

Chapter 3

NON-LINEAR FREQUENCY COMPRESSION IN HEARING AIDS

Chapter aim: This chapter serves as a theoretical basis for the empirical research and provides a critical evaluation as well as interpretation of the relevant literature. The focus is on non-linear frequency compression hearing aids as well as on other frequency lowering hearing aids described in the literature.

3.1 INTRODUCTION

In the current consumer-driven era of health care, health professionals need to be able to demonstrate to both the community and resource providers that the services they provide have a positive impact on their clients' functional status and quality of life (Uriarte, Denzin, Dunstan, Sellars & Hickson, 2005:384). It is not surprising that there is ongoing concern among providers of hearing health care about the effectiveness of hearing aid fittings (Cox, 2005:420). Currently, a lot of service providers are unaware of the existence of frequency lowering hearing aids while others fit these hearing aids without proper knowledge or scientific evidence of their efficacy. There is a need to promote practitioners' ability to recognize the potential of promising new treatments and technologies, like non-linear frequency compression hearing aids, and to apply it appropriately (Cox, 2005:420).

Evidence based practice offers a new perspective on the responsibilities of researchers, teachers, learners, and practitioners like audiologists as well as hearing aid acousticians. It recognizes that in an age of information explosion health care practitioners should acquire skills that allow them to rely more on their own resources and less on traditional sources of authority evaluating new developments and treatments; else they may not maintain currency of knowledge. Evidence based practice is an orientation that promotes continuous patient-driven revising of treatment

protocols to incorporate new knowledge about treatment effectiveness (Cox, 2005:420) that would result in more accountable hearing aid fittings to clients.

Several studies were conducted focusing on various frequency lowering hearing aids and their benefit for speech perception. There is, however, still a limitation in the specific provision of reliable fitting with frequency lowering hearing aids and their amplification of music stimuli. This study addresses the principles of evidence based practice to ensure that all treatment options should be data based (Cox, 2005:422) in terms of collecting scientific information on the influence of non-linear frequency compression hearing aids on music perception.

3.2 FREQUENCY LOWERING TECHNOLOGY AND TERMINOLOGY ISSUES

The loss of audibility of high frequency sounds often compromises speech understanding and the appreciation of music as well as nature's sounds (Kuk *et al.*, 2006: par. 2). In recent years, commercially available hearing aids have employed a variety of frequency lowering strategies for high frequency information to be moved to a lower frequency region as an option for clinical use (Glista & McDermott, 2008:2; Scollie *et al.*, 2008:2; McDermott & Knight, 2001:121). The target beneficiaries of this technique are usually people with a severe to profound hearing loss in the high frequencies who cannot benefit from conventional amplification (Kuk *et al.*, 2006: par. 3) but other degrees of hearing loss are also considered today.

Three current frequency lowering strategies have been mentioned in Chapter 1, namely proportional frequency compression, linear frequency transposition and non-linear frequency compression. Despite the publication of excellent reviews of frequency lowering strategies, some of the terminology for the different processing schemes is often used interchangeably and terminology is not standardized (Glista, Scollie, Bagatto, Seewald, Parsa & Johnson, 2009:633). Some researchers used the term "frequency shifting" as the generic term for all devices that utilize frequency lowering (Erber, 1971:530), while others referred to these devices as "frequency lowering" devices (Braida, Durlach, Lippman, Hicks, Rabinowitz and Reed (1978:102). Furthermore, proportional frequency compression incorporates both transposition and compression strategies, and are referred to by some authors as a frequency transposition device

and by others as a frequency compression device (Ross, 2005: par. 4). All these frequency lowering strategies mainly differ from one another along three dimensions (Glista & McDermott, 2008:2; Scollie *et al.*, 2008:2):

- whether the frequency lowering processing is always on (i.e. unconditional lowering) or is time-varying and only active under certain conditions (i.e. conditional lowering);
- whether the frequency lowering is achieved by shifting frequencies down (do the shifted frequencies overlap with the un-shifted frequencies, i.e. transposition) or narrowing the output bandwidth (i.e. compression); and
- whether the lowering is done for all frequencies (i.e. linear or proportional) or is restricted to only a portion of the frequency spectrum (i.e. non-linear or non-proportional).

For the purpose of the current study, **proportional frequency compression** refers to the reduction of the frequency bandwidth by lowering all the spectral components of the signal by a constant factor, **linear frequency transposition** refers to the lowering of the high frequency components of the signal by a fixed amount and **non-linear frequency compression** refers to the reduction of the bandwidth by only lowering the high frequency components of the signal in increasing degrees. **Frequency lowering** will be used as the generic term to refer to all the above-mentioned strategies.

3.3 PREVIOUS FREQUENCY LOWERING HEARING AIDS

Various frequency lowering techniques have been incorporated in frequency lowering hearing aids before. These early frequency lowering circuitries included (Braida *et al.*, 1978):

- Frequency shifting: All spectral components of the entire frequency spectrum are shifted downwards by a fixed displacement.
- Slow-playback: Pre-recorded sounds are replayed at a slower rate than the original signal, and each spectral component is lowered in frequency by a multiplicative factor equal to the slowdown factor.

- Time-compressed slow-playback: Essentially the same as slow-playback, but speech is compressed in time, deleting segments periodically, deleting successive pitch periods of voiced sounds, and deleting segments according to phonological rules.
- Transposition: Only high frequency components of the frequency spectrum are shifted downwards by a fixed displacement.
- Vocoding: Bandwidth reduction is achieved by filtering speech through a low-pass filter. The vocoder transmits a signal that is descriptive of the vocal sound source and the fundamental frequency of voiced sounds.
- Zero-crossing-rate division: Speech is filtered into four pass-bands, and the resulting signal is processed to achieve a frequency spectrum band reduction by a factor of two.

A relatively simple form of frequency lowering is to shift each frequency component of the sound by a constant factor (McDermott & Dean, 2000:353). A possible advantage of this form of transposition is that ratios among the frequency components of the signal are not changed by the processing. This may be beneficial for speech perception because frequency ratios (such as that between the first and the second formants) convey important information. On the other hand, an obvious disadvantage is that the overall pitch of the speech signal is also lowered causing, for example, a female speaker to sound like a male speaker. However, in contrast to some other frequency-lowering techniques, transposition by a uniform factor provides a high quality signal that could plausibly provide additional speech information to listeners with steeply sloping audiograms (McDermott & Dean, 2000:353).

The first attempts at frequency lowering were made well before non-linear and digital technology was applied to hearing aids (Kuk *et al.*, 2006: par. 4). One early strategy used non-linear modulation techniques to shift high frequency speech components to a lower frequency range (Simpson *et al.*, 2006:619). The downward shift was typically disproportionate, meaning that frequency ratios contained in the spectral information were not preserved during processing. The resulting signals were mixed with those obtained from lower frequencies (Simpson *et al.*, 2006:619). Another attempted scheme in the sixties implemented disproportionate frequency shifting in which high frequency energy was passed through a non-linear modulator that converted it into low frequency noise. Several studies of these early types of frequency lowering

methods reported little success in benefiting speech understanding. This may have happened for a variety of reasons including that much of the information regarding the spectral shape of the incoming signal was lost as a result of the processing technique. As mentioned, these methods did not preserve frequency ratios in the high frequencies when they were shifted to lower frequencies. In addition, they may have provided some additional high frequency information at the expense of other perceptual cues by overlapping the shifted and un-shifted signals (Simpson *et al.*, 2006:619).

About ten years ago a body worn transposer hearing aid was introduced – this was met with little acceptance, possibly because of cosmetic reasons (Ross, 2000: par. 3). It differed from previous attempts in that it not only electronically shifted the higher frequencies to lower ones, but also compressed them in the frequency domain (frequency compression) while leaving, if desired, the lower frequencies untouched. Moreover, it operated in a way that kept the ratio between adjacent sounds intact. If an incoming speech sound, like the broad spectrum sound [s], had some energy peaks at 3 kHz, 4 kHz, 6 kHz and 8 kHz, and the frequency compressor used a factor of two, then all the peaks would be halved in frequency before being delivered to a listener. Consequently these energy peaks of [s] would now be at 1.5 kHz, 2 kHz, 3 kHz and 4 kHz respectively, possibly rendering at least some of the peaks audible for a person with a high frequency hearing loss (Ross, 2000: par. 3). This kind of proportionate shifting is very important for speech perception, since we know that perception is less affected by acoustic variations in the speech signal when the ratio relationship between energy peaks is maintained (Ross, 2000: par. 4). The aid designed ten years ago now has newer versions. These system works mainly by analyzing incoming speech signals and determining whether the sounds are voiced or voiceless. If voiceless, which signifies a high-frequency consonant, the incoming sound is frequency compressed to the pre-set degree. When the next sound comes along, usually a vowel in the normal syllabic sequence, the aid reverts to its normal amplification pattern. The voiced sounds are simply passed through and processed as determined during the initial programming. When the next voiceless sound is detected, the frequency compression circuit is again activated (Ross, 2000: par. 7). In effect, what is happening in this alternating process is that all the high frequency consonants are squeezed and shifted lower in frequency, leaving the vowels and lower frequency consonants untouched (Ross, 2000: par. 8).

More recent frequency lowering strategies included proportional frequency compression and approaches that 'sharpen' the spectrum of the transposed sound or the various transposed features. Although these approaches are significantly more complex than the earlier attempts and they all resulted in better aided thresholds, their acceptance has been relatively limited (Kuk *et al.*, 2006: par.5). Whilst lowering the frequencies, these methods also altered other aspects of speech known to be important for perception. Some of these approaches created unnatural sounding speech, distorted gross temporal and rhythmic patterns, and extended durations (slow playback) of the speech signals. In the slow playback method, segments of the speech signal were recorded and then played back at a lower speed than employed for recording (Simpson *et al.*, 2006:620; Parent *et al.*, 1997:355). In these devices, the activation of frequency lowering is dependent upon the incoming signal. An incoming signal dominated by components at frequencies above 2.5 kHz is shifted down by a factor that is programmable for each listener. If the input signal is not dominated by frequencies above 2.5 kHz, then all signals are amplified with no frequency lowering (Simpson *et al.*, 2006:620). Other aids created reversed spectrums (amplitude modulation based techniques) which is difficult to even recognize as speech by experienced listeners (Kuk *et al.*, 2006: par. 6). Proportional frequency shifting offers the advantage that the ratios among frequency components are not changed by the processing (Simpson *et al.*, 2006:620).

Earlier, Turner and Hurtig (1999:884) conducted a study with a proportional frequency compression scheme which preserved the natural ratios between the frequency components of speech and also generally preserved the temporal envelopes of the signal. Results indicated significant improvements in speech recognition for hearing impaired listeners with most of the participants demonstrating a benefit for hearing material spoken by female speakers versus male speakers (Turner & Hurtig, 1999:885). In another study conducted with a frequency compression scheme, the scheme provided perceptual performance superior to the performance of conventionally fitted hearing aids for words presented at a moderate level in quiet conditions (Simpson *et al.*, 2005:289). The scheme divided incoming signals into two broad bands based on a chosen cut-off frequency ranging from 1.6 kHz to 2.5 kHz. Signal components below the cut-off frequency were amplified with appropriate frequency shaping and amplitude compression but without frequency lowering. Signal components above the cut-off were compressed in frequency

in addition to amplification. The frequency compression was non-linear and applied progressively larger shifts to components having increasingly high frequencies (Simpson *et al.*, 2006:620). A possible advantage of the scheme is that there is no spectral overlap between the shifted and un-shifted signals. This results in the first formant and most of the second formant frequency range being preserved, since the device does not shift low and mid frequency information. A possible disadvantage of the scheme is that it does not preserve frequency ratios for these high frequencies that are compressed. It leaves, however, the possibility that the perception of certain sounds, such as music, may be affected adversely (Simpson *et al.*, 2006:620). Specifically, these hearing aids provided better recognition of monosyllabic words than conventionally fitted hearing aids, greater high frequency sensation levels were achieved and half of the subjects obtained a significant phoneme score increase with the other half showing no difference in score (Simpson *et al.*, 2005:282). In yet another study, patients also were found to benefit from digital frequency compression when speech is presented against background noise and subjective ratings revealed a tendency for increased ease of communication with digital frequency compression hearing aids (Gifford *et al.*, 2007:1200).

Despite the recent use of digital signal processing techniques in frequency lowering, artefacts and unnatural sounds were still unavoidable (Kuk *et al.*, 2006: par. 7). Some reported that the transposed sounds are 'unnatural', 'hollow or echoic' and 'more difficult to understand'. Another commonly reported artefact is the perception of 'clicks', which many listeners find annoying. Thus, despite its potential for speech intelligibility improvement with extensive training, many adults found it difficult to accept frequency lowering hearing aids (Kuk *et al.*, 2006: par. 7).

A minimum of artefacts or unnaturalness will result if the frequency lowering method retains the relationship of the original frequency components in the final signal (Kuk *et al.*, 2006: par. 9). Preferably, the relationships of the harmonic components should stay the same, the spectral transitions should move in the same direction as the original un-transposed signal, and the segmental-temporal characteristics should stay untouched. One should not remove or sacrifice any acoustic cues that listeners use before frequency lowering. In addition, the processed speech signal should retain the extra-linguistic (prosodic) cues such as its pitch, tempo and loudness. Otherwise, it will initially make it more difficult for listeners to accept the new sound images and

therefore lengthen training and relearning time (Kuk *et al.*, 2006: par. 9). One criterion is to lower only the frequencies that are necessary to be lowered. For example, if someone has audible hearing up to 3 kHz, one should only lower sounds above 3 kHz. This has the advantage of focusing only on relevant sounds (Kuk *et al.*, 2006: par. 10). Another criterion is to apply the 'right' amount of processing for the individual. This is because the more aggressive the lowering, the more unnatural the sound perception becomes. A conservative or less aggressive approach will minimize the disturbance of the original signals and avoid any potential interaction between the original signals and the processed ones. A final criterion is to preserve the temporal structure of the original signal in order to retain any transition cues. This implies that the frequency lowering system should have the flexibility and specificity to meet the individual wearer's needs (Kuk *et al.*, 2006: par. 12).

So far, hearing aids incorporating frequency lowering have not found widespread acceptance and has produced mixed findings (Munro, 2007:15; Moore, 2001a:30). However, promising results have been found in some studies of commercially available devices. The limited benefit demonstrated in studies so far may partly have occurred because the frequency lowering hearing aids have been fitted to patients without clear knowledge of the extent of the dead regions (Munro, 2007:15; Moore, 2001a:30). Also, when comparing the different approaches, large differences in implementation, resulting in differences in sound quality and potential speech understanding benefit are apparent (Glista & McDermott, 2008:2). Clearly, more research is needed in this area (Moore, 2001a:30) and it is important to point out that providing audibility of high frequency information to listeners with severe to profound hearing losses remains a controversial topic (Bagatto *et al.*, 2008: par. 2).

Currently, no studies exist that attempts a comparison between the various strategies. However, some evidence does exist to support the use of some forms of frequency lowering devices (Scollie, *et al.*, 2008:2). Frequency transposition and frequency compression technology are the two main types of frequency lowering technologies available today (Glista, Scollie, Polonenko & Sulkers, 2009: par. 2; Bagatto *et al.*, 2008: par. 3). For the purposes of this study, the researcher will discuss these two frequency lowering technologies in more detail in the sections to follow.

3.4 FREQUENCY TRANSPOSITION

Frequency transposition shifts the signal down the frequency axis by a fixed amount (Glista *et al.*, 2009:633; Bagatto *et al.*, 2008: par. 3). All frequency transposition algorithms identify a frequency above which they transpose (Kuk, 2007: par. 2). This frequency is called the start frequency and the region of sounds that would be transposed is called the source. In general, sounds in this region will be lowered in frequency (e.g. from 4 kHz to 2 kHz). Sounds below the start frequency are amplified based on the individual's degree of hearing loss at those frequencies. Transposition moves sounds from the source region to a 'target' region immediately below the start frequency. The transposed sounds are mixed with the original sounds and receive amplification appropriate for the frequency (Kuk, 2007: par 3).

The main disadvantage of frequency transposition is that the original spectrum is substantially preserved (Jerger, 2009:288). Only a limited range of high frequencies is superimposed on the original spectrum and therefore the audibility of high frequency consonants is aided without serious distortion of the vocal characteristics of the talker. Another disadvantage is the difficulty in avoiding artefacts when the transposed signal is added to the original signal (Jerger, 2009:288). An additional problem with transposition is that it does not reduce the bandwidth of the hearing aid; it only shifts the signal down. This creates very strong distortions when the transposed frequency is greater than the signal frequency (Davis, 2005: par. 2).

Various frequency transposition hearing aids have been reported. Most of them could separately adjust the degree of transposition for unvoiced speech from that of voiced speech and suggested that frequency transposition is beneficial for persons with a high frequency hearing loss (Sakamoto, Goto, Tateno & Kaga, 2000:327). One relatively early frequency transposition scheme operated by detecting whether the incoming signal was above or below a particular high frequency (Glista & McDermott, 2008:2). If the signal was above this frequency, it activated the frequency transposition and shifted all frequencies within the amplified sound. One weakness of this scheme is that high frequency inputs are difficult to detect reliably, especially in situations with competing noise. Furthermore, enabling and disabling transposition can produce distracting artefacts that are audible to some hearing aid users (Glista & McDermott, 2008:2).

The AVR Transonic FT-40 was the first commercially available transposition device (Glista *et al.*, 2009:633). This device used a processing unit to analyze incoming signals and apply frequency lowering to sounds with predominantly high frequency energy (above 2.5 kHz). Early studies indicated mixed outcomes with the body-worn FT-40 in adults and children, concluding that the FT-40 system was suitable for a select group of listeners. AVR Sonovations later introduced the ImpaCt BTE hearing aid (Glista *et al.*, 2009:633). McDermott and Knight (2001) found limited benefit attributable to the ImpaCt transposition signal processing when evaluated on adult listeners. This could be contributed by factors like differences in participants' age, training, and audiometric configuration. The ImpaCt has also been evaluated in children, suggesting that a significant word recognition benefit could be achieved for children with severe hearing loss when using transposing hearing aids, in comparison to conventional ones (Glista *et al.*, 2009:633).

Overall, most previous transposition trials were of limited success and the disappointing results may be related to the methods of frequency transposition, as well as to the lack of ability at that time to diagnose the presence and extent of dead regions (Robinson *et al.*, 2007:294). Many previous transposition schemes used unconditional transposition. It was found that the perception of semi-vowels and nasals was degraded using an unconditional transposition scheme, but this was prevented when conditional transposition was implemented (Robinson *et al.*, 2007:306). When conditional transposition was implemented, which meant that only consonants with significant high frequency information were transposed, a benefit for consonant detection was perceived (Robinson *et al.*, 2007:306).

Several years ago Widex Hearing Aid Company reintroduced frequency lowering as an optional signal processing feature in its Inteo family of hearing aids (Kuk, Keenan, Korhonen & Lau, 2009:466). This feature uses linear frequency transposition (called the Audibility Extender) to lower information above a programmable start frequency to a lower frequency region. The start frequency can be selectively determined for each individual, based on the hearing loss configuration (Auriemma, Kuk, Lau, Marshall, Thiele, Pikora, Quick & Stenger, 2009:291). In this algorithm, the most prominent peak located in the source octave (above start frequency) is identified and transposed linearly by one octave. Sounds below the start frequency are left

amplified. The transposed signal is then band-pass filtered around the transposed peak with a bandwidth of one octave to limit any potential masking effects. Finally, the transposed sounds are amplified and mixed with the original signal as the final output (Kuk *et al.*, 2009:466).

The linear frequency transposition algorithm used in the device referred to above is unique in several ways (Kuk *et al.*, 2009:466): First, the amount of frequency displacement at any instant in time is directly related to the location of the highest spectral peak of the original signal in the source octave. This was done to ensure that the harmonic relationship of the transposed and the original signal remains at exactly one octave for the most dominant frequency. This could preserve the naturalness and pleasantness of the output signal delivered to the listener. Second, the processing is unconditional, that is, it is active all the time. This ensures that the lowering of any high frequency information is not dependent on the reliability of any activation criteria such as voicing detection. These design criteria may help to minimize any discontinuities in the output signal, reduce artefacts and provide consistent processing (Auriemmo *et al.*, 2009:291; Kuk *et al.*, 2009:466).

In a study focusing on this technology, nine normal hearing adults with a simulated hearing loss at and above 1.6 kHz were tested on the identification of transposed voiceless consonants before and after they completed three 15 minutes self-paced training. It was found that transposition improved the identification scores of the stimuli by 14.4% over non-transposed stimuli after 30 minutes of training with the transposed stimuli (Kuk *et al.*, 2009:466). Another study by Auriemmo *et al.*, (2009) examined the efficacy of linear frequency transposition in 10 children with severe to profound hearing loss at and above 3 kHz (Kuk *et al.*, 2009:467). Phoneme recognition and articulation performance were compared among the children's own hearing aids and the study hearing aids with and without linear frequency transposition. The results indicated significant improvements in vowel and consonant recognition and accuracy of fricative production after six weeks of linear frequency transposition use, and suggest that linear frequency transposition is a potentially useful feature for school-aged children with a severe to profound high frequency sensory neural hearing loss (Auriemmo *et al.*, 2009:301; Kuk *et al.*, 2009:467). They also examined subjective preferences of these children for linear frequency transposition and the impact of linear frequency transposition on awareness of environmental sounds. Results

indicated that for speech stimuli, children report the linear frequency transposition program as preferred or equally preferable to the default program 60% of the time at the initial fitting. This preference remained relatively stable after three and six week's use of the linear frequency transposition. This was not the case for adult users of linear frequency transposition who initially preferred the default program over the transposition and whose preference changed only after two weeks of use time. Awareness of environmental sounds was significantly improved after six weeks of use of linear frequency transposition compared to the own hearing aid (Auriemmo *et al.*, 2009:301).

In yet another study with linear frequency transposition it was found to improve nonsense syllable identification, especially syllables containing fricatives, in quiet and also in noise. On the other hand, the speech benefit was not apparent for all phoneme classes at the initial visit. For some phonemes there was a slight but non-significant decrease in identification which was temporary in nature and resolved within two months. Studies also indicated that linear frequency transposition significantly improved hearing of everyday sounds¹² and the identification of consonants (Kuk *et al.*, 2009:475). Kuk *et al.*, (2009:476) further examined consonant identification in quiet and in noise with the linear frequency transposition hearing aids. It is important to remember that the objective of frequency lowering is not to improve speech understanding in noise but to provide audibility of the unreachable high frequency information as a lower frequency substitute. Rather than removing parts of the input signal like a noise reduction algorithm or a directional microphone, a frequency lowering algorithm adds to the overall audible input to the ear (Kuk *et al.*, 2009:476). This may result in a louder output and some even speculated that it could lead to a poorer performance in noise. Their study however concluded that linear frequency transposition does not make speech understanding in noise more difficult, and that the benefit of linear frequency transposition in noise remains similar to that in quiet environments (Kuk *et al.*, 2009:476).

The same technology was evaluated with thin-tube, open-ear fittings and showed improved consonant recognition, vowel identification and perception of every day sounds (Kuk *et al.*,

¹² Include sounds like bird songs, warning signals such as alarms and timers, etc.

2007:62). Several reasons why this algorithm may result in a more positive outcome than those reported previously include (Kuk *et al.*, 2007:60):

- Sounds are transposed by one octave. This means that in a high frequency hearing loss the transposed sounds will fall on the slope of the audiogram where survival of the hair cells and neurons may be more ensured. Furthermore, recent studies showed that frequency discrimination around the slope of the audiogram is more sensitive than at other regions in people with a steeply sloping hearing loss. It is logical to speculate that the transposed sounds will have the highest likelihood of being utilized.
- Because the transposition does not alter the temporal and spectral structures below the start frequency, the speech cues within the original sound would be better preserved. This minimizes the extent of distortion and the potential degradation of sound quality and speech intelligibility.
- Because people fitted with a thin-tube, open-ear device in general have residual hearing up to 2 kHz to 3 kHz, the start frequency for transposition could be high (4 kHz). This would leave much of the original sounds unaltered and minimize the amount of overlap of the transposed sounds on the original sounds. This may better preserve the sound quality and lead to a higher acceptance for the transposed sounds.

It needs to be emphasized that the above performances was noted when the subjects were initially fitted with the default settings without additional fine tuning to meet the wearer's hearing needs. Furthermore, no experience with the transposed sounds was provided prior to the study. With additional experience and fine tuning, one would have considered the individual hearing needs when setting the optimal transposition parameters. This could further improve the preference for linear frequency transposition technology (Kuk *et al.*, 2006: par. 41).

3.5 NON-LINEAR FREQUENCY COMPRESSION

While frequency transposition shifts the signal down the frequency axis by a fixed amount, non-linear frequency compression compresses the output bandwidth of the signal by a specified ratio (Bagatto *et al.*, 2008: par. 3). The advantage of frequency compression is that it more closely

reflects the familiar octave structure of the frequency scale (Jerger, 2009:288). If, for example, each frequency is shifted by a proportion of 0.5, then 4 kHz becomes 2 kHz, 3 kHz becomes 1.5 kHz, 2 kHz becomes 1 kHz, and so forth. This avoids the problem of the negative frequencies resulting from linear transposition, but the problem resulting from the downward shift of the fundamental frequency of voicing remains (Jerger, 2009:288).

Frequency compression is an innovative solution to the challenge of poor perception of high frequency sounds and with this technique, it is possible to 'match' the bandwidth of the incoming speech signal to the damaged ear's limited band of greatest sensitivity, rather than attempting to force the damaged high frequency sensory units to 'respond' (Davis, 2001: par. 4). In comparison, frequency compression reduces both the frequency and the bandwidth by a pre-set ratio. Due to the fact that the spectrum is 'squeezed' by frequency compression, operating in real-time requires a complex algorithm that maintains the critical information (Davis, 2005: par. 3). A form of frequency compression which is widely used today is non-linear frequency compression (Bagatto *et al.*, 2008: par. 2) and as the hearing aids used in the current study consisted of a non-linear frequency compression algorithm, this technology will be described in more detail below.

Recently, a product named SoundRecover (first implemented in Phonak Naida instruments), was developed. SoundRecover is a multi-channel, non-linear frequency-compression algorithm designed specifically for hearing aid wearers who have difficulty hearing key high-frequency speech information such as the fricatives [f] and [s] (Glista & McDermott, 2008:1; Nyffeler, 2008b:22). This non-linear frequency compression algorithm extends the audible range by compressing and shifting otherwise inaudible high frequencies into an adjacent lower frequency area with less cochlear damage – this broadens the bandwidth for natural production of sounds without them being harsh or tinny and avoids the production of annoying artefacts (McDermott *et al.*, 2010:34; Stuermann, 2009:1; Glista & McDermott, 2008:3). It further does not involve any mixing of frequency-shifted signals with other signals already present at lower frequencies and the processing does not depend on detecting specific features of incoming sounds, such as the dominant peak frequency in the source octave, as is the case with linear frequency transposition (McDermott, 2010:1). Instead, all frequencies above a so-called cut-off frequency are lowered by a progressively increasing amount. The increase in the amount of lowering across frequencies

is determined by a second parameter, the frequency-compression ratio. A visual presentation of the difference between frequency transposition and non-linear frequency compression (SoundRecover) is provided in Figure 3-1.

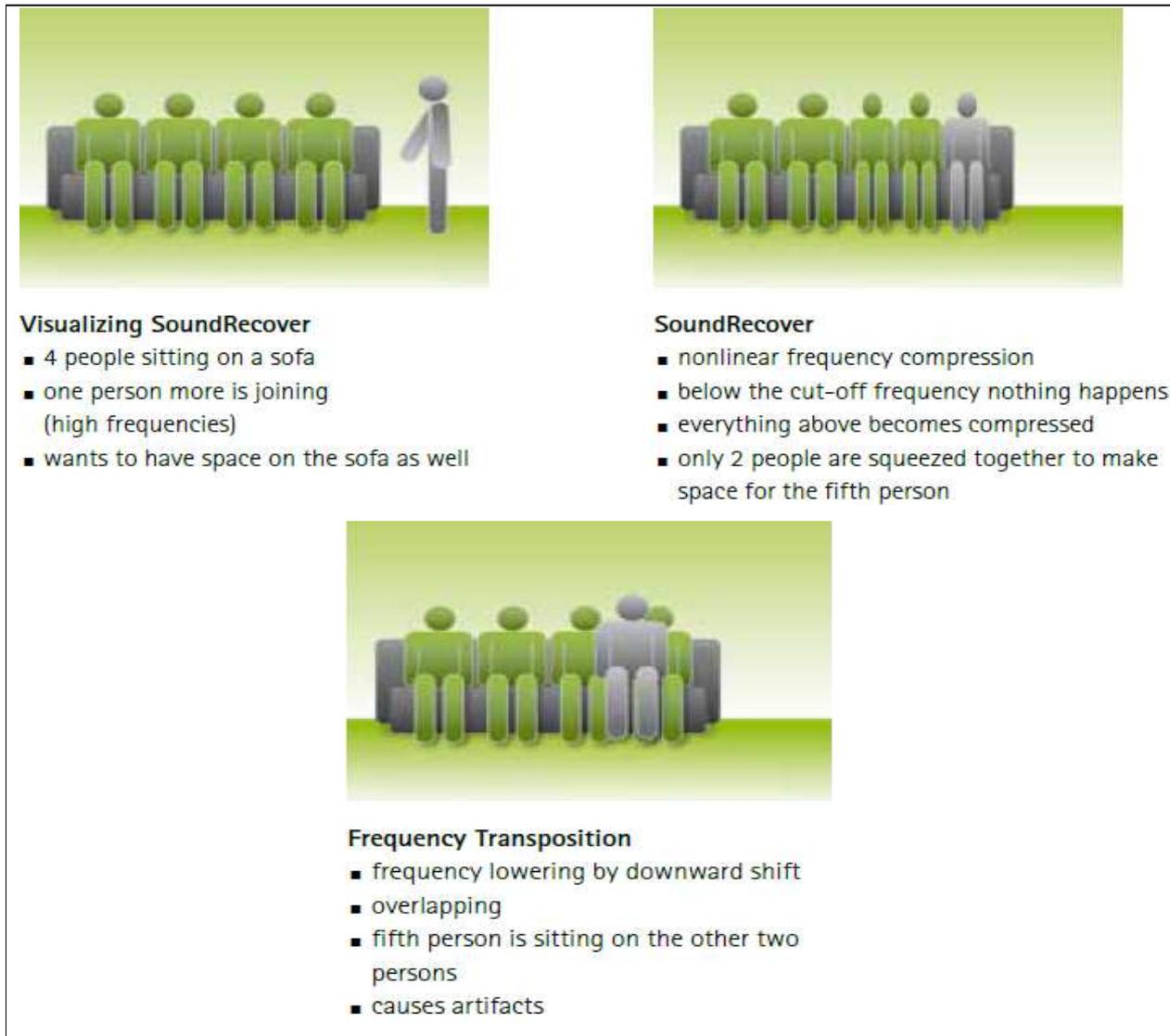


Figure 3-1: Visual presentation of the differences between SoundRecover and linear frequency transposition (Phonak, 2009).

The main differences between frequency transposition and non-linear frequency compression as highlighted in Figure 3-1 are also summarized in Table 3-1 below with specific focus being

placed on linear frequency transposition as frequency transposition circuitry and how it differs from non-linear frequency compression.

Table 3-1: Main differences between non-linear frequency compression and linear frequency transposition

Non-linear frequency compression	Linear frequency transposition
Compresses the output bandwidth of the signal by a specified ratio	Shifts the signal down the frequency axis by a fixed amount
Non-linear amplification	Linear amplification
Applies a frequency compression ratio to the high frequency band, narrowing it in bandwidth but not mixing it with low frequency energy	Transposed sounds are mixed with the original sounds and receive amplification appropriate for the frequency

From the above it is evident that both non-linear frequency compression and linear frequency transposition shifts the high frequency information to lower frequencies but different procedures are followed to accomplish it – this might have an influence on the quality of the information that the hearing aid wearer perceives.

With the SoundRecover algorithm, digital signal processing is used to separately control non-linear frequency compression in the lower versus higher frequencies (Glista *et al.*, 2008:1). The lower frequency region is uncompressed and normally amplified, preserving natural formant ratios of speech and other sounds and therefore a natural sound quality. The higher frequencies undergo clinician-adjustable non-linear frequency compression processing in increasing degrees to higher input frequencies (Nyffeler, 2008a:2). The amount of compression is limited to ensure that compressed frequencies do not interfere with the frequencies below the cut-off. This also ensures that artefacts are minimized and a clear sound quality is maintained. The initial frequency compression setting is automatically calculated by the fitting software for each wearer and can be easily fine-tuned if needed.

The shape of the non-linear frequency compression function, and therefore the effect on the listener’s perception, can be controlled by adjusting two parameters, i.e. the cut-off frequency and the compression ratio (Glista & McDermott, 2008:4). It is important to be able to adjust

compression rates individually since the ideal compression rates differ for each individual because each individual has a uniquely shaped auditory filter (Yasu, Hishitani, Arai & Murahara, 2004:62). By adjusting the compression, the quality and intelligibility of speech sounds can be improved for persons with a hearing loss (Yasu *et al.*, 2004:62) and for adult users, both the hearing levels at specific frequencies and the slope of the audiogram across frequencies are taken into account (Glista & McDermott, 2008:3). For calculation of the cut-off frequency, relatively high frequencies are selected if the hearing impairment is mild or the audiogram is flat (McDermott, 2008:3). Lower cut-off frequencies are selected for more severe levels of impairment or for audiograms with relatively steep slopes. The frequency compression ratio is then derived from the cut-off frequency. The compression ratio effectively determines the strength of the frequency compression processing above the cut-off frequency. For example, large compression ratios result in a stronger degree of frequency compression, because a wider range of input frequencies is compressed into a given range of output frequencies (Glista & McDermott, 2008:3). The cut-off frequency and the compression ratio are present within restricted ranges of 1.5 kHz to 6 kHz and 1,5:1 to 4:1 respectively (McDermott, 2010:3). Figure 3-2 displays the effect of the cut-off frequency in the determination of the amount of non-linear frequency compression taking place:

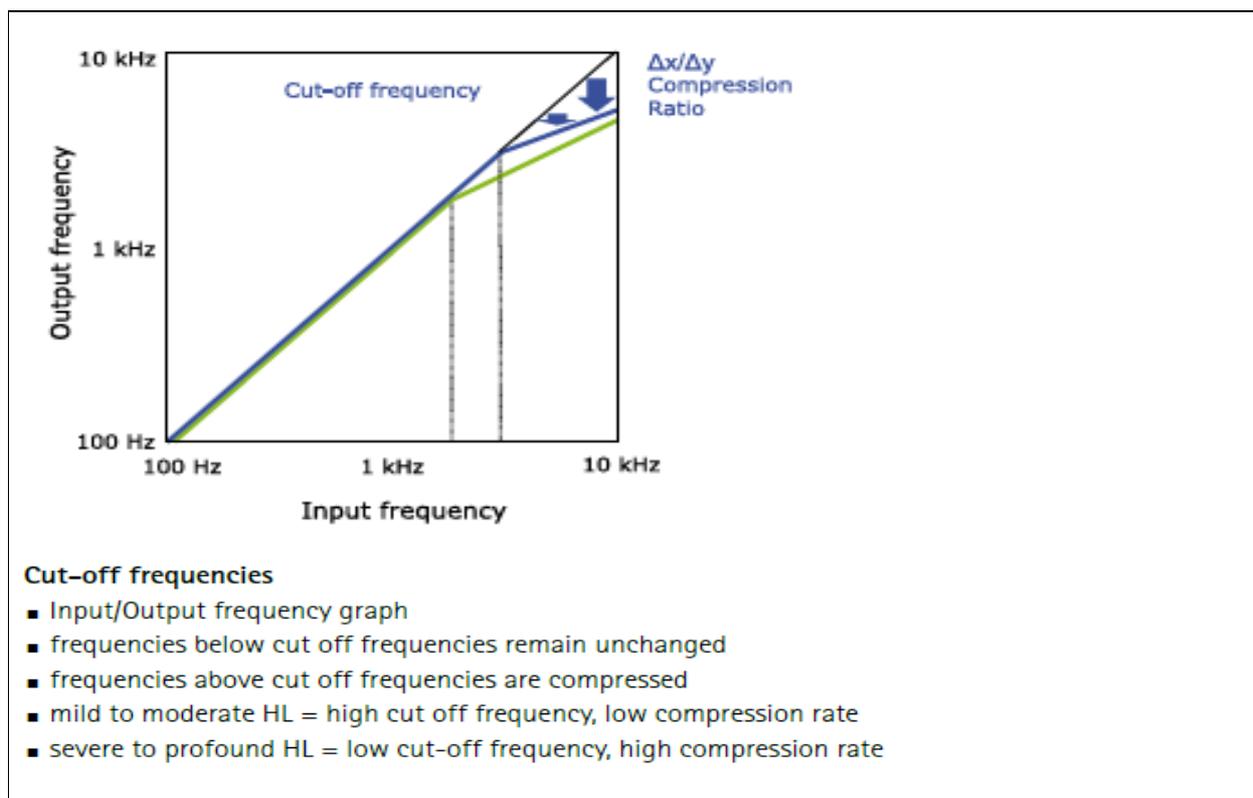


Figure 3-2: Cut-off frequency as parameter that control non-linear frequency compression algorithm (Phonak, 2009:1)

From the above-mentioned figure it is clear that the frequencies below the cut-off frequency remain unchanged while the frequencies above the cut-off frequency are compressed.

In theory, a clinician can strengthen the amount of non-linear frequency compression by providing frequency lowering over a broader band (by using a lower cut-off frequency), or by compressing to a greater degree (by using a higher compression ratio). In actual use, however, the two controls are combined into one, with each adjustment resulting in either stronger or weaker SoundRecover settings via changes to the cut-off frequency and/or the compression ratio (Glista & Scollie, 2009b:1). Besides this, the non-linear frequency compression algorithm is also designed to prevent acoustic feedback and discomfort resulting from excessive loudness due to high levels of high-frequency amplification (Nyffeler, 2008b:22). Specific information about SoundRecover includes (Glista & McDermott, 2008:3):

- it is active all the time (when activated);
- a pre-selected range of high frequencies is compressed, based on the listener's hearing loss;
- no special frequency analysis of incoming signals is required; and
- the frequency compressed output signals do not overlap with lower frequencies.

This non-linear frequency compression algorithm was developed and verified in extensive clinical trials in Australia with severe to profound hearing loss users (Glista & McDermott, 2008:5). Clinical field studies have shown that the use of this algorithm restores high-frequency audibility for speech and environmental sounds resulting in spontaneous user acceptance, quick acclimatization, improvement in perception of the wearer's own voice quality and reduced feedback (Glista & McDermott, 2008:6; Nyffeler, 2008b:22). It was also found to increase the pleasantness of sound in quiet and noisy situations, resulting in a highly satisfactory overall impression (Nyffeler, 2008b:26).

Results of a study by Scollie *et al.*, (2008:2) revealed that adults fitted with non-linear frequency compression hearing aids showed significant objective benefit in understanding high frequency speech sounds. Adults with moderate to severe hearing losses showed greater benefits than adults with steeply sloping losses. In another study, participants showed significant improvement in speech recognition tasks when this algorithm was enabled (Bagatto *et al.*, 2008: par. 16). It is noteworthy that, for persons whose results did not show benefit from this frequency lowering scheme, there was no negative impact on speech intelligibility (Stuermann, 2009:2).

Questions about the sound quality of specific sounds when listened to with non-linear frequency compression revealed that subjects initially found that fricatives sounded different. This may reflect the effect of the non-linear frequency compression on the audibility of high-frequency sounds. Over time, however, the sound quality ratings improved consistently. In addition, subjects rated their own voice sound quality as more pleasant with non-linear frequency compression activated than with their own hearing instruments (Nyffeler, 2008b:24). There also have been extensive field studies with adults and children in Canada and Germany that have shown the benefits of this algorithm and this can be summarized as follows (Glista *et al.*, 2008:1):

- increased detection, distinction and recognition of sounds;
- significant improvement in intonation and overall voice quality;
- improved hearing of high-pitched sounds and better speech understanding (most noticeable for high-pitched talkers such as women and children, softly spoken people, and high frequency sounds such as [s] and [f]); and
- reduced feedback.

In a study where the non-linear frequency compression algorithm was used in a different hearing aid (Phonak Audéo), it resulted in improved speech intelligibility for soft speech in quiet situations and provided significant improvement in noisy environments, particularly after an acclimatization period of four weeks. The general first impression of participants of this frequency lowering algorithm was that sounds were more clear or sharp with the algorithm activated than without it, but remained pleasant (Stuermann, 2009:2). Participants also described their own voices as clearer, not too shrill, but with a pleasant brightness (Stuermann, 2009:2). This study also included assessment of subjective perception of sound quality with non-linear frequency compression by giving participants a remote control to use for choosing between two programs, one with non-linear frequency compression activated and one without non-linear frequency compression. Participants did not know in which program the algorithm was active. Data logging results revealed that the non-linear frequency compression 'active' program was selected 91% of the time (Stuermann, 2009:2).

The preliminary findings of a study by Wolfe, Caraway, John, Schafer and Nyffeler (2009:35) suggest that non-linear frequency compression has the potential to substantially improve acquisition and identification of high frequency speech signals and environmental sounds compared to conventional high-end digital amplification. Subjective comments from participants in this study also revealed that none of them objected to the non-linear frequency compression algorithm; instead, many reported better speech understanding (Wolfe, *et al.*, 2009:34). Further research on this topic found that the non-linear frequency compression processor improved speech sound detection thresholds and consonant as well as plural recognition scores for adults; vowel perception was not significantly changed (Glista *et al.*, 2009:642). It was also obvious that children were more likely to show preference for non-linear frequency compression processing

than were adults. Variance in outcome results at the individual level was considerable as some individuals experienced greater or lesser benefit than the candidacy predictors would lead one to expect. Therefore, further research is needed to generalize predictions of candidacy for this technology (Glista *et al.*, 2009:642).

It is not yet clear whether there is a minimum limit to the degree of hearing impairment above which frequency compression is either not helpful or produces an unacceptable sound quality (McDermott, 2008:3). Extensive trials have demonstrated the benefits of using non-linear frequency compression in many adults and children with severe to profound hearing loss (McDermott, 2010:1). Similar benefits may also be obtained by users who have less severe losses, since current research suggests that even persons with mild hearing losses found that non-linear frequency compression can provide comfortable listening if the cut-off frequency is set relatively high (above 4 kHz) (McDermott, 2010:4). This is not surprising, because there is little or no harmonic pitch information present in most types of sound at the high frequencies that are affected by frequency compression with such settings. On the other hand, useful information is present in some high frequency sounds, particularly the fricative consonants of speech. It is certainly plausible that the perception of those sounds would be improved by limited application of frequency compression (McDermott, 2008:3). Even people with normal hearing would theoretically benefit from SoundRecover under certain listening conditions. In particular, when using a telephone, which has an upper frequency limit below 4 kHz, it can be difficult to understand unfamiliar words if they contain certain high frequency phonemes. For example, over the phone [s] is easily confused with [f], and in many instances is not audible at all. Under these conditions some frequency compression above a relatively high cut-off frequency could improve the listener's ability to hear and to discriminate such speech sounds. Therefore, it is highly likely that non-linear frequency compression, when appropriately fitted, could benefit a high percentage of hearing aid users (McDermott, 2010:4). To what extent perceptual benefit can be obtained depends on both the technical function of the frequency-lowering scheme and on the way the variable parameters of the scheme are fitted to the hearing aid user (McDermott, 2010: 2).

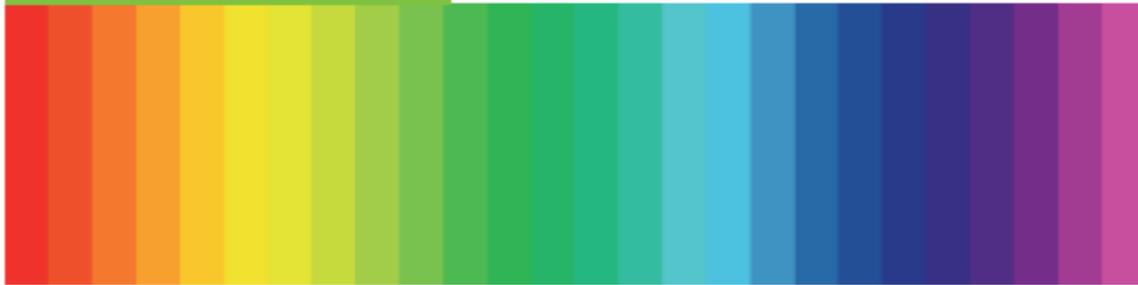
Recently non-linear frequency compression has been evaluated on persons with mild hearing loss. Boretzki and Kegel (2009:6) found that the identification of the [s] sound have been shown

to improve with the use of this algorithm. This suggests that understanding speech passages with low loudness predictability was improved, since the findings indicated initial improvements in speech recognition for high frequency weighted speech material. Also, detection thresholds for high frequency inputs were lower, which may have resulted in improved audibility of high-frequency consonants. Furthermore, test subjects subjectively perceived hearing with non-linear frequency compression as more comfortable than without it. These authors concluded that non-linear frequency compression should be considered as an option for subjects with mild to moderately-severe hearing loss (Boretzki & Kegel, 2009:6). Interesting however, a study done on the significant overall benefit from non-linear frequency compression, found that children were more likely to benefit from this algorithm than adults; also, participants with greater hearing loss confined more to the high frequencies were more likely to benefit (Glista *et al.*, 2009: par. 3; Glista *et al.*, 2009:642).

More recently it was found that non-linear frequency compression is a viable means to provide consistent audibility of sounds through to 8 kHz for children with a moderate hearing loss (Nyffeler, 2010:1). A group of children experienced significant improvements in audibility and recognition of high frequency speech sounds after only six weeks of use. Preliminary analysis also suggests that these children experienced improvements in their production of fricatives and affricates, and it appears that extended use of this algorithm may allow further improvement in speech recognition. Furthermore, none of the children objected to the use of non-linear frequency compression and although they were blinded to which setting they were using during the trials, nine out of fifteen children expressed a preference for this algorithm (Nyffeler, 2010:2).

Lastly, it was found that non-linear frequency compression resulted in more satisfaction and greater benefit for hearing aid users in both quiet and noisy environments and improved the speech recognition threshold of seven out of eleven subjects (Bohnert, Nyffeler & Keilmann, 2010:6). They also concluded that it seemed that participants with a more severe hearing loss in the high frequencies benefited more from this algorithm (Bohnert *et al.*, 2010:7). A visual representation of the working of the non-linear frequency compression algorithm is provided in Figure 3-3.

Normal hearing



With normal hearing, we perceive a wide range of clear, distinct sounds, represented in this analogy by a color spectrum with red representing the lowest frequency and violet as the highest frequency.

Hearing loss



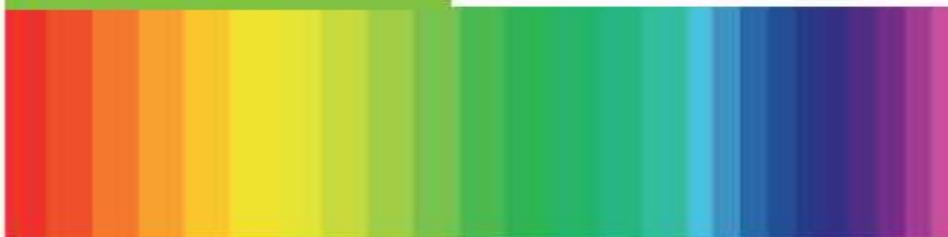
Sensori-neural hearing loss not only makes sounds harder to hear, (shown here by the faded colors), but also less distinct or distorted (shown here by the blurring or mixing of the colors).

Standard amplification



While standard amplification might bring back audibility, high frequency sounds, in particular, can still remain distorted and indistinct.

SoundRecover



By compressing and shifting high frequency sounds into an area of healthier cochlear function, SoundRecover brings back the full spectrum of sounds so they are both audible and distinct, without distortion.

Figure 3-3: Visual representation of non-linear frequency compression (Phonak, 2009).

The use of non-linear frequency compression signal processing requires individualized fine tuning, in order to optimize the audibility of the frequency-lowered band (Scollie *et al.*, 2008:7). If sounds are lowered too much, speech may take on a lisping quality that may be noticeable and objectionable to the wearer. If sounds are not lowered enough, the end user may not derive any additional benefit over and above what the hearing aid provides without non-linear frequency compression processing (Scollie *et al.*, 2008:7). Therefore it is important that the audiologist or hearing aid acoustician is aware of the adjustable features that influence the strength of this algorithm and apply it according to each hearing aid user's preference.

3.6 HEARING HEALTH CARE IN THE SOUTH AFRICAN CONTEXT

Hearing health care services do not fall into the category of high profile or glamorous specialties but they do have the potential to improve the quality of life of the very large number of people with a hearing loss who would benefit from new technology (Davis, 2006:39), for example non-linear frequency compression technology.

Healthcare systems are changing the way people think about health and health care by placing considerable emphasis on promoting healthy lifestyle choices, early identification of health problems together with early support to overcome them, personalization of healthcare, quality assured, evidence-based intervention, and involvement of the general public in decisions about health care (Davis, 2006:40). Life-threatening conditions attract more public support and government action to reduce morbidity, mortality and chronic conditions, with a less visible disability such as a hearing loss being less of a priority. Hearing loss almost always develops gradually, is not life-threatening and, in the view of the general public, does not merit urgent intervention. Taking the above into account, it becomes obvious that music perception with hearing aids would be considered even less of a priority since it can easily be seen as a luxury and not as basic need. However, as mentioned before, music plays a central role in all human cultures, and for humans the experience of music is an important contribution to quality of life (Luis *et al.*, 2007:686). In order to maintain healthy individuals and healthy societies it therefore is important to address this matter.

The degree of unmet needs, the late age of presentation of most patients and the problems they have in adapting to hearing aids at an older age suggest that screening for hearing impairment in older people ought to be investigated as a priority (Davis, 2006:44). Hearing impairment in adults is a highly prevalent major public health problem that is often left too late before available services are accessed. There is a lack of capacity in audiological services (worldwide), especially with increasing numbers of people seeking help. Enabling audiologists to efficiently practise their profession is one of the keys to filling this capacity gap (Davis, 2006:41).

According to the World Health Organisation (1998) every individual has the right to optimal health care, including hearing health care, and it is the responsibility of the government to provide these services to all people. The South African government's policy with regard to health states that all South Africans have the right to essential and comprehensive health care services (White Paper for the Transformation of the Health System in South Africa, 1997). Although this policy exists in theory it is, due to several factors including limited resources and facilities, not possible to apply these principles in practice.

South Africa's health care system consists of a large public sector with a smaller private sector where health care varies from the most basic primary health care that is provided by the government to highly specialized services available in the private sector. The public sector serves around 80% of the population and is characterised by a shortage of basic equipment, medication, trained personnel as well as inadequate essential resources like water and electricity provision (National Department of Health, 2004). Furthermore, the diversity in language and culture in South Africa, as well as the growing awareness of recognition of this diversity, present a challenge to therapists regarding service delivery to persons with a hearing loss (Louw & Avenant, 2002:145). It is well-known that deafness has taken precedence over ethnicity in the deaf community and it has been erroneously assumed that deafness precludes ethnic and racial group membership. The following factors influencing service delivery in the South African context, especially in rural areas, can be highlighted (Louw & Avenant, 2002:146-147):

- The South African population is characterized as a multi-cultural society and shows great diversity in geography, language and culture. Currently, the majority of audiologists belong to

a minority cultural group and cultural mismatches between professionals and the clients they serve exist, which is further compounded by language barriers.

- The family structure in many families tends to be extended, rather than nuclear and may also be multi-generational – specifically in the context of high HIV/AIDS infection rates in South Africa. This often implies that hearing health care is not the main priority in the family.
- Families differ in their perception of disabilities and a characteristic of African families is often their fatalistic attitude towards disability which leads to an accepting, passive attitude to hearing problems and may negatively impact on their seeking intervention services for family members with a hearing loss.
- Due to limited schooling and limited access to printed information, many persons from low-income families are disoriented and confused regarding their expectation in terms of normal hearing and hearing health services.
- Health beliefs and practices may further play a role in families seeking intervention. Traditional healers may form an integral part of a family's approach to illness and health. Technology and Western medical practices may be viewed as an intrusion on accepted and respected traditional activities and rituals. Families may be reluctant to make use of professional services and devices such as hearing aids.
- The African emphasis on community may also impact on the provision of intervention services to persons with a hearing loss. In African cultures co-operation, interdependence and the well-being of the group are rated higher than the individual.
- Another African concept, namely that of time, needs to be taken into account in the planning of provision of intervention services. In Western models, future planning and independent communication are fundamental to the process. However, in traditional African culture time is a two dimensional phenomenon, with a long history, a present and virtually no future. Future events are viewed as 'no time' and have no place in the concept of time since the future is unknown and can not be understood.

Other aspects that influence service delivery in the South African context are the high costs involved in hearing health care, poverty, insufficient supported government services as well as negative attitudes and ignorance of health care workers (Loening-Voysey, 2002:105). In South

Africa many people do not receive health care services since treatment of hearing disorders may lead to discrimination in the community.

From the above it is evident that hearing health care service delivery in South Africa is challenging and that these factors have to be addressed in an innovative way to provide culturally congruent and sensitive hearing health care services to South Africans.

3.7 CONCLUSION

Frequency lowering hearing aids have produced mixed results, with some studies showing substantial improvement and others showing no improvement or even degradation in performance (Stelmachowicz, Pittman, Hoover, Lewis & Moeller, 2004:561). However, the signal processing schemes across studies have differed substantially in concept and implementation. Other differences across studies were likely influenced by the nature of the frequency lowering algorithm, materials used for assessment as well as the severity and type of audiometric configuration of the participants (Gifford *et al.*, 2007:1195). In addition, some studies included subjects who clearly were not candidates for this type of technology (Stelmachowicz *et al.*, 2004:561).

Early efforts to exploit frequency lowering schemes encountered two serious problems (Jerger, 2009:288): First, it became evident early on that the hearing aid user would have to learn new acoustic precepts. Second, because of limitations in early analog technology, disturbing conversion artefacts could not be easily removed from the mixture of the original and the transposed signals in transposition algorithms. Modern digital signal processing has however substantially changed the playing field, renewing interest in frequency lowering strategies (Jerger, 2009:288).

Although frequency lowering strategies like non-linear frequency compression holds certain challenges for the hearing aid user, research has demonstrated that adult listeners can rather quickly learn to make use of high frequency information shifted to lower frequencies (Munro, 2007:14). One should keep in mind that the processed sounds were never heard by hearing aid

users before and as such it is unrealistic to expect listeners to identify the new sounds without adequate training and experience (Kuk *et al.*, 2006: par.8).

The case studies referred to above underline the need for hearing care professionals to carefully consider all available options when treating high frequency hearing loss. The results of these cases support changing conventional amplification to amplification with frequency lowering technology (Davis, 2001: par. 20; Boothroyd & Medwetsky, 1992:156).

3.8 SUMMARY

This chapter provides an in depth discussion of the current available literature on frequency transposition and frequency compression hearing aids. Non-linear frequency compression technology, a feature of the hearing aids used in this study as data collection apparatus, is also described in detail.

Every person is immersed in an environment filled with sound, and being able to understand speech is not the only function of hearing. For most people, listening to music is also a significant and enjoyable experience. Therefore, it is not surprising that people with a hearing aid frequently express a wish to be able to enjoy listening to music with their device (McDermott, 2005:65). With the theoretical background described in Chapters 1-3, this study aims to address the need for musical enjoyment of non-linear frequency compression hearing aid users by following the procedures set out in Chapter 4.