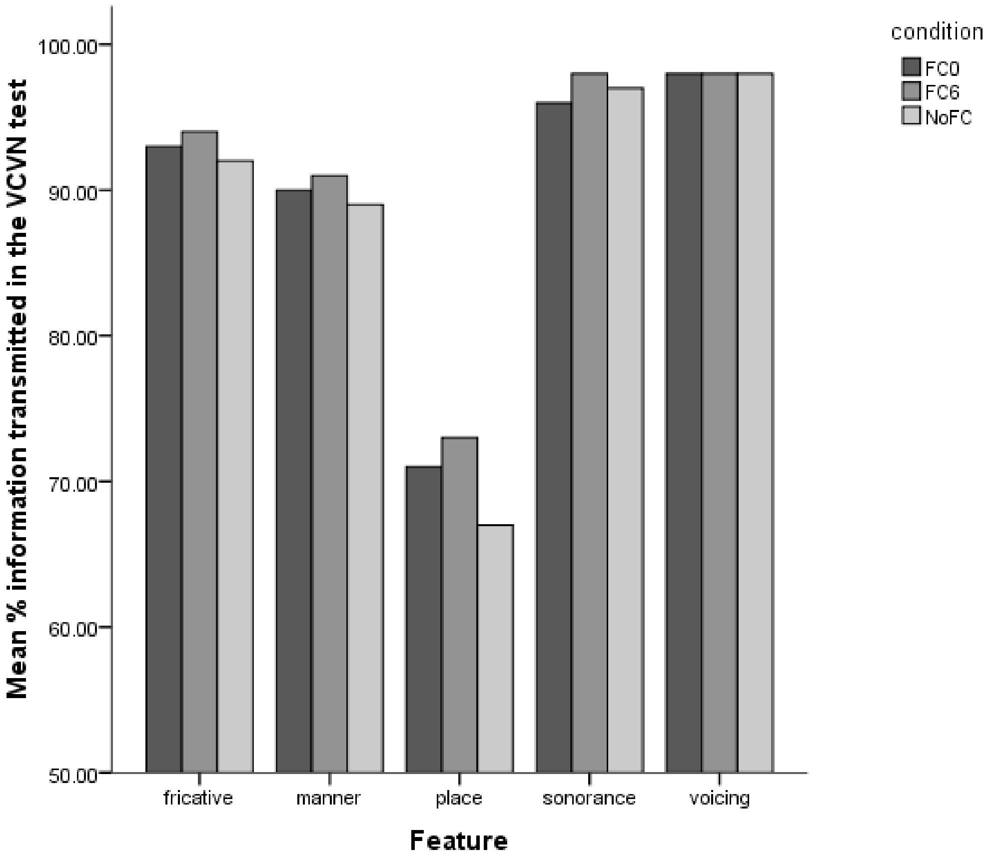
condition
FC0
FC6
NoFC
Mean % information transmitted in the VCVN test
100.00
90.00
80.00
70.00
60.00
50.00
fricative
manner
place
sonorance
voicing
Feature

Figure 9

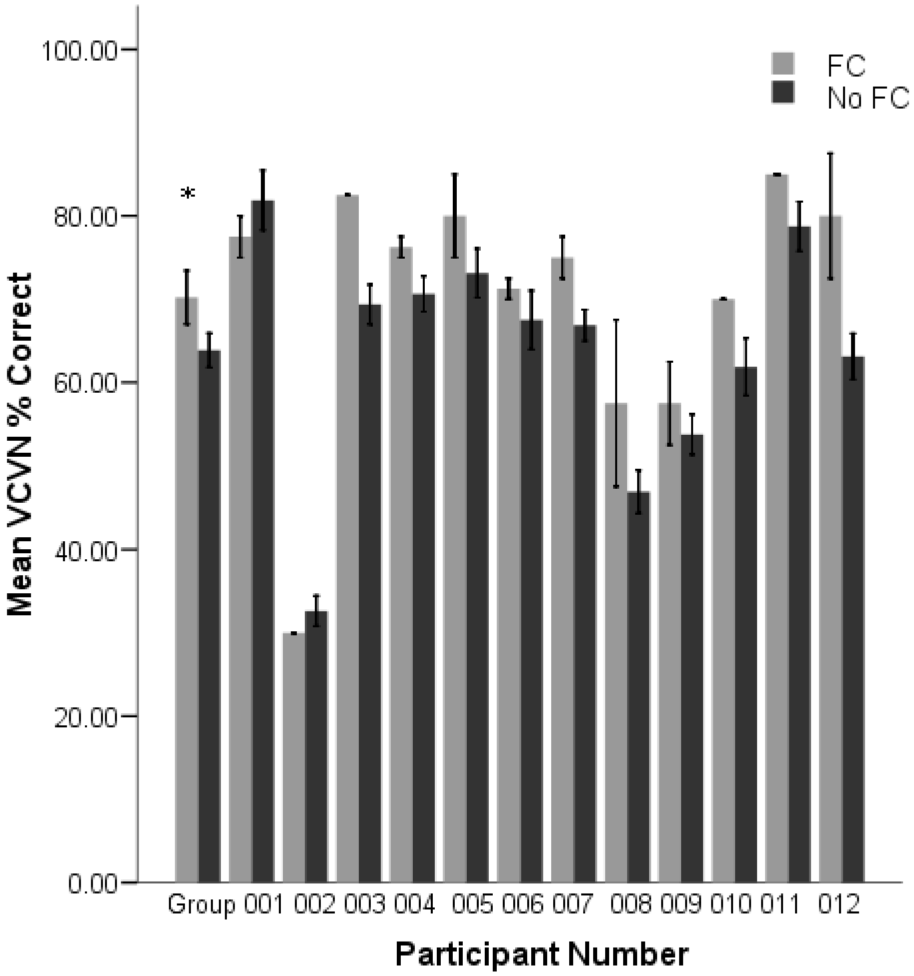
100.00
80.00
60.00
40.00
20.00
0.00
Mean VCVN % Correct
FC
No FC
*
Group
001
002
003
004
005
006
007
008
009
010
011
012
Participant Number

Figure 10

		Response																			
		b	**d**	**g**	**w**	**y**	**r**	**l**	**v**	**z**	**j**	**m**	**n**	**p**	**t**	**k**	**f**	**th**	**s**	**sh**	**ch**
Stimulus	**b**	**73**	3	0	0	0	0	0	18	0	0	1	0	0	0	0	0	1	0	0	0
	d	6	**74**	11	0	0	0	0	2	2	0	0	0	1	0	0	0	0	0	0	0
	g	10	20	**65**	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
	w	0	0	0	**66**	0	19	5	5	0	0	1	0	0	0	0	0	0	0	0	0
	y	0	0	0	5	**44**	9	5	14	9	0	5	0	0	0	0	1	4	0	0	0
	r	1	0	0	28	1	**49**	9	2	0	0	6	0	0	0	0	0	0	0	0	0
	l	1	0	0	2	0	1	**70**	12	0	0	9	0	0	0	0	0	1	0	0	0
	v	1	2	0	1	0	0	0	**72**	7	0	2	0	1	1	0	6	3	0	0	0
	z	2	6	1	2	0	0	1	42	**33**	0	0	0	0	0	0	3	5	0	1	0
	j	0	7	2	0	0	0	0	1	0	**84**	0	0	1	1	0	0	0	0	0	0
	m	0	0	0	2	0	3	10	1	0	0	**69**	11	0	0	0	0	0	0	0	0
	n	0	0	0	1	0	2	8	0	0	0	75	**10**	0	0	0	0	0	0	0	0
	p	0	0	1	0	0	0	0	0	0	0	0	0	**82**	3	7	0	3	0	0	0
	t	0	0	0	0	0	0	0	0	0	0	0	0	9	**82**	2	0	2	1	0	0
	k	0	1	0	0	0	0	0	0	0	0	0	0	13	17	**60**	0	1	1	0	3
	f	0	0	0	0	0	0	0	0	3	0	0	0	4	1	1	**41**	25	18	3	0
	th	0	1	0	0	0	0	0	0	3	0	0	0	8	9	1	14	**39**	20	1	0
	s	0	2	0	0	0	0	0	1	1	0	0	0	4	2	0	14	17	**51**	3	1
	sh	0	0	0	0	0	0	0	0	0	0	0	0	0	4	0	0	1	1	**90**	0
	ch	0	0	0	0	0	0	0	0	0	2	0	0	0	10	1	0	3	0	0	**80**

Figure 11

		Response																			
		b	**d**	**g**	**w**	**y**	**r**	**l**	**v**	**z**	**j**	**m**	**n**	**p**	**t**	**k**	**f**	**th**	**s**	**sh**	**ch**
Stimulus	**b**	1	-1	0	0	0	0	0	-2	0	0	-1	0	0	0	0	0	3	0	0	0
	d	-2	14	-11	0	0	0	0	0	-2	0	0	0	-1	0	0	0	0	0	2	0
	g	0	-2	3	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	0	0
	w	0	0	0	0	0	7	-5	-5	0	0	1	2	0	0	0	0	0	0	0	0
	y	0	0	0	-3	-8	-3	5	0	1	0	9	0	0	0	0	-1	-2	0	0	2
	r	-1	0	0	-14	-1	13	-1	6	0	0	-2	0	0	0	0	0	0	0	0	0
	l	1	0	0	0	0	3	0	-4	0	0	-1	0	0	0	0	2	-1	0	0	0
	v	1	-2	0	-1	0	0	2	12	-5	0	-2	0	-1	-1	0	-4	1	0	0	0
	z	-2	-6	-1	2	0	0	-1	-34	45	0	0	0	0	0	0	1	-5	2	-1	0
	j	0	-3	2	0	0	0	0	-1	0	0	0	0	-1	1	0	0	2	0	0	0
	m	0	0	0	-2	0	-1	-4	-1	0	0	-3	11	0	0	0	0	0	0	0	0
	n	0	0	0	-1	0	2	-8	0	0	0	-1	8	0	0	0	0	0	0	0	0
	p	0	0	-1	0	0	0	0	2	0	0	0	0	6	-1	-5	0	-1	0	0	0
	t	0	0	0	0	0	0	0	0	0	2	0	0	-5	-2	2	0	2	-1	0	2
	k	0	-1	0	0	0	0	0	0	0	0	0	0	-11	-5	16	0	3	-1	2	-3
	f	0	0	0	0	0	0	0	2	-1	0	0	0	0	-1	-1	-9	7	4	-1	0
	th	2	-1	0	0	0	0	0	0	-1	0	0	0	-6	-5	-1	0	5	6	1	0
	s	0	0	0	0	0	0	0	-1	1	0	0	0	-2	-2	0	-12	-15	29	1	1
	sh	0	0	0	0	0	0	0	0	0	0	0	0	0	-4	0	0	-1	-1	6	0
	ch	0	0	0	0	0	0	0	0	0	0	0	0	0	-6	3	0	1	0	0	2

Figure 11 continued

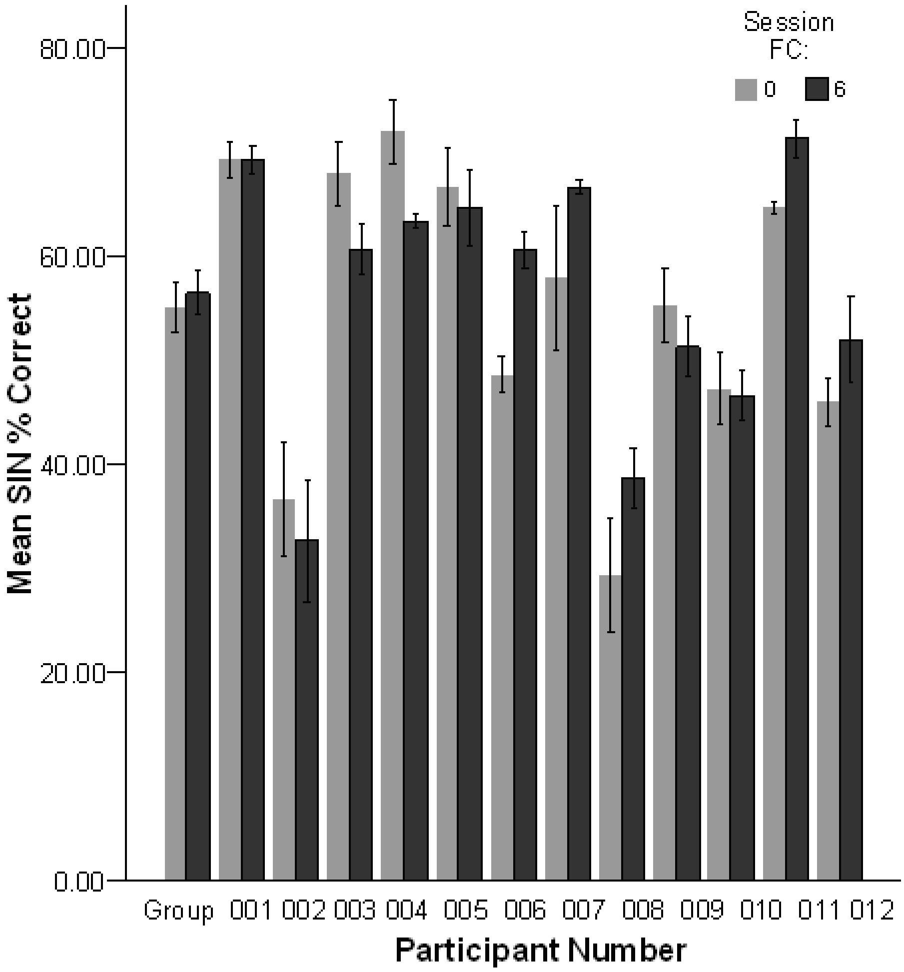
Session FC:
0
6
80.00
60.00
40.00
20.00
0.00
Mean SIN % Correct
Group
001
002
003
004
005
006
007
008
009
010
011
012
Participant Number

Figure 12

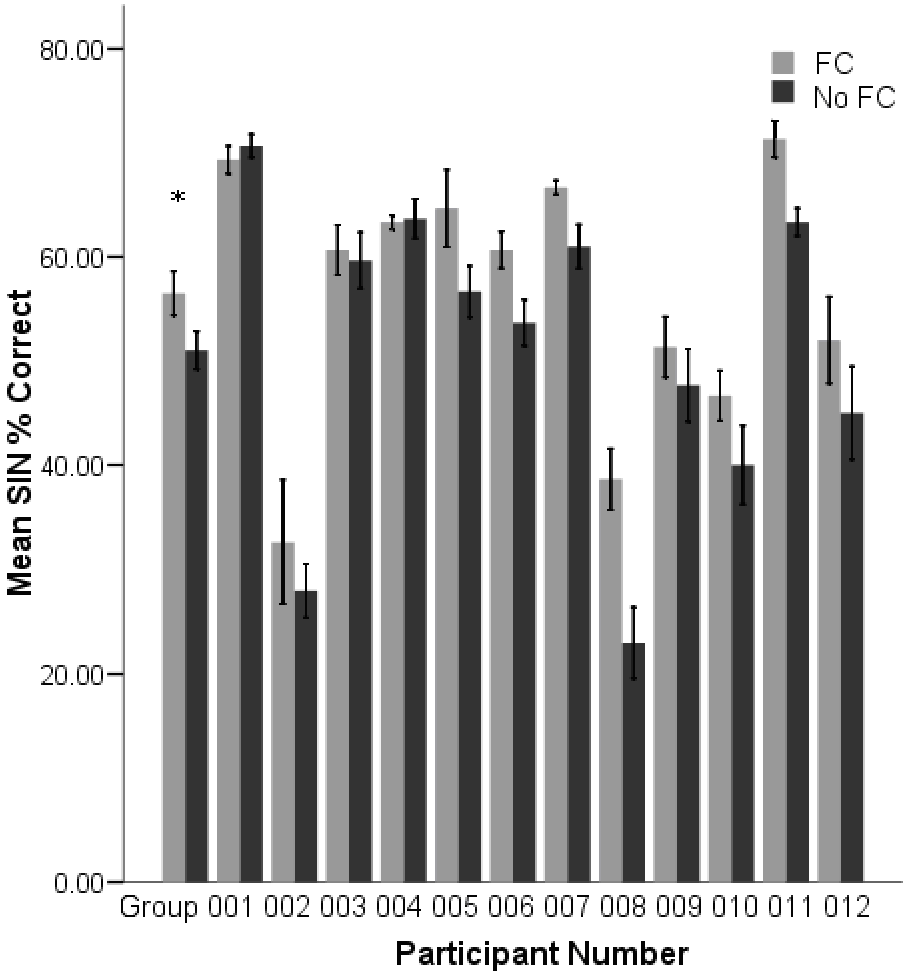
Mean SIN % Correct
80.00
60.00
40.00
20.00
0.00
FC
No FC
*
Group
001
002
003
004
005
006
007
008
009
010
011
012
Participant Number

Figure 13

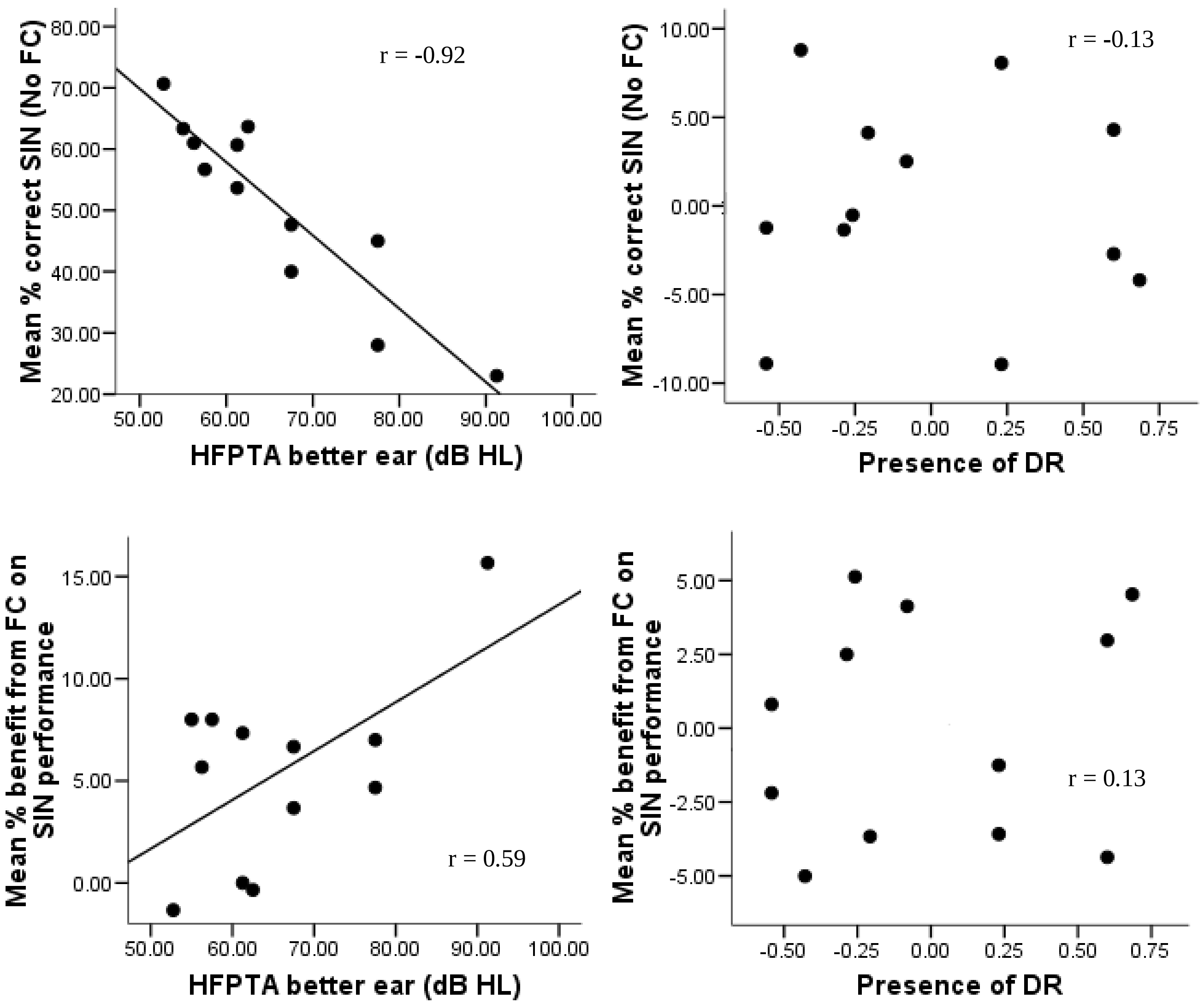
Mean % correct SIN (No FC)
80.00
70.00
60.00
50.00
40.00
30.00
20.00
r = -0.92
50.00
60.00
70.00
80.00
90.00
100.00
HFPTA better ear (dB HL)
Mean % correct SIN (No FC)
10.00
5.00
0.00
-5.00
-10.00
r = -0.13
-0.50
-0.25
0.00
0.25
0.50
0.75
Presence of DR
Mean % benefit from FC on SIN performance
15.00
10.00
5.00
0.00
r = 0.59
50.00
60.00
70.00
80.00
90.00
100.00
HFPTA better ear (dB HL)
Mean % benefit from FC on SIN performance
5.00
2.50
0.00
-2.50
-5.00
r = 0.13
-0.50
-0.25
0.00
0.25
0.50
0.75
Presence of DR

Figure 14

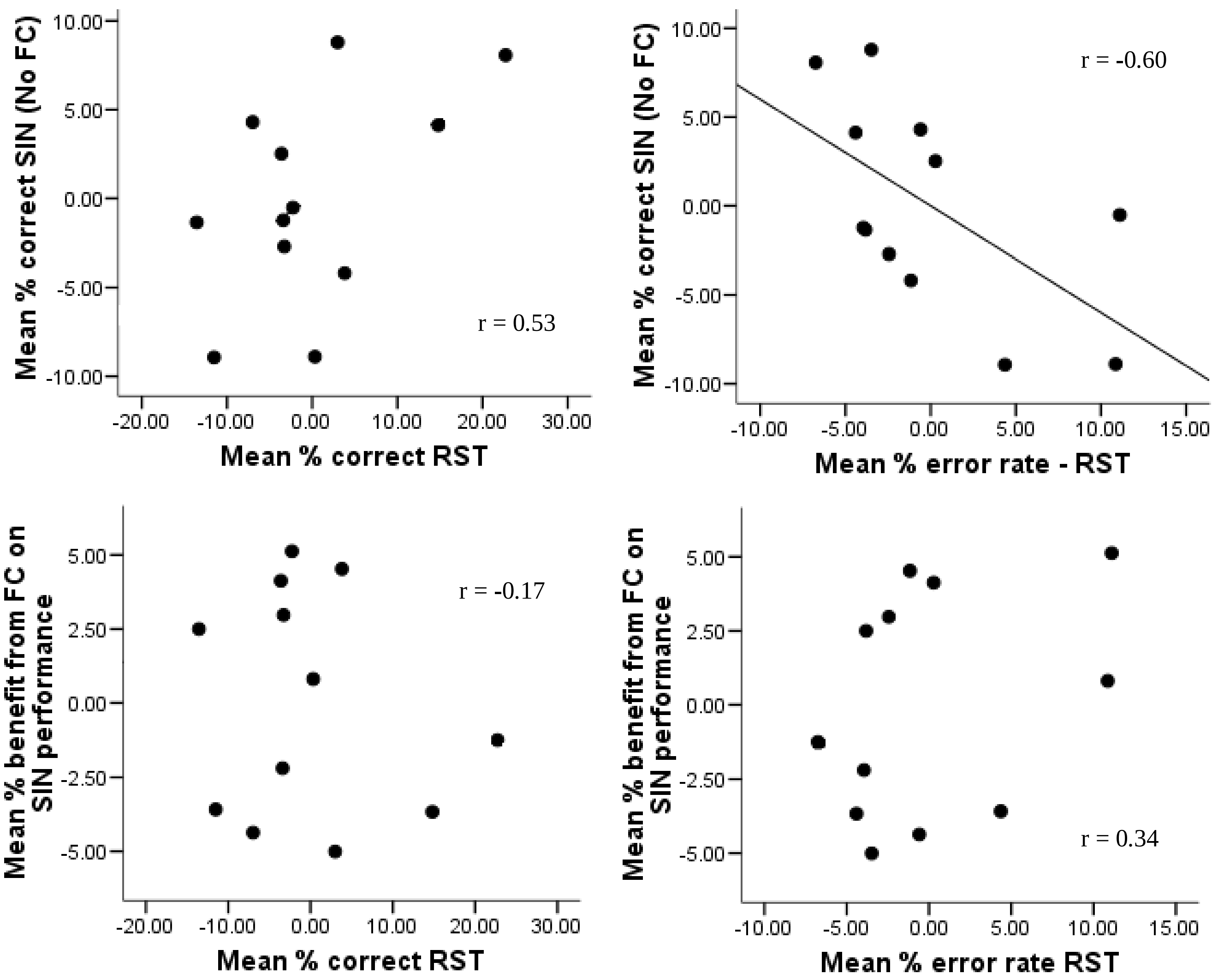
Mean % correct SIN (No FC)
10.00
5.00
0.00
-5.00
-10.00
-20.00
-10.00
0.00
10.00
20.00
30.00
Mean % correct RST
r = 0.53
Mean % correct SIN (No FC)
10.00
5.00
0.00
-5.00
-10.00
-10.00
-5.00
0.00
5.00
10.00
15.00
Mean % error rate - RST
r = -0.60
Mean % benefit from FC on SIN performance
5.00
2.50
0.00
-2.50
-5.00
-20.00
-10.00
0.00
10.00
20.00
30.00
Mean % correct RST
r = -0.17
Mean % benefit from FC on SIN performance
5.00
2.50
0.00
-2.50
-5.00
-10.00
-5.00
0.00
5.00
10.00
15.00
Mean % error rate RST
r = 0.34

Figure 15

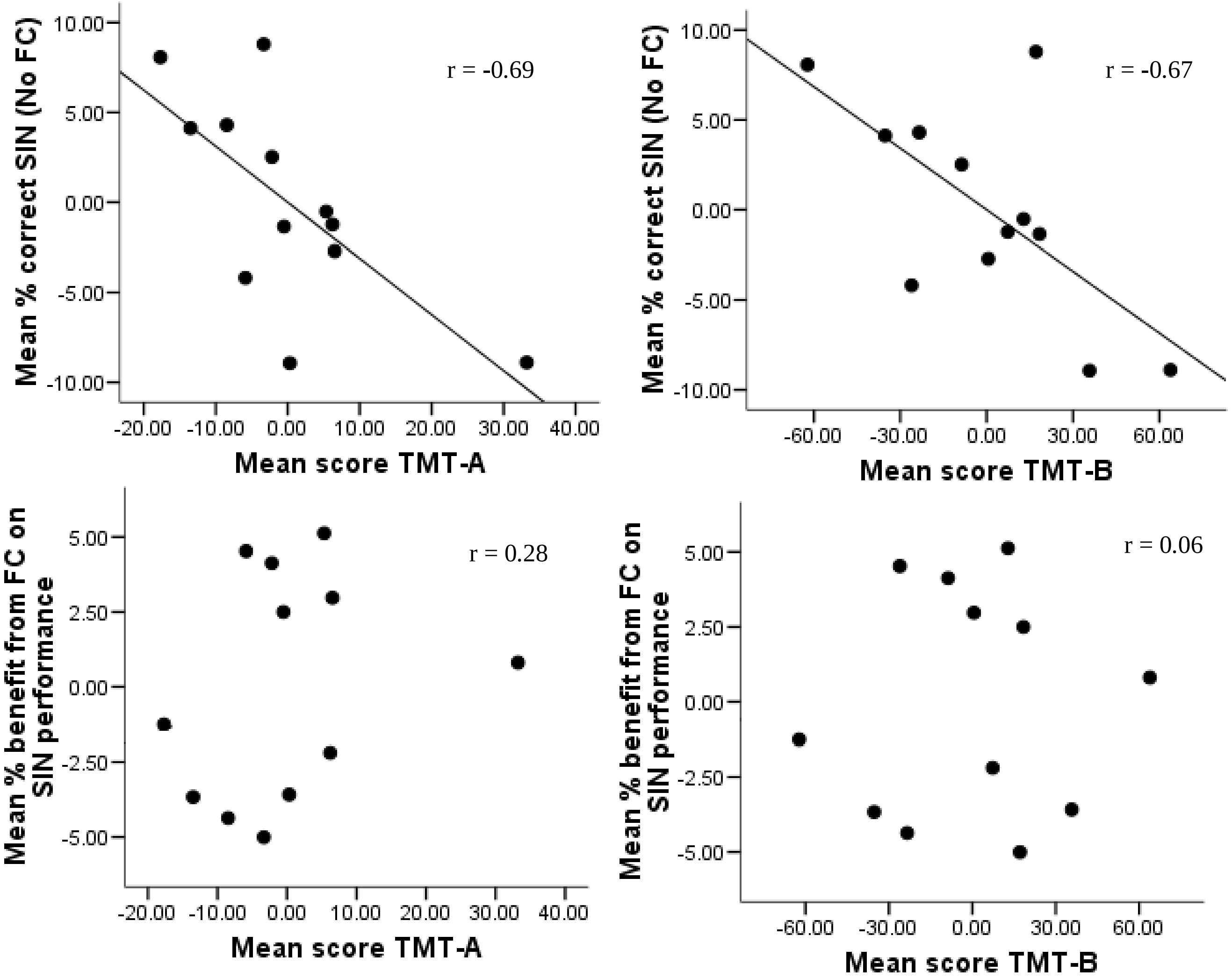
Mean % correct SIN (No FC)
10.00
5.00
0.00
-5.00
-10.00
r = -0.69
-20.00
-10.00
0.00
10.00
20.00
30.00
40.00
Mean score TMT-A
Mean % correct SIN (No FC)
10.00
5.00
0.00
-5.00
-10.00
r = -0.67
-60.00
-30.00
0.00
30.00
60.00
Mean score TMT-B
Mean % benefit from FC on SIN performance
5.00
2.50
0.00
-2.50
-5.00
r = 0.28
-20.00
-10.00
0.00
10.00
20.00
30.00
40.00
Mean score TMT-A
Mean % benefit from FC on SIN performance
5.00
2.50
0.00
-2.50
-5.00
r = 0.06
-60.00
-30.00
0.00
30.00
60.00
Mean score TMT-B

Figure 16

CHAPTER 7

CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH

In this chapter, the conclusions derived from the results of the experiments conducted will be discussed in relation to the research questions underpinning the thesis. Finally, suggestions for future research on NLFC amplification are presented.

7.1 CONCLUSIONS

7.1.1 Does frequency compression provide significant benefit above that provided by conventional amplification?

The results of the study showed that the use of NLFC led to significant improvements in all measures of speech perception compared to performance with conventional amplification (Chapter 6). Measures included a consonant in noise recognition task, which this study was the first to administer to NLFC hearing aid users. In addition, this study was the first to report a significant improvement to sentence in noise recognition with the use of frequency compression. This novel finding is likely to be related to differences in the nature of the sentence stimuli used in this and earlier studies. Specifically, the IEEE sentences used in this study contain much less contextual information than those used in earlier studies (CUNY sentences, Simpson et al, 2006; BKB sentences, Wolfe et al, 2010, 1011).

The difference in findings, relating to sentence in noise perception, between the present study and earlier studies may also relate to variations in the selection of frequency compression parameters. The results of the first experiment to investigate the effect of NLFC on categorical perception in listeners with normal hearing (Chapter 4) indicated that NLFC affects the identification of high frequency phonemes rather than the ability to discriminate between them. The decision to incorporate this finding into the NLFC fitting process resulted in the application of stronger NLFC settings than those prescribed by the manufacturer. It is possible that these settings facilitated greater benefit to speech in noise perception by making audible higher frequencies (important for separating speech and noise) than the prescribed setting would allow. These findings suggest that, for some individuals, it may be beneficial for clinicians to apply stronger NLFC settings than the default prescription but further research is needed to identify which listeners are likely to benefit from the application of stronger NLFC settings. However, improvements in audibility of high frequency information should be considered alongside a possible reduction in sound quality if the settings applied are too high. Further research is needed to identify which listeners are likely to benefit from the application of stronger NLFC settings and to determine the impact of stronger settings on sound quality.

The results of this study also provide preliminary evidence that NLFC may not lead to self reported improvement in benefit, even if improvements are apparent on lab-based speech measures. If this finding were replicated in a study of larger scale, the implication would be that clinicians should be aware that even if a listener does not report any additional benefit from NLFC, improvements to speech perception may have actually taken place.

7.1.2 Are there changes in perceptual abilities over time following the provision of frequency compression hearing aids?

This study was the first to systematically investigate acclimatisation to NLFC in adult users, along with being the first study to investigate early acclimatisation (in the first six weeks after fitting) to NLFC (Chapter 6). The results show limited evidence of acclimatisation, with observed changes being specific to a reduction in confusions between phonemes which were adversely affected by NLFC at the initial fitting session. There were no large decreases in the correct identification of any phoneme but changes in the pattern of confusions between some lower frequency consonants were observed (likely as a result of frequency compression affecting high frequency formant transitions) when stimuli were presented in a background of noise. The results provide no further evidence of changes over time to speech processed by NLFC. The clinical implication of this is that if a patient fails to perform well with NLFC initially, they are unlikely to obtain much additional benefit over time, at least in the first six weeks post fitting. It is possible that greater evidence of acclimatisation would be seen if participants were tested after a few months of NLFC use or if different outcome measures were used. Unfortunately, due to practical limitations, it was not possible to run the acclimatisation study (chapter 6) over a longer period of time. Munro and Lutman (2003) found that perceptual changes, following the provision of conventional linear hearing aids, commenced at around 4 weeks, yet scores had not reached an asymptote when the study ended at 12-15 weeks post fitting. Wolfe et al (2011) report some (albeit limited) evidence of acclimatisation between 6 weeks and 6 months of NLFC hearing aid use, again primarily limited to high frequency phonemes. It is unlikely that such specific acclimatisation, as evidenced in the results of Wolfe et al (2011) and of the present study, would be clinically significant.

7.1.3 Is it possible to predict benefit from frequency compression hearing aids using audiological or cognitive factors?

The results of this study indicate that severity of high frequency hearing loss is predictive of benefit from NLFC on sentence in noise recognition. This is in agreement with the results reported by Glista et al (2009) but at odds with the results of Simpson et al (2006). Further research using a larger number of participants with a greater range in configuration and severity of hearing loss is needed to disambiguate these conflicting findings. This study was the first to investigate the relationship between cochlear dead regions and benefit from NLFC. The results provide no evidence that dead regions influence either benefit from NLFC, or speech in noise recognition with conventional amplification. This is in agreement with findings reported by Dillon et al (2011) suggesting that dead regions do not contribute significantly to speech intelligibility scores in listeners using conventional hearing aids fitted in accordance with the NAL-NL2 prescription method (Keidser et al, 2011) once the effect of severity of hearing loss has been accounted for.

The present study was also the first to investigate the relationship between cognition and benefit from NLFC. Pilot data from normally hearing listeners (presented in Chapter 5) showed that performance on cognitive tests was only predictive of sentence in noise recognition without frequency compression. This pattern was also evident in the results of the longitudinal study (with hearing impaired listeners, Chapter 6) which indicate that there is no link between cognition and benefit from frequency compression. However, in agreement with the data from normally hearing listeners, a significant correlation was found between performance on some cognitive tests and speech in noise performance with frequency compression disabled. Whilst this is not directly relevant to the original aims of the study, the findings merit further discussion. Many previous studies have demonstrated the link between cognition and speech recognition in noise with working memory span appearing to be the best predictor of performance (see Akeroyd, 2008, for a review). However, in the current study, the measure of working memory span (WMS; percentage correct on the RST) was not predictive of speech in noise recognition. Instead, performance on the tests indexing processes associated with executive function control (such as selective attention and task switching, as measured by the TMT A& B and the error rate on the RST) were the stronger predictors of speech in noise perception with conventional amplification.

This is a novel finding and suggests that the relationship between WMS and speech in noise perception, reported in previous literature, may relate specifically to the influence of executive function on performance in WMS tasks. If this were shown to be correct, there may be important implications clinically. Currently, cognitive tests are not routinely used as part of the hearing aid fitting process. One likely reason for this is that many cognitive tests, particularly those of WMS, are lengthy and taxing for the participant. In short, they are not suitable for use in a clinical setting. On the other hand, tests such as the TMT-A and B take only minutes to perform and require only a response sheet, stopwatch and a pencil to administer, therefore making them potentially suitable for clinical use. For patients with dexterity issues, one can calculate a ratio of time spent on the TMT-B to time spent on the TMT-A, to obtain a measure of performance that should be relatively unaffected by problems with dexterity. Pending the results of future research, information about performance on such tests could then be used to inform clinical decisions on hearing aid settings and how best to counsel hearing aid users in terms of predicted benefit from amplification.

The lack of relationship between performance on the cognitive tests and benefit from NLFC suggests that cognitive status does not need to be considered when fitting NLFC hearing aids. The implication of this is that NLFC may provide additional benefit to that provided by conventional amplification, even to less cognitively able patients.

7.2 NOVELTY OF THE RESEARCH

In summary, a number of novel findings have been reported in this thesis. This study was the first to examine the:

- effect of NLFC on the recognition of consonants in noise
- time course of auditory acclimatisation to NLFC in adults
- effect of NLFC on categorical perception
- relationship between cognition and benefit from NLFC
- relationship between dead regions and benefit from NLFC

7.3 DIRECTIONS FOR FUTURE RESEARCH

This section highlights ten areas in which further research is needed. The topics discussed are as follows:

- What is the best method of selecting frequency compression settings?
- Are there long term changes to the perception of frequency compressed speech?
- Is listening effort affected by frequency compression?
- Should the extent and edge frequency of a dead region be taken into consideration when selecting frequency compression parameters?
- Does the provision of active training affect the time course or magnitude of changes over time to frequency compressed speech?
- How does frequency compression affect subjective outcome measures?
- Does degree of benefit from frequency compression vary between new and experienced hearing aid users?
- How good a predictor of benefit from frequency compression is severity or configuration of hearing loss?
- Which outcome measures are the most appropriate to use when assessing the effect of frequency compression on speech perception?
- Which cognitive processes are responsible for the relationship between cognition and speech in noise perception with conventional amplification?

7.3.1 What is the best method of selecting frequency compression settings?

Current guidelines suggest that when assessing the suitability of a frequency compression setting, one should check that the listener is able to correctly identify the phonemes /s/ and /ʃ/ (Glista et al, 2009). This is an attempt to ensure that the NLFC setting applied does not lead to an increase in phonemic confusions. A similar fitting criterion was adopted in the present study (although only discrimination of the phonemes was required). The findings suggest that this method does not eliminate phonemic confusions, but rather alters the nature of them. Further research is needed to systematically investigate how different frequency compression settings affect phonemic recognition and discrimination and how best to utilise this information in the fitting process.

7.3.2. Are there long term changes to the perception of frequency compressed speech?

The results of the current study suggest that auditory acclimatisation in the initial few weeks following the fitting of NLFC is minimal and limited to changes in the identification of some high frequency phonemes. However, to date, there has been no research into long term changes over time to the perception of frequency compressed speech in adult listeners. A large scale study is needed to identify whether any additional changes occur in the months following the provision of a frequency compression device. Measures of consonant and sentence recognition in noise should be repeated at regular intervals following the provision of NLFC hearing aids. Ideally, the study sample should contain individuals with a range of high frequency hearing losses to make the results as generalisable as possible. In order to disentangle acclimatisation to frequency compression from procedural learning and/or acclimatisation to other aspects of signal processing, two control groups, matched on hearing loss and age, would be required. One control group should consist of listeners that have been fitted with new hearing aids without NLFC. Changes over time in the performance of this group would provide an index of acclimatisation to aspects of signal processing other than frequency compression. The second control group should be tested using hearing aids that they have been wearing, without alterations to the settings, for at least one year. Changes in the performance of this group would provide an index of procedural learning. In theory, the second control group could be made up of listeners with normal hearing. However, given that most hearing aid users are elderly, and most elderly people have some degree of hearing loss, it may be difficult to find sufficient numbers of normally hearing listeners that are matched in age with the hearing impaired participants.

7.3.3 Is listening effort affected by frequency compression?

The results of the current study show that frequency compression can lead to significant improvements in speech perception when compared to performance with conventional hearing aids. However, to date, there has been no research into the relationship between frequency compression and listening effort. An auditory dual task paradigm could be used to assess within subjects differences in performance when frequency compression is disabled versus when it is enabled. Additionally, it may be possible to examine physiological correlates of listening effort during the speech task. This could be achieved by using pupillometry to measure pupil dilation (see for example, Zekfeld et al, 2011). It may also be interesting to assess whether the effect of frequency compression on listening effort varies over time.

7.3.4. Should the extent and edge frequency of a dead region be taken into consideration when selecting frequency compression parameters?

The findings of the current study indicate that whether or not a listener has dead regions does not relate strongly to the amount of benefit obtained from NLFC. However, these results are based on a small sample of listeners who were categorised as having evidence of a dead region or not. It may be that, if the extent and edge frequency of dead regions are taken into account, there is a relationship with benefit from frequency compression. Future research should focus on recruiting listeners with a range of configurations of dead regions. Ideally, a within subjects paradigm should be employed in which two frequency compression settings are applied in a counterbalanced order. One could then compare performance with the conventional setting with performance using a setting that accounts for the extent and configuration of the dead region. This could potentially be done by altering the compression ratio or cut off frequency such that the compressed stimuli are not moved into a region beyond 70% above the edge frequency of the dead region. Research has suggested that providing amplification beyond this point is of limited benefit to listeners with a dead region (Vickers et al, 2001). It may therefore be the case that compressing high frequency information into this region is also of limited benefit to the listener.

7.3.5. Does the provision of active training affect the time course or magnitude of changes over time to frequency compressed speech?

The results of the present study provide limited evidence of changes over time to the perception of frequency compressed speech. Further research is needed to investigate whether providing some form of active auditory training leads to improvements in speech perception greater than those resulting from passive acclimatisation. Additionally, an analysis of which training parameters (for example, choice of stimuli, level of presentation, presence of background noise, and so forth) are the most likely to result in improvements that are generalisable to real-life listening situations should be conducted. The possible effects of training focussing on improving cognitive skills, such as attention or task switching abilities, on speech perception may also be an interesting area in which to conduct future research.

7.3.6. How does frequency compression affect subjective outcome measures?

A preliminary investigation into the effect of frequency compression on self reported outcome was conducted as part of this study. The results provide no evidence of a difference in self reported outcome when frequency compression was enabled or disabled. However, self report measures tend to be low in test-retest reliability, which may have masked any potential differences in the current study. In order to investigate this further, self report measures need to be administered to a much larger sample. Alternatively, an audit could be carried out to investigate the rate of acceptance of frequency compression devices in a clinical setting. This measure may provide an indirect measure of satisfaction with NLFC. Furthermore, it may then be possible to identify factors predicting NLFC acceptance.

7.3.7. Does degree of benefit from frequency compression vary between new and experienced hearing aid users?

Whilst the results of the current study show that frequency compression may provide significant benefit to speech perception, all participants in the trial were experienced hearing aid users. To date, there has been very little research on frequency compression outcomes in new hearing aid users and no study has explicitly investigated the influence of previous hearing aid use on benefit from frequency compression. An insight into this issue may prove to be very useful in influencing clinical decisions relating to candidacy for NLFC and enabling clinicians to give patients an indication of the perceptual changes expected with the use of NLFC.

7.3.8. How good a predictor of benefit from frequency compression is severity or configuration of hearing loss?

The results of the current study suggest that listeners with more severe high frequency losses are likely to obtain greater benefit from NLFC than those with better high frequency thresholds. This is in agreement with the findings reported by Glista et al

(2009) but not consistent with the results of Simpson et al (2006) who found no evidence of benefit from NLFC in a group of listeners with steeply sloping audiograms. A large scale systematic study is therefore required to determine the nature of the relationship between hearing loss and benefit from NLFC. Both the severity and the configuration of the loss (including whether the loss is symmetrical or not) should be considered.

7.3.9. Which outcome measures are the most appropriate to use when assessing the effect of frequency compression on speech perception?

Previous studies of frequency compression have primarily concentrated on assessing the effect of NLFC on speech perception in quiet. The current study was the first to investigate how frequency compression affects the perception of nonsense syllables in noise. The results of this test indicate that any effect seen in a nonsense syllable in quiet task is also reflected, along with additional changes, in performance in noise. Furthermore, ceiling effects on the consonant in quiet task are likely to have affected the results in the case of some listeners. One of the weaknesses of the current study is that it was not possible to statistically investigate the effect of NLFC at an individual level due to a lack of statistical power. It may be beneficial for future research to focus on using a smaller number of outcome measures (specifically sentence and consonant recognition in noise tasks), this enabling the use of a larger number of stimuli. This would give the results greater power and allow for the statistical analysis of results at both group and individual levels.

7.3.10. Which cognitive processes are responsible for the relationship between cognition and speech in noise perception with conventional amplification?

The results of the current study demonstrate that performance on the TMT-A and/or B may be predictive of amplified sentence in noise recognition (although not of additional benefit from NLFC). One area on which future research could focus is on conducting a larger study investigating the predictive power of performance on TMT-A and B on speech in noise outcomes.

A related area of interest is to isolate which cognitive factors explain the established link between WMS and speech in noise perception. One possible way of achieving this would be to create variants of the RST that load more heavily on certain aspects of cognition than others. One could then assess which versions of the test were most predictive of speech in noise performance. This information could then potentially be used to develop more sensitive measures that could be viable for use in a clinical setting.

7.4. SUMMARY

In summary, the results of the current study suggest that frequency compression may provide significant benefit to speech perception outcomes for many listeners with a sensorineural hearing loss. Much of this benefit seems to relate to the improved audibility of high frequency sounds resulting from frequency compression. Currently, technological limitations mean that it is often not possible to ensure audibility of high frequency sounds using conventional hearing aids. This is due to problems with feedback or to the limited bandwidth of frequencies amplified by hearing aids. It is possible in the future that technology will advance sufficiently to enable the audibility of high frequency information without the need for frequency compression. However, at present, non-linear frequency compression may be considered a useful tool in the treatment of sensorineural hearing loss, conferring additional benefits to those obtained by the use of conventional hearing aids.

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Appendix 1 – Details of the pilot study for chapter 4.

A pilot study was conducted in which 4 participants with normal hearing were asked to identify a series of speech tokens as either /s/ or /ʃ/. A total of 24 tokens were presented, 12 of which formed a continuum between natural /s/ and /ʃ/ sounds. The remaining 12 were from a continuum between artificially created /s/ and /ʃ/ sounds. The artificial continuum was created using a Klatt synthesiser to resynthesise natural speech. These stimuli were created (and used successfully) by Hazan and Barrett (2000). The 24 tokens were presented in random order at a comfortable listening level. The results are displayed in Figure 1 overleaf. The upper figure shows responses to the stimuli in the natural condition with the lower figure depicting responses to the synthetic stimuli. The pattern of responses given to the natural stimuli indicate that they were identified much more consistently than the artificial stimuli. Thus the natural continuum of stimuli was selected for use in the final identification and discrimination tasks. The fact that some stimuli in the artificial continuum were inconsistently identified in the present study, but not in the results reported by Hazan and Barrett (2000), may be related to the fact that in that study the consonants were presented in a vowel-consonant-vowel format, whereas in the present study, the consonants were presented in isolation. Thus listeners in Hazan and Barretts (2000) study may have had access to vowel transitions which were not present in the stimuli used in the current study.

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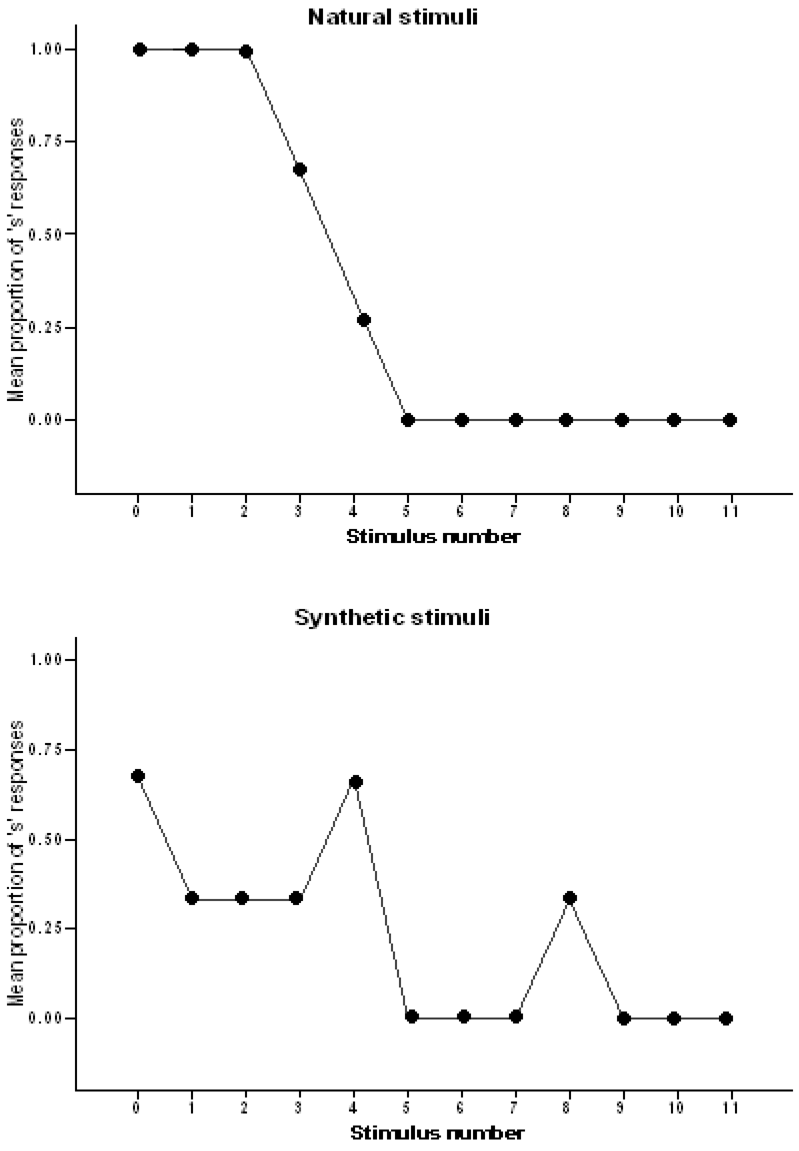

Figure 1. *The mean proportion of times each stimulus was identified as /s/ using natural stimuli (upper figure) and synthetic stimuli (lower figure).*

Appendix 2: Counselling questionnaire

Participant No.

Counselling Questionnaire

Session Number:

Date:

How well do you think you hear:

1. Soft sounds?
2. Medium sounds?
3. Loud sounds?
4. High pitched sounds?
5. Low pitched sounds?

How well does the HA perform in quiet environments?

How well does the HA perform in noisy environments?

Any particular situations in which you feel the HA performs particularly well?

Any particular situations in which you feel the HA performs particularly badly?

Colds/ear infections/illnesses?

Further comments?

Data logging: