

Chapter 1

ORIENTATION AND PROBLEM STATEMENT

Chapter aim: In this chapter the formulated research question and the rationale for the study are stated, the relevant terminology is explained and a view of the content and organization of the study are outlined.

1.1 INTRODUCTION



(Retrieved from http://www.sheetmusicplus.com/store/smp_inside.html?cart=3449918755262746&item=4382372&page=01)

The lyrics of the well-known song above are relevant to many people throughout their lives. There certainly are other vital aspects to life, but as Revit (2009:12) postulates: *'Unless some people regularly engage in musical activities, their enjoyment of living seems to decline rapidly'*. Some people may feel that the emphasis placed on music as a precursor to enjoyment of life may not be justified – possibly because they are able to hear music unhindered. For people with a silent disability such as a hearing loss this is certainly true. The fact that hearing loss has often been described as an invisible handicap illustrates why so many people fail to recognize its full impact on their lives (Chartrand, 2008: par. 48). Music is an integral part of our daily life and one is confronted with music on numerous occasions each day. Hearing loss excludes many people from this daily exposure and therefore it is extremely important for individuals with a hearing loss to also have access to music.

High frequency hearing loss is by far the most common audiometric configuration found in individuals fitted with hearing aids (Glista & McDermott, 2008:1; Nyffeler, 2008b:22; Munro, 2007:2; McDermott, Dorkos, Dean & Ching, 1999:1323; Hogan & Turner, 1998:432). In response to this phenomenon a common clinical practice in fitting hearing aids to individuals with a high frequency hearing loss is to provide additional amplification in the higher frequencies (Ross, 2002: par. 1; Turner, 1999:10). However, this is often problematic, since some people may unknowingly present with dead cochlear regions and perceive high frequency amplification as distorted or noise-like in quality (Munro, 2007:3; Vestergaard, 2003:250; Yanz, 2002: par. 31).

High frequency amplification plays an important role in speech understanding because high frequency speech sounds generally convey key information for understanding speech (Ross, 2002: par. 2). An important example is the sound [s]. Its sibilant acoustical energy extends across a wide frequency range, from about 3 kHz to 8 kHz, which may make it difficult or even impossible for people with a high frequency hearing loss to identify (Stelmachowicz, Pittman, Hoover & Lewis, 2002:316). What is true for the [s] sound can also, to a lesser degree, be applied to other consonants (Ross, 2002: par. 2). High frequency amplification is also necessary for the audibility and identification of high-pitched environmental sounds like doorbells, alarms and music (Glista & McDermott, 2008:2). Although the majority of music pitches exists in the lower half of the auditory spectrum with fundamental frequencies at approximately 1 kHz and below, the higher frequency resonances occurring above the fundamental frequency of musical notes assists the listener in distinguishing the sound of one instrument from another (Revit, 2009:14).

Most people with a hearing loss express a need to hear speech optimally (Chasin, 2004:10). However, more and more people with hearing problems are expressing an equal need for their hearing aids to be fitted optimally for listening to music (Chasin, 2005: par. 10). As one may expect, hearing aids were previously designed with speech in mind, not music. Lately, and however long overdue, a concern about the fidelity of music processing by hearing aids has come to the fore (Chasin, 2004:10).

1.2 RATIONALE

A survey conducted in the United States of America estimated that around 10% of the United States' population reported hearing difficulties (Better Hearing Institute, 2009: par. 2). The majority (65%) of these people are younger than 65 years of age (Better Hearing Institute, 2009: par. 4). In the United Kingdom one in five adults has a bilateral hearing loss at a level of 25 dB HL¹ or more, which negatively affects hearing and communication (Davis, 2006:39).

According to the 2001 South African Census (Statistics South Africa, 2001) there is an estimated 1 991 398 people living with a disability of which approximately 313 594 (15.7%) have a hearing loss, rendering hearing disabilities the third largest disability in South Africa, affecting one sixth of its population. The accuracy of statistics regarding the prevalence of hearing disorders in South Africa is questionable due to non-comprehensive diagnosis, incomplete or delayed reporting as well as limited access to health care services. This can be attributed to a lack of identification of hearing disorders and subsequent referral to audiological services by doctors (Davis, 2006:39). These limitations in identifying hearing disorders in South Africa inevitably results in inadequate provision of hearing aids to those who are in need.

The plight of most people with a hearing loss can be alleviated with hearing aids, although four out of five Americans with a hearing loss do not use these (O'Neill, Summer & Shirey, 1999:1). Furthermore, it was found that only approximately 15% of people with a hearing loss currently own hearing aids (Boretzki & Kegel, 2009:1). The main reasons why people do not use hearing aids are related to the cost of hearing aids, vanity, and the stigma associated with wearing them. Furthermore, one third of persons with a hearing loss believe that hearing aids will not be beneficial with the problems they experience, or believe that their hearing loss is only minimal and therefore does not justify the use of a hearing aid (O'Neill *et al.*, 1999:5). These views contribute to the fact that a hearing loss is not viewed as a dramatic health problem requiring urgent intervention (Davis, 2006:42). Due to the reasons mentioned above, it may be assumed that the prevalence of hearing disorders in South Africa is higher than current statistics indicate.

¹Hearing level (0 dB is average normal hearing for each audiometric test frequency)

Traditionally, statistics on hearing loss have shown the geriatric population to be the most vulnerable (O'Neill *et al.*, 1999:4). However, over the last three decades there has been a sharp increase in the number of younger people with hearing problems. This phenomenon can be ascribed to an increase in environmental noise (O'Neill *et al.*, 1999:4) as well as increased use of personal listening devices and the increase in life expectancy (Eureka Science News, 2008: par. 2). Apart from these factors there are a number of conditions that may lead to the development of a hearing disorder of which the most common in adults is presbycusis² (O'Neill *et al.*, 1999:2). The second most common condition is noise-induced hearing loss³, followed by other possible causes like viral or bacterial infections, ototoxicity, birth defects, illness and injuries (Launer & Kühnel, 2001:113; O'Neill *et al.*, 1999:2). Acquired hearing loss is often associated with dysfunction of the outer and inner hair cells of the cochlea while congenital hearing loss may involve abnormalities in many structures and systems other than the outer and inner hair cells of the cochlea, such as abnormal cochlear metabolism, abnormal sodium or potassium concentrations, malformation of the tectorial membrane, collapse or rupture of Reisner's membrane, ossification, demyelization of the auditory nerve and many more (Moore, 2001b:153; Moore, Huss, Vickers, Glasberg & Alcantara, 2000:222).

As mentioned above, cochlear hearing loss often involves damage to the outer and inner hair cells; the stereocilia may be distorted or destroyed, or entire hair cells may die (Moore, 1996:133). The outer hair cells are generally more vulnerable to damage than the inner hair cells and it is suggested that damage in the cochlea at hearing levels above 50 dB HL is not limited to the outer hair cells but also affects the inner hair cells (Huss & Moore, 2005:608; Summers, Molis, Müsch, Walden, Surr & Cord, 2003:133; Ching, Dillon & Katsh, 2001:145). Consequences of outer hair cell loss include elevated absolute thresholds, reduced frequency selectivity⁴, difficulties understanding speech (especially in the presence of background noise)

² A gradual age-related reduction in the ability to hear high-pitched sounds (Launer & Kühnel, 2001:113)

³ Caused by a single exposure to an extremely loud sound or by continuous exposure to sounds at high intensity levels over a period of time (Launer & Kühnel, 2001:113)

⁴ Refers to the ability of the auditory system to separate and resolve the components in a complex sound. This is due to the fact that the auditory filters are broader in persons with a hearing loss compared to those with normal hearing (Moore, 1996:136-137).

and loudness recruitment⁵ (Kluk & Moore, 2006: par. 5; Turner & Cummings, 1999:54; Moore, 1996:133). Healthy inner hair cells act as transducers, transforming basilar membrane vibration into action potentials in the neurons of the auditory nerve; with a loss of inner hair cells one would experience a reduced efficiency in transduction that leads to elevated absolute thresholds, 'noisy' transmission of information in the auditory nerve as well as no transduction of basilar membrane vibration (Kluk & Moore, 2006: par. 8). Therefore, even if sounds are amplified to well above the threshold for detection, the perception of those sounds by a person with a sensory neural hearing loss is usually abnormal.

From the above it is evident that sensory neural hearing loss can have a substantial negative impact on the life of a person with the hearing loss and his/her family, as it also influences their emotional, physical and social well-being. People with a hearing loss are more likely to report symptoms of depression, anxiety, defensiveness, frustration, impatience, dissatisfaction with life, withdrawal from social activities, increased stress levels, problems with employment and access to information sources (Chartrand, 2008: par. 23; O'Neill *et al.*, 1999:1). One of the reasons for increased stress in individuals with hearing loss is in all likelihood related to the increased incidence of communication failures they experience (Kuk & Peeters, 2008: par. 2). The most pronounced effects of hearing loss are often emotional and psychological in nature and are best described in terms of the psycho-emotional⁶ levels of hearing as explained by Chartrand (2008: par. 5):

- *The Primitive (background) level:* This level involves the auditory background of life, much of it indiscernible but nevertheless crucial for one's sense of security in a noisy world (Chartrand, 2008: par. 6). The background noise may be the never ending drone of traffic from a nearby freeway or the cheerful chirping of birds. Any and all of these sounds, as part of our natural or everyday environment, form the ambient backdrop of life and living. Remove these suddenly, and the feeling can be one of isolation, despair, emptiness and insecurity. Changing the intensity of background noise relative to the rest of life's signals (communication) can give rise

⁵ Refers to the abnormal perception of loudness that may occur due to hearing loss. The person will hear a relatively soft sound as "soft" but as the loudness level increases, the rate of an increase in loudness with increasing sound level is greater than normal. For sounds with inherent amplitude fluctuations, such as music, this results in an exaggeration of the perceived dynamic qualities as the sound appears to fluctuate more in loudness than it would for a normal hearing person (Moore, 1996:139).

⁶ Describing the psychological interaction with the emotions it evokes

to an invited signal level of hearing, bringing constant disruption and emotional disturbance to the unfortunate listener. Most background sounds are in the low frequency domain, the area where the majority of hearing-impaired individuals maintain near-normal hearing function (Chartrand, 2008: par. 8).

- *The Signal (alerting) level:* This level refers to the innate and acquired knowledge about what to approach and what to avoid. Our first exposure to fire, thunder and lightning all represent warning signals that have been learned and stored in the human subconscious. No learning is required to provide emotional responses to these signals (Chartrand, 2008: par. 9). In contrast, we acquire, through experience, a whole new nomenclature of warning and alerting signals – the ring of a telephone, the sirens of emergency vehicles and many more. Whether sound asleep or wide awake, with normal auditory ability no one needs to draw our attention to or interpret these signals for us. They garner involuntary attention to the point of distraction until responded to (Chartrand, 2008: par. 10).
- *The Symbolic (communication) level:* This level of human hearing is most associated with language and verbal communication (Chartrand, 2008: par. 11). So important is this level of perception to one's psychosocial well-being that an average five year old child, with no formal training and little or no ability to read, already demonstrates a working vocabulary of up to 5000 words. Words help us organize patterns of thought, express emotions, and gain or exchange knowledge, as well as assist us in bonding with our fellow beings. A strong correlation between vocabulary size and social, emotional, vocational, and financial development has been demonstrated as the heart of societal development depends heavily on the development of verbal and written language (Chartrand, 2008: par. 12).

In terms of human relationships, educational and vocational progress as well as psycho-emotional well-being, what is the impact of hearing acuity diminishing over time? Firstly, with an advancing hearing loss, we find a role reversal between the primitive and signal levels of hearing as the loss advances. As the backgrounds of life becomes distorted or not clear enough for interpretation at the subconscious level, background noise rises into the signal level where sounds become alarming and distracting. This means that everyday sounds –traffic, machinery, etc – no longer can be shuffled into the background of one's subconscious, but are now unwantedly thrust into the foreground of one's attention (Chartrand, 2008: par. 14). Most common in this

development are losses where the high frequencies plummet, making the background-laden low frequencies more audible. Generally, the worse the high frequency loss, the more disruptive the background sounds become and the more aversive they are to one's emotional well-being (Chartrand, 2008: par. 15).

If the primitive level of hearing rises to the signal level, where does the signal level go? Since signal levels may become distorted, softer and possibly not even audible, their usefulness in the scheme of personal security becomes less defined. That is why it can be unsafe to function in the hustle and bustle of life with poor hearing (Chartrand, 2008: par. 18). Within the context of normal healthy human relationships, the preservation of the symbolic level of hearing, or verbal communication, is important to one's social-emotional well-being because hearing adds to the ability to function and advance unfettered within society (Chartrand, 2008: par. 19). The loss of the symbolic level (speech communication) of hearing also means the loss of what is referred to as 'intimate communication'. The loss of intimate communication means the loss of encouragement as well as the nuances of speech that signal empathy or sympathy. As uncorrected hearing loss approaches the stage of severe loss, not only do the softened tones that express empathy and sensitivity disappear for the individual with the hearing loss, but they begin to disappear from his/her own voice as well (Chartrand, 2008: par. 20).

Since hearing loss is 'invisible', those in one's social network may be at a complete loss in understanding what the person with the hearing loss is experiencing (Chartrand, 2008: par. 24). As a result, relationship difficulties more often arise in the lives of individuals with a hearing loss than in people with normal hearing. Divorce rates are higher, as well as estrangement from children and friends. Social dysfunction often leads to higher rates of alcoholism and substance abuse (Chartrand, 2008: par. 25). Labour force participation rates are lower for people with a hearing loss and it is reported that a hearing loss often limits them to a specific type of work and salary level (Eureka Science News, 2008: par. 1). In almost every human challenge, one would expect sufferers to know and recognize their sensory deficiency. The truth is, however, that shortcomings in the hearing and communicative domains are difficult to detect. Instead, life can become a treadmill of embarrassments, feelings of inadequacy, misunderstandings,

rationalizations and blame-games until deeper psychosocial barriers prevent the person from seeking help (Chartrand, 2008: par. 26).

From the above it is evident that a hearing loss diminishes quality of life for the affected person and also for his/her family members (Davis, 2006:42). Due to the fact that our quantity of life has increased dramatically over the last century, the concept of quality of life is a popular topic of conversation. Since healthcare has been so successful at increasing life expectancy, efforts are now focusing on ensuring that as we age, we also live well and function well in our day-to-day activities (Chisolm, 2007:10). These aspects highlight the importance of effective amplification, including the amplification of music – as a means of improving the quality of life of persons with a hearing loss (Kuk & Peeters, 2008: par.2).

One of the most challenging hearing loss configurations for audiologists is a precipitously sloping sensory neural hearing loss (Auriemmo, Kuk & Stenger, 2008:50). Not surprisingly, high frequency hearing loss represents the largest number of uncorrected cases (Chartrand, 2008: par. 30). Poor perception of high frequency sounds can cause difficulty in recognizing certain speech sounds, such as the fricative consonants [s] (sun), [t] (task) and [f] (frog) (Glista & McDermott, 2008:2). Almost all of the energy of the consonant [s] is confined to a high frequency range with a peak at 8 kHz or higher. People with a hearing loss make more perceptual errors with [s] than with any other sound in the English language. This is unfortunate, since [s] is not only one of the most frequently occurring sounds in English, but also provides more grammatical information⁷ than any other sound (Kortekaas & Stelmachowicz, 2000:645; Boothroyd & Medwetsky, 1992:151).

People with a high frequency hearing loss have difficulty understanding speech because of reduced audibility and, because, for those with severe hearing losses, the individual's proficiency at extracting information from an audible signal is reduced by the need to listen at high sound pressure levels; it is further reduced when sensation level exceeds about 20 dB (Mackersie,

⁷ Distinguishes between singular and plural nouns, contractions (it's), 3rd person present tense, present versus past tense and possessive pronouns (Glista & McDermott, 2008:2)

Crocker & Davis, 2004:499; Ching, Dillon & Byrne, 1998:1139; Arehart, King & McLean-Mudgett, 1997:1434). These aspects are described in more detail below.

As speech cannot be understood if it cannot be heard, audibility is undoubtedly a major goal of amplification for people with a hearing loss (Mackersie *et al.*, 2004:499). In restoring audibility, it is often assumed that the listener can extract speech cues over the entire range of speech frequencies. This assumption is true for a person with a mild to moderate hearing loss, but untrue for a severe hearing loss at the high frequencies (Ching *et al.*, 2001:141; Ching *et al.*, 1998:1137). Mackersie *et al.*, (2004:499) observed that the efficiency with which listeners with high frequency hearing losses used audible high frequency information decreased with an increase in hearing loss. Hogan and Turner (1998:439) reported that the contribution of high frequency information to speech recognition was less than is the case in normal hearing listeners once thresholds exceeded 55 dB HL. In both studies, the majority of listeners with 4 kHz thresholds of 80 dB HL or higher were unable to make use of audible high frequency information and some listeners showed a decrease in speech intelligibility when this information was made audible.

The second reason why people with a hearing loss experience difficulty in identifying speech sounds is because they have to listen at high sound-pressure levels (Ching *et al.*, 2001:142). It seems possible that a level distortion factor is needed for any listener because frequency and temporal resolution ability decrease at high presentation levels and hence appear to decrease with hearing loss (Ching *et al.*, 1998:1137).

Furthermore, amplification of high frequencies to high sensation levels for people with severe losses at these frequencies could be detrimental to speech intelligibility. Studies conducted by Ching *et al.*, (2001:142) indicated that for people with a severely sloping hearing loss speech scores deteriorated with increased bandwidth at high sensation levels whereas a definite improvement in speech scores is evident with an increase in bandwidth (from 1.4 kHz to 2.8 kHz) for persons without a severe, high frequency hearing loss. This is also confirmed in another study, showing that for a group of adults with moderate to severe high frequency loss word

recognition improved when amplification bandwidth was extended from 1.6 kHz to 3.2 kHz, but no further improvement was obtained when the bandwidth was extended to 6.4 kHz.

All of the above support the proposition that when a hearing loss is extreme at the high frequencies, it was not beneficial to attempt to provide an audible signal at those frequencies (Ching *et al.*, 2001:142). With this information taken into account, provision of high frequency audibility for listeners with a severe high frequency hearing loss is further complicated by the small dynamic range⁸ of hearing and acoustic feedback that will limit the amount of usable gain.

However, speech comprehension is not the only ability adversely affected by high frequency hearing loss. High-pitched environmental sounds like alarms, doorbells, telephone ring tones and music may also be difficult to detect and/or identify. Some of these sounds are valuable, mainly because they enhance the quality of a person's overall hearing experience. Additional significance includes the security of being able to quickly and easily recognize high-pitched alarms (Glista & McDermott, 2008:2). Furthermore, for adults, poor perception of high frequency sounds may lead to difficulty in maintaining the quality of their own speech whereas young children will have difficulty in learning to produce speech sounds that contain high frequencies (Glista & McDermott, 2008:1; Kuk, Korhonen, Peeters, Keenan, Jessen & Anderson, 2006:44).

Persons with a high frequency sensorineural hearing loss differ in the benefit they gain from amplification of high frequencies when listening to speech (Baer, Moore & Kluk, 2002:1133). For many years there have been reports suggesting that people with a moderate-to-severe hearing loss in the high frequencies often do not benefit from amplification of the high frequencies, or that their hearing is even worse when high frequencies are amplified (Plyer, Madix, Thelin & Johnston, 2007:150). This may be because sufficient high frequency gain can not be achieved by the hearing aid to reach audibility without feedback occurring (Parent, Chemiel & Jerger, 1997:355). It may also be that the severity of the hearing loss in the high frequency region is so great that it is unaidable (Kuk *et al.*, 2006: par. 1; Arehart *et al.*, 1997:1442). Furthermore, even when sounds can be made audible, they may not be discriminated or recognized (Glista &

⁸ Difference between the level of discomfort and the threshold of audibility (Simpson, McDermott & Dowell, 2005:42)

McDermott, 2008:1); this is the scenario for those people who present with cochlear dead regions (Baer *et al.*, 2002:1133).

Cochlear dead regions refer to a loss of function of the inner hair cells and/or neurons within specific regions in the cochlea (Moore, 2009:10). The inner hair cells are laid out in a row along the length of the basilar membrane and are the sensory receptors that are responsible for converting acoustic energy into electrical energy by directly stimulating the fibres of the auditory nerve (Ross, 2002: par. 5). Each inner hair cell responds to the vibration of the basilar membrane in the regions where it is located. In return, each region is tuned and responds most strongly to one specific frequency, called the characteristic frequency. The characteristic frequency is low toward the apex of the cochlea and high towards its base (Moore, 2009:10). When the inner hair cells and/or neurons are not functioning at a given place along the basilar membrane, no acoustic information along that region of the basilar membrane is transmitted to the brain (Moore, 2001b:153). Since inner hair cell damage is often associated with outer hair cell damage, the tuning of the basilar membrane, inner hair cells and neurons may be abnormal in an ear with a dead region, even over regions which are not dead (Moore, 2009:10; Moore, 2001a:2).

Often in the case of a cochlear dead region a tone producing peak vibration in that region is detected by off-place listening which means that the tone is detected at a place where the amount of basilar membrane vibration is lower, but the inner hair cells and neurons are functioning more effectively (Markesis, Kapadia, Munro & Moore, 2006:91; Kluk & Moore, 2005:115; Munro, Felthouse, Moore & Kapadia, 2004: par. 1; Cairns, Frith, Munro & Moore, 2007:575). This phenomenon can be explained by normal cochlear dynamics. Each part of the cochlea has a characteristic frequency to which it is tuned. When input sounds are very soft, only a tiny specific region of the outer hair cells in the cochlea is activated. The outer hair cells then energize the corresponding inner hair cells that, in turn, stimulate a specific narrow area of the corresponding nerve fibres (Ross, 2002: par. 8). When exposed to high intensity sounds, the cochlea (actually the basilar membrane within the cochlea) displays a broad excitation pattern and quite a large number of adjacent hair cells may be stimulated. In its normal functioning, the auditory system suppresses signals arriving from locations other than the portion for which it is specifically tuned. On the other hand, when the greatest movement of the basilar membrane

occurs in areas where there are cochlear dead regions, then these adjacent areas, with intact inner hair cells, may stimulate auditory nerve fibres and produce an auditory sensation (Ross, 2002: par. 9). Subjectively the audible result of these off-centre locations may be perceived as noise and distortion and they interfere with sound comprehension because they are sending misinformation to the brain regarding the acoustic composition of an incoming sound. Thus, the diagnosis of cochlear dead regions may have implications for candidature for and benefit from amplification (Moore, Killen & Munro, 2003:466; Vickers, Baer & Moore, 2001:149).

Most often a dead region is located toward the basal end of the basilar membrane, which normally responds to high frequencies but it can also occur at the apical end of the cochlea which will result in a low frequency dead region (Moore, 2009:12). The extent of a dead region is defined in terms of its edge frequency, which corresponds to the characteristic frequency of the inner hair cells and/or neurons immediately adjacent to the dead region (Kluk & Moore, 2006:464; Munro, Felthouse, Moore & Kapadia, 2005:470). A dead region in any part of the cochlea can arise as a result of genetic factors, infections, auto-immune disease, aging, noise toxicity or exposure to toxic agents (Taleb, Faulkner & Cunningham, 2006:42). There is no relationship between gender, age and the presence or absence of dead regions (Aazh & Moore, 2007:104). There is also no definitive audiometric pattern associated with dead regions but there are certain audiometric features that are more likely to be present in the presence of a cochlear dead region (Munro, 2007:3).

The presence of cochlear dead regions seems to be rare for audiometric frequencies where the hearing loss is 55 dB HL or less, but becomes increasingly common when the hearing loss is 75 dB HL or more (Moore, 2009:12; Moore 2001a:4). Prevalence data for cochlear dead regions in adults with a sensory neural hearing loss was provided by a study in which 317 adults who attended an Audiology department for the fitting of a hearing aid were assessed. A total of 54% of these adults met the criteria for a dead region at one or more frequencies. Evidence of a dead region when the hearing threshold was 60 dB HL or better was rare, and these researchers concluded that most adults who showed evidence of dead regions had a hearing threshold at, or greater than, 65 dB HL (Munro, 2007:8). This latter study recommended testing for the presence of dead regions when the hearing threshold exceeded 60 dB HL. This recommendation was

confirmed by Markesis *et al.*, (2006:97) who found that dead regions are relatively common (85-87%) in people with steeply sloping hearing losses with moderate to profound thresholds at the high frequencies. Moore (2001a:30) also indicated that dead regions are very common with a hearing loss that rapidly increases (more than 50 dB per octave) with increasing frequency. Furthermore, studies by Gifford, Dorman, Spahr and McKarns (2007), Moore (2001a), Vickers *et al.*, (2001), Ching *et al.*, (2001), Turner and Cummings (1999) as well as Ching *et al.*, (1998) clearly show that, when the hearing loss exceeds 55 dB at the high frequencies, amplification of high frequencies is often not beneficial.

The presence of dead regions in the studies mentioned above may vary for a number of reasons for example the cut-off frequency tested as some studies did not test above 4 kHz where dead regions are probably very common (Munro, 2007:10). Furthermore, some of the studies listed above used pre-selected groups of patients and this probably explains the highly variable occurrence of dead regions (Munro, 2007:10). It can be concluded that a 'high risk' group for clinically significant dead regions would be individuals with an extensive hearing loss of 60 dB HL or greater at all frequencies above 1 kHz (Munro, 2007:15).

When a dead region is present, the audiogram will give a misleading impression of the degree of hearing loss for a tone of which the frequency falls in the dead region (Moore, 2001a:3). Effectively, the 'true' hearing loss in a dead region is infinite, but the audiogram may sometimes indicate only a moderate one. A high frequency dead region is usually associated with a severe to profound hearing loss at the high frequencies and the audiogram is often steeply sloping (Moore, 2001a:6). Dead regions may, however, occur even when the audiogram is not steeply sloping; therefore, the slope of the audiogram does not serve as a reliable feature for assessing the presence or absence of dead regions (Moore, 2001a:7). An even more difficult task is to define the extent of any dead region by only looking at an audiogram (Moore, 2001a:7).

Accurate diagnosis of dead regions cannot be achieved using the audiometric threshold at the test frequency alone (Aazh & Moore, 2007:103; Mackersie *et al.*, 2004:499). The Threshold Equalizing Noise test (TEN) has been used to identify cochlear dead regions and involves the measurement of pure-tone thresholds in the presence of broadband noise spectrally shaped to

produce equal masked thresholds across frequencies (Moore, 2009:16). Dead regions at specific frequencies are indicated by elevated thresholds in the presence of this masking noise (Mackersie *et al.*, 2004:500). The TEN test was found to detect a dead region 95% of the time (Moore, 2009:16). It can be used clinically to gain insight into the likely benefit to be obtained from providing a hearing aid, also to provide information that may help in the selection of an appropriate hearing aid and furthermore to assist in assessing candidacy for hearing aids and cochlear implants (Moore, 2004:107; Moore *et al.*, 2003:473).

Although the TEN test serves as a useful tool for detecting dead regions, it does not precisely define the edge frequency (Munro, 2007:6). A solution is to identify the edge frequency using psychophysical tuning curves (PTCs). A PTC shows the level of a narrowband masker required to mask a low level signal, plotted as a function of masker centre frequency. The lowest masker level required to mask the signal defines the tip of the PTC – this is the frequency at which the masker is most effective. In normal hearing listeners the tip of the PTC usually lies close to the signal frequency. In listeners that have a hearing loss without a dead region, the tip of the PTC is usually broader but still close to the signal frequency. In cases where the signal frequency is within a dead region the tip will be shifted away from the signal frequency. The tip of the PTC will be shifted to the frequency which corresponds to the place on the basilar membrane where the signal is being detected. This identifies the edge of the dead region. When the tip of the PTC is shifted towards a lower frequency, this indicates a high frequency dead region and vice versa. Traditionally PTC measurements are time consuming, as each one requires measurement of many masked thresholds in order to define the frequency at the tip (Munro, 2007:7).

There are several theoretical reasons why people with dead regions may extract little or no information from frequency components of speech that fall within a dead region, even when those components are sufficiently amplified to make them audible. These reasons include (Moore, 2001a:20; Vickers, Moore & Baer, 2001:1172):

- The frequency components are received through the 'wrong' place in the cochlea. For example, if there is a high-frequency dead region, amplified high-frequency components will be detected and analyzed via the frequency channels that are tuned to lower frequencies. This mismatch

between frequency and place may lead to difficulty in interpreting the information derived from the high frequencies.

- If the components falling in the dead region are amplified sufficiently to make them audible, they will be detected and analyzed via the same neural channels that are used for other frequencies, and this may impair the analysis of those other frequencies. For example, if there is a low-frequency dead region, the amplified low-frequency components will be detected and analyzed through the same neural channels as are used for the medium and high frequencies. Since speech is a broadband signal, usually containing components covering a wide frequency range, this may lead to some form of 'information overload' in those channels.
- Information in speech, such as information about formant frequencies, may partly be coded in the time patterns of the neural impulses. The analysis of temporal information may normally be done on a place-specific basis. For example, the neural machinery required to 'decode' temporal information about frequencies around 1 kHz may be restricted to neural channels with characteristic frequencies close to 1 kHz. When there is a mismatch between the frequencies of speech components and the place where they are detected, the temporal decoding mechanisms required to analyze those speech components may not operate effectively.

Pure tones are often described as sounding highly distorted or noise-like when they fall in a dead region (Munro, 2007:3; Moore, 2001a:24). Furthermore, compromised inner hair cell integrity, as defined by the identification of dead regions, has been associated with reduced accuracy of pitch perception, reduced tonality of pure tones, and reduced utility of high frequency speech information in speech recognition (Ricketts, Dittberner & Johnson, 2008:169). Frequency discrimination measurements also suggest that frequency tones falling in a dead region do not evoke a clear pitch or can have an abnormal timbre (McDermott & Dean, 2000:353). Specifically, the studies of pitch perception which included people with dead regions indicate the following (Moore, 2001a:27):

- Pitch matches (of a tone with itself, within one ear) are often erratic, and frequency discrimination is poor for tones with frequencies falling in a dead region. This indicates that such tones do not evoke a clear pitch sensation.

- Pitch matches across ears of subjects with asymmetric hearing loss, and octave matches within ears, indicate that tones falling within a dead region sometimes are perceived with a near 'normal' pitch and sometimes are perceived with a pitch distinctly different from 'normal'.
- The shifted pitches found in some subjects indicate that the pitch of low frequency tones is not represented solely by a temporal code. It is possible that there needs to be a correspondence between place and temporal information for a 'normal' pitch to be perceived.

While amplification may allow the frequencies corresponding to the dead region to be detected via spread of excitation, this does not necessarily improve speech recognition for frequencies that fall inside the dead region (Moore, 2009:16, Launer & Kühnel, 2001:118). Thus, the diagnosis of the presence and extent of cochlear dead regions may have implications for candidature for and benefit from amplification as their needs differ from persons with no dead regions⁹ (Cairns *et al.*, 2007:575; Munro, 2007:1). This may therefore play an important part in hearing aid success (Bentler, 2006:91).

The main goal of a hearing aid fitting is to provide audibility over a broad frequency spectrum with a variety of input levels (Bagatto, Scollie, Glista, Parsa & Seewald, 2008: par. 1). For listeners with high frequency sensorineural hearing loss, this goal may for several reasons be difficult to meet with amplitude compression technology. Firstly, this technology is limited in its ability to provide the appropriate amount of gain for soft, high frequency sounds. Conventional amplification may not provide sufficient audibility for consonants such as [s], [f] and [t] for sloping high frequency hearing losses (Glista, Scollie, Bagatto & Seewald, 2008:1). If suitable gain is achieved in the high frequency region, acoustic feedback may occur when the instrument is worn by the listener (Glista *et al.*, 2008:1). Feedback¹⁰ is a long-standing problem in hearing aids (Freed & Soli, 2006:382) and when occurring, the application of a feedback management strategy and/or gain reduction is a common solution (Flynn & Schmidtke Flynn, 2006:58). Additionally, conventional hearing aids have a narrow output bandwidth and do not consistently make high frequency sounds audible for listeners (Bagatto *et al.*, 2008: par. 1). These factors

⁹ For persons without dead regions, restoration of audibility through high frequency amplification usually leads to improved intelligibility (Moore *et al.*, 2003:466; Baer *et al.*, 2002:1133; Stelmachowicz, 2001:174).

¹⁰ Feedback results from the repeated amplification (and growth) of a particular sound through an amplification circuit (Merks, Banerjee & Trine, 2006: par. 2).

limit the audibility of important high frequency sounds, especially for individuals with sloping and/or severe to profound hearing losses.

Despite the shortcomings of traditional amplification, few alternative rehabilitation options have been available to listeners with relatively good low frequency hearing and precipitous high frequency hearing loss (Gifford *et al.*, 2007:1195). Due to the fact that a sensory neural hearing loss is not remediable with medication or surgery (Hogan & Turner, 1998:432), a hearing aid still is the preferred form of treatment because amplification is non-invasive and low-risk with considerable potential benefits (Johnson & Danhauer, 2006:30). Another possibility is cochlear implants, which provide high frequency information through direct electrical stimulation of the spiral ganglion cells in the basal region of the cochlea. Although this treatment option involves a risk of damaging neural tissue in the apical region of the cochlea, multiple studies have demonstrated that an electrode array can be inserted to the cochlea without destroying residual low-frequency hearing and therefore can be an effective and safe treatment option (Gifford *et al.*, 2007:1195; Kuk, Peeters, Keenan & Lau, 2007:60, McDermott, 2004:49). Not all persons with such a hearing loss are however candidates for cochlear implantation (Clark, 2003:551) or can afford a cochlear implant due to the financial costs (Clark, 2003:769; DeConde Johnson, Benson & Seaton, 1997:92). Especially in South Africa that is characterized by high levels of unemployment and poverty (Statistics South Africa, 2001), a hearing instrument can be a more economical alternative for a cochlear implant.

In their search for technology that would provide their hearing aid wearers with the most complete picture, dispensing professionals may need to rethink how hearing aids amplify speech and other sounds, how the amplified signal is delivered to the impaired ear and how to assess hearing aid benefit (Davis, 2001:37). If this is taken into account, another intervention option emerges. This involves the use of frequency lowering amplification (Gifford *et al.*, 2007:1195) where high frequency sounds are processed and delivered to the lower frequencies, where people are likely to have more residual hearing (Ross, 2000: par. 2; McDermott *et al.*, 1999:1323). In extreme cases, where there is little or no residual hearing at relatively high frequencies, frequency lowering is probably the only way of enabling hearing aid users to detect high frequency sounds (McDermott *et al.*, 1999:1323).

Many researchers over the years have suggested the possibility of frequency lowering as a means of making speech sounds audible to patients with dead regions (Moore, 2009:16; Bagatto *et al.*, 2008: par. 2; Moore & Alcantara, 2001:277). There are, however, several potential problems posed by frequency lowering (Moore, 2001a:30). Firstly, there is likely to be a limit to the amount of information that can be 'squeezed' into the limited region of residual hearing since there is a danger of 'overloading' that region. Secondly, the lowered information is presented to the 'wrong' place in the cochlea which may lead to difficulty in interpreting the information (Moore, 2001a:30; Moore *et al.*, 2000:206) and require an extended learning period to make effective use of information from the lowered frequencies. Thirdly, when background noise is present, portions of the noise that were previously inaudible, may be lowered to a frequency region where it is more audible, and this may offset any advantage that would otherwise be gained from the lowering (Moore, 2001a:30).

Various signal processing strategies have emerged to allow frequency lowering so that information can be more easily accessed by the listener. At first, target beneficiaries of this technique were people with a severe-to-profound loss in the high frequencies who could not benefit from conventional amplification (Kuk *et al.*, 2006: par. 3), but with improvements in this technology other degrees of hearing loss are also considered. There are three main types of frequency lowering strategies available at present; these are summarized in Table 1-1:

Table 1-1: Frequency lowering strategies available at present

STRATEGY	SIGNAL PROCESSING
Proportional frequency compression often referred to as 'frequency transposition'	Hearing aids that utilize proportional frequency compression shift the entire sound signal downwards by a constant factor, thus preserving the natural ratios between the frequency components of speech (Jerger, 2009:288; Turner & Hurtig, 1999:884).
Linear frequency transposition	The linear frequency transposition strategy only shifts the high frequency information of a sound signal downwards by a fixed amount and not the whole frequency spectrum (Jerger, 2009:288; Kuk <i>et al.</i> , 2006).
Non-linear frequency compression	Hearing aids with non-linear frequency compression technology compress only the high frequencies of a sound signal in increasing degrees. This is determined by a cut-off frequency calculated according to the person's audiometric thresholds. All frequencies below the cut-off frequency are amplified in a normal manner (Bagatto <i>et al.</i> , 2008: par. 2; Glista & McDermott, 2008:2).

Mixed results were obtained from adult studies using proportional frequency compression. Turner and Hurtig (1999:884) found significant improvements in speech recognition for many of their participants with a hearing loss, but this was not confirmed in a similar study by McDermott and Dean (2000:359), who found that proportional frequency compression did not improve the speech perception of adults with sloping, high frequency hearing losses. In another study, Simpson, Hersbach and McDermott (2005:289) found that this type of frequency lowering improves the recognition of monosyllabic words but again this was not confirmed as a later study found no significant benefit when proportional frequency compression was used to assess speech recognition (Simpson, Hersbach & McDermott, 2006:629).

Linear frequency transposition studies have also produced mixed results. Rees and Velmans (1993:58) found that children demonstrated a marked benefit from linear frequency transposition but Robinson, Baer and Moore (2007:305) found that although this frequency lowering strategy increased the recognition of affricates and fricatives in adults, in some cases it was at the expense of other speech sounds. A more recent development of linear frequency transposition did however demonstrate improved recognition of high frequency sounds (Kuk *et al.*, 2006:45) and resulted in better perception of consonants (Kuk *et al.*, 2007:63).

Non-linear frequency compression is a recent frequency lowering scheme that has shown some promising speech related results for adults and children with a severe to profound hearing loss. With the use of this frequency lowering strategy, significant improvement in at least one speech recognition task was obtained, as well as improvement in the production of high frequency speech sounds (Bagatto *et al.*, 2008: par. 7). Currently more studies are in progress to validate the efficacy of this technology. This information will be discussed in more detail in Chapter 3.

When comparing the different approaches, large differences in manner of implementation resulting in differences in sound quality and potential speech understanding benefit are apparent and should be considered when evaluating the reported results. It is however evident from the above that most research on frequency lowering strategies focused on improvements in speech intelligibility, without any mentioning of the potential influence of these strategies on music

perception (Scollie, Glista, Bagatto & Seewald, 2008:8) – and this while an integral part of people’s daily lives entails listening to music and other non-speech sounds.

Music can be defined as humanly organized sound, formed intentionally, into a recognizable aesthetic entity directed from a maker to a known or unforeseen listener, publicly through the medium of a performer, or privately by a performer as listener (Godt, 2005:84). While enjoyment is certainly one of its main purposes, music also serves as a medium that models social structures and facilitates the acquisition of social competence by young people (Cross, 2006:80). Music can legitimately be regarded as part of the same human communicative toolkit as language when viewed from the perspective of pragmatics. Its semantic indeterminacy, together with its capacities to entertain, provides a potent medium for human interaction (Cross, 2006:80) as music is often inseparably associated with some event, activity, or behaviour (Godt, 2005:83). With this taken into account, the majority of people wearing hearing aids complain of the reduced sound quality of music heard through their personal amplification (Chasin, 2003b:36). This may be due to the fact that most hearing aids are designed with the focus on hearing speech sounds and not music; this is problematic since there are various major differences between music and speech. These differences are presented and discussed in Table 1-2.

Table 1-2: Differences between music and speech

MUSIC	SPEECH
<p>Origin Music can be generated by a wide range of instruments and varies dramatically depending on playing style, type of music, and number of musical instruments (Chasin, 2004:10).</p>	<p>Speech comes from a human sound generator that is remarkably similar from person to person (Chasin, 2005: par. 6). As it is produced by the human vocal tract it is generated by a limited number of articulators including the nose, tongue position, and lip configuration.</p>
<p>Loudness Music is louder than speech (Chasin & Schmidt, 2009:32). Depending on the music played or listened to, various musical instruments can generate sounds from very soft (20-30 dB SPL) to loud (Chasin 2007: par. 3). Even quiet instrumental music can be in excess of 90 dB SPL with sustained levels of higher than 105 dB SPL. This is true for both classical and popular forms of music (Chasin & Schmidt, 2009: 32). The dynamic range of music as an input to a hearing aid is therefore in the order of 100 dB (Chasin 2010:27).</p>	<p>Because all speech derives from the human tract, meaning similar human lungs imparting similar sub-glottal pressures to drive the chords, the potential intensity range is well defined and also quite restricted to approximately 30-35 dB (Chasin, 2007: par. 3). The most intense components of speech are the low back vowels e.g. [a] as in father. At the level of the listener's ear these sounds, even when shouted, rarely exceed 85 dB SPL (Chasin, 2003b:36). Speech at average conversational levels is typically in the 65-70 dB SPL range with intense components ranging up to the 85 dB SPL (Chasin 2010:27). Loud speech or screaming can be slightly more intense but typically only in the lower frequency regions. The dynamic range of speech as an input to a hearing aid is therefore in the order of 30-35 dB (Chasin, 2007: par. 3).</p>
<p>Variability Music, in contrast to speech, is usually more intense, highly variable and contains very quick changes from soft to loud (Chasin & Russo, 2004:36: Chasin, 2003a: par. 18). Unlike speech which is usually 'loud-soft-loud....' because loud vowels are frequently followed by soft consonants, followed by louder vowels, music is not predictable (Chasin, 2005: par. 7). Music can derive from many sources such as the vocal tract, various music instruments and also any number of musical instruments (Chasin, 2007: par. 2). Any of these sources can be amplified or un-amplified. Even if un-amplified, the music may be low or high in intensity, depending on the musical instruments included (Chasin, 2007: par. 2). There is simply no music 'target' when programming hearing aids as there is for amplified speech (Chasin, 2007: par. 2).</p>	<p>Speech is relatively well defined with well established and predictable perceptual characteristics – most of its loudness comes from the low pitched vowels and most of the speech clarity comes from the higher pitched consonant sounds (Chasin & Russo, 2004:36).</p>
<p>Crest factor A crest factor refers to the difference between the average level of a sound and the peak sound. Music, which is usually generated by hard-walled, minimally damped instruments, has a crest factor of 18-20 dB (Chasin, 2004:10). This has implications for setting the compression circuit as music may cause compression systems to enter the non-linear phase at a lower intensity than would be appropriate for the individual (Chasin, 2007: par. 4).</p>	<p>Since speech is generated by the vocal tract, the output spectrum is highly damped (Chasin, 2004:10). Before a spoken word is heard, the vocal energy passes by the soft tongue, soft cheeks and lips and a nasal cavity full of soft tissue. The soft tissue dampens the sound to such a degree that the peaks are generally only 12 dB more intense than the average intensity of speech (Chasin 2007: par. 4). For a given hearing loss, a musical input would require less gain in order to have the same output as a typically less intense speech input (Chasin, 2003a: par. 15). The crest factor for speech is about 12 dB.</p>

MUSIC	SPEECH
<p>Important frequency region</p> <p>Although the highest orchestral pitches may reach 4 kHz-5 kHz, the majority of music pitches exist in the lower half of the auditory spectrum, with corresponding fundamental frequencies at approximately 1 kHz and below (Revit, 2009:14). For example, 63 of the notes of an 88-key piano keyboard have pitches with fundamental frequencies below 1 kHz. In the human singing voice, almost all of the pitches have fundamental frequencies below 1 kHz. The highest pitch, designated 'soprano' (C6), has a corresponding fundamental frequency of 1046.5 Hz (Revit, 2009:14). At the low-pitch end, the lowest normal note of a guitar has a fundamental frequency of 82.4 Hz. For these low notes the pitch is perceived even if the fundamental is missing. However, the fundamental is often important for hearing the balance of one note against another, as well as for hearing the natural warmth and fullness of low-pitch notes (Revit, 2009:14). The higher frequencies are of course also important for music (Revit, 2009:14). The sustained notes and percussion of music may be considered correlates of the vowels and consonants of speech. With speech, vocal tract resonances (formants), which occur at frequencies well above the fundamental frequency (pitch) of a voice, help the listener to distinguish one vowel from another. Similarly, resonances occurring above the fundamental frequency of musical notes help the listener to distinguish the sound of one instrument from another (Revit, 2009:14). In speech, the frequencies of the formant resonances are determined largely by manipulations of the volumes of air in the supra-glottal vocal tract. In musical instruments, the resonances are usually determined by fixed geometric properties of the instrument (e.g. tubing and pipe lengths), creating emphasis at one or several of the upper harmonics of a given note (Revit, 2009:14). Generally, the highest important vowel formant, F3, can be centred as high as about 3 kHz. Instrumental harmonic resonances may occur in that same range, but they often extend much higher. For example, the violin (which is very rich in harmonics), often has significant harmonics above 5 kHz (Revit, 2009:14). Most of the pitches of musical notes fall at or below 1 kHz and therefore sufficient adjustability should be available for fine tuning, essentially balancing those pitches. Also, as instrumental resonances occur at higher frequencies, fine tuning may also be required for smooth responses in the upper frequencies.</p>	<p>The most important spectral range is above 1 kHz, meaning essentially that the frequencies at or above 1 kHz contributes the highest percentage of the importance of a speech signal for intelligibility (Revit 2009: 12). Therefore, it's not uncommon that the main focus of hearing aid fitting programs is given to fine-tuning the frequency response at or above 1 kHz (Revit, 2009:12).</p>

Table 1-2 above addresses the differences between music and speech as stimuli to hearing aids. There are however, also shared phenomena in the processing of speech and music. The best example of such commonalities is perhaps that both require a broad bandwidth and the smoothest response possible, given the constraints of modern technology. This not only helps to improve sound quality, but optimizes the transient response to such an extent that amplified music will be a better replication of the original input (Chasin, 2006:22). It is however evident that a hearing aid which performs well with speech signals may not perform well with music, the reason being that musical signals are much more variable than speech and our perception of music is more sensitive to distortion (Ryan, 2009:38; Chasin, 2005: par. 7). It is important to understand the

differences between music and speech in order to understand the programming of internal algorithm changes necessary for music as an input to a hearing aid (Chasin, 2005: par. 6).

Guidelines have been provided for the optimal hearing aid for music lovers and include (Chasin, 2006:22; Chasin & Russo, 2004:45; Chasin 2004:16; Chasin, 2003b:41):

- A high input-limiting level of at least 105 dB SPL
- Wide dynamic range compression (WDRC) to prevent the compression circuit from entering its non-linear phase prematurely (Chasin, 2003b:40) with a higher threshold knee-point (TK) than prescribed for speech. Compression characteristics for speech are set based on the crest factor of speech which is around 12 dB (Chasin, 2007: par. 13). For speech, wide dynamic range compression systems function to limit overly intense outputs and to ensure that soft sounds are heard as soft sounds, medium sounds as medium sounds, and intense sounds as intense sounds (but not too intense). In short, these systems take the dynamic range of speech (30-35dB) and alter it to correspond with the dynamic range of the person with a hearing loss. The dynamic range of music is typically 50 to 70 dB greater than that of speech. Having said this, it turns out that, clinically, no major changes need to be made since the more intense components of music are just in a different part of the input-output curve of the compression function (Chasin 2007: par. 13). The difference lies in whether the compression system uses a peak detector. If the hearing aid utilizes a peak detector to activate the compression circuit, the knee-point should be set about 5-8 dB higher for a music program than for speech; this is related to the larger crest factor of music (Chasin 2007: par. 13).
- A single channel system (or multi-channel system in which each channel has similar compression ratios). The rationale behind a single channel is that in music, unlike speech, the balance between the lower frequency fundamental energy and the higher frequency harmonic energy is crucial for the perception of optimal sound quality (Chasin, 2003b:40). Therefore it is necessary to use a single-channel hearing aid that maintains this balance. In sharp contrast to hearing speech, one channel, or many channels with the same compression ratios and knee-points, appears to be the appropriate choice for listening to music (Chasin 2007, par. 12). Unlike speech, the relative balance between the lower-frequency fundamental energy and the higher-frequency harmonics is crucial for most types of music. High-fidelity music is related to

many parameters, one of which is the audibility of the higher frequency harmonics at the correct amplitude. Poor fidelity can result from the intensity of these harmonics being too low or too high. A multi-channel hearing aid that uses differing knee-points and degrees of compression for various channels runs the distinct risk of severely altering this important low-frequency (fundamental)/high frequency (harmonic) balance. Subsequently, a 'music program' within a hearing aid should be one channel or equivalently, a multi-channel system where all compression parameters are set in a similar fashion (Chasin 2007: par. 12).

- Omni-directional settings. In most cases, there is fairly good signal-to-noise ratio for the music versus noise, so reducing noise with directional microphones are not compensated in such a manner that there is a significant low-frequency loss of transduced sound. While this may be beneficial for speech in some environments, it unnecessarily removes valuable musical information.
- Less low-frequency amplification for bass instruments such as the cello. Phonetic versus phonemic perceptual requirements refers to the difference between what is actually heard – the physical vibrations in the air (phonetic) as opposed to the perceptual needs or requirements of the individual (phonemic) (Chasin 2007: par. 5). For speech, despite the fact that for all languages of the world, the long-term speech spectrum contains most of its energy in the lower-frequency region and less in the higher frequency region (its phonetic manifestation); the clarity derives from the mid- and high frequency regions. This mismatch between energy (phonetic) and clarity (phonemic) is complex (Chasin 2007: par. 5). In contrast to speech, some musicians need to hear the lower-frequency sounds more than others, regardless of the output (phonetics) of the instrument (Chasin 2007: par. 6). A clarinet player, for example, is typically satisfied with the tone only if the lower frequency inter-resonant breathiness is at a certain level, despite the fact that the clarinet can generate significant amounts of high-frequency energy. This is in sharp contrast to a violin player who needs to hear the magnitude of the higher frequency harmonics before he/she can judge the sound to be good. The clarinet and violin both have similar energy spectra (phonetics) but dramatically differing uses of the sound (phonemics) (Chasin 2007: par. 6).
- Disabled or minimized noise reduction and feedback management systems as some hearing systems can confuse music with noise and/or feedback and will therefore reduce its intensity. In most cases, since spectral intensity is greater for music than for speech, feedback is not an

issue and therefore, if at all possible, disabling any feedback reduction system would be the optimal approach for listening to or playing music (Chasin, 2007: par. 15). As with feedback-reduction systems, it would be best to disable the noise reduction system when listening to music. Typically, the signal-to-noise ratio is quite favourable making noise reduction unnecessary (Chasin 2007: par. 16). However, for some hearing aids, the noise reduction system cannot be disabled; since the primary benefit of noise reduction systems seems to be in improving listening comfort rather than reducing noise, choosing an approach for music that has a minimal noise-reducing effect may be beneficial for a music program (Chasin 2007: par. 16).

Historically, the primary concern for hearing aid design and fitting was optimization for speech input (Chasin & Russo, 2004:35). However, other types of inputs are now increasingly being investigated, especially music as input signal to a hearing aid. Not only is the technology for music input still in its infancy, but the research and clinical knowledge and understanding of what musicians and music lovers need to hear is also still in its early stages (Chasin & Russo, 2004:35). Many manufacturers do state that the music program of their digital hearing aid should be as simple as possible, without any of the features available for speech input programs. This may or may not be the case for music and, more research is clearly required in this area (Chasin & Russo, 2004:45).

1.3 PROBLEM STATEMENT AND RESEARCH QUESTION

All of the above-mentioned studies focused on speech as input stimuli for non-linear frequency compression hearing aids and there is no indication of how non-linear frequency compression will influence the perception of music (Scollie *et al.*, 2008:8). Most people with a hearing loss express a need to hear speech optimally, but increasing numbers of people with hearing problems are expressing an equal need for their hearing aids to be fitted optimally for listening to music (Chasin 2005, par. 10; Chasin, 2004:10).

While hearing aids have improved dramatically, they are not yet perfect (Chasin, 2008: par. 1). Various approaches have been followed by the hearing aid industry to optimize a hearing aid or a

program within a hearing aid for music. Some manufacturers have sought to reduce the low frequency amplification and output, others have tried to increase the gain and output (Chasin, 2003b:36). Still others have employed a strategy of increasing mid-frequency gain and output to optimize the long term spectrum of music. These approaches have met with only limited clinical success (Chasin, 2003b:36) and therefore a vast opportunity exists for evaluating music listening with non-linear frequency compression technology.

Due to the complex nature of music, amplification of musical stimuli poses a challenge to audiologists. Studies of frequency lowering hearing aids and music seem to be very limited, but non-linear frequency compression may be beneficial for adults who love to listen to music. Stelmachowicz (2001:174) stresses that a distinction should be made between a decrease in performance and a failure to observe an improvement when working with persons with a hearing loss. Non-linear frequency compression may not provide much benefit for the perception of music or may improve the quality of music for hearing aid users. Therefore, the need exists for research data on non-linear frequency compression technology and music perception. Thus, in light of the discussion above, the following question arises:

Does non-linear frequency compression affect the perception of music by adults presenting with a moderate to severe hearing loss, and if so, in which way?

As can be seen from the above, music is highly complex and therefore music perception with hearing aids is difficult to assess. Furthermore, no standard test of music perception exists (Wessel, Fitz, Battenberg, Schmeder & Edwards, 2007:1) and the few music perception tests that are commercially available are advanced and designed to examine the skills of individuals with formal musical training (Don, Schellenberg & Rourke, 1999:158). Therefore, in order for the current research to answer the above-mentioned question, a music perception test for the assessment of music perception in adult hearing aid wearers had to be compiled.

In order to address the research question comprehensively, a research project was implemented that consisted of a theoretical as well as an empirical component. The basic structure of this research project is provided in section 1.6.

1.4 CLARIFICATION OF TERMINOLOGY

Short clarifications are provided for some of the audiological and medical terms that are referred in the research project. These terms are presented in alphabetical sequence:

- **Adult:** An adult is a fully developed and mature person (Collins, 1989:14). Legally, an adult is considered as a person who by virtue of attaining a certain age, generally eighteen, is able to manage his or her own affairs (Brink, 1997:520). The age specified by the law, the 'legal age of majority', indicates that a person acquired full legal capacity to be bound by various contracts/documents that he or she enters into with others and to commit to legal acts such as voting in elections and entering marriage. For the purpose of this study, the age of eighteen was accepted as the entering age into adulthood and therefore no persons under the age of eighteen participated in this study.
- **Amusia:** The inability to recognize musical tones or rhythms or to reproduce those (Cooper, Tobey & Loizou, 2008:618).
- **Auditory cortex:** Auditory area of the cerebral cortex located on the transverse temporal gyrus (Heschl's gyrus) of the temporal lobe (Stach, 2003:30).
- **Auditory fusion:** Refers to the size of the temporal interval between two events that is required for them to be perceived as two separate events rather than fused as one. Thus, auditory fusion thresholds represent a psychophysical indicator of temporal resolving power for central sensory information processing (Rammsayer & Altenmuller, 2006:38).
- **Bandwidth:** Refers to the range of frequencies (lower to upper) being processed by a communication channel, but often used loosely to describe the upper frequency of the signal of interest, assuming that the lower frequency is negligibly small. Widening the bandwidth means increasing the frequency range, and thereby enabling more information to be delivered through the channel (McDermott, Baldwin & Nyffeler, 2010:34). Even though the normal young ear has an upper frequency limit of hearing of about 20 kHz, digital hearing aid amplifiers are generally limited by designers to a bandwidth of about 8 kHz in order to prevent aliasing (Agnew, 2000:40).
- **Characteristic frequency:** The frequency to which an auditory nerve fibre is most sensitive (Preminger, Carpenter & Ziegler, 2005:601).

- **Cochlear dead regions:** An area in the cochlea where inner hair cells are non-functioning, preventing transduction of sound in that region (Moore, 2001b:153).
- **Cochlear nucleus of brainstem:** A collection of neuron cell bodies in the lower brain stem (pons) that synapses with fibres from the auditory (VIII) cranial nerve leading from the cochlea (Mueller & Hall, 1998: 914).
- **Compression knee-point:** The minimum input decibel level at which compression circuitry is activated in a hearing aid, also known as compression threshold (Stach, 2003:64).
- **Compression ratio:** The decibel ratio of acoustic input to amplifier output in a hearing aid (Stach, 2003:64). In the case of non-linear frequency compression technology this refers to the amount of compression applied to frequencies above the cut-off frequency (McDermott, 2010:3).
- **Cut-off frequency:** In the case of non-linear frequency compression this refers to the point above which the frequency compression and lowering is applied (McDermott, 2010:3).
- **Decibel (dB):** One tenth of a bel that represents the unit of sound intensity on a logarithmic scale (Brink, 1997:94).
- **Decibel hearing level (dB HL):** A decibel scale referenced to accepted standards for normal hearing (0 dB is average normal hearing for each audiometric test frequency) (Mueller & Hall, 1998:918).
- **Decibel sound pressure level (dB SPL):** A decibel scale referenced to a physical standard for intensity (Mueller & Hall, 1998:918).
- **DPOAE:** Distortion product oto-acoustic emissions are responses generated when the cochlea is stimulated simultaneously by two pure tone frequencies of which the ratio is between 1.1 to 1.3 (Plante & Beeson, 1999:38).
- **Dynamic range:** Difference in decibel (dB) between hearing threshold and discomfort level (Mueller & Hall, 1998:922).
- **Frequency:** The number of cycles occurring per unit of time, or which would occur per unit of time if all subsequent cycles were identical with the cycle under consideration, is the frequency. The frequency is the reciprocal of the period. The unit is the Hertz (Hz) or cycle per second (cps) (Mueller & Hall, 1998:926).
- **Frequency compression:** In terms of acoustics, compression is defined as a portion of the sound-wave cycle in which particles of the transmission medium are compacted. In hearing

aid circuitry it refers to nonlinear amplifier gain used either to limit maximum output (compression limiting) or to match amplifier gain to an individual's loudness growth (dynamic-range compression) (Stach, 2003:62), but is also used in frequency compression hearing aids. A frequency compression hearing aid is a hearing device that is designed to compress higher frequency energy into lower frequency amplification, especially for use in patients with dead regions at high frequencies (Nyffeler, 2008b:22). By compressing and lowering otherwise inaudible high frequencies into an adjacent lower frequency area, the audible range is extended.

- **Frequency lowering:** A general term that refers to signal processing that lowers high frequency sounds to lower frequencies (Ross, 2005: par. 5).
- **Frequency transposition:** A hearing aid with frequency transposition shifts the signal down the frequency axis by a fixed number (Bagatto *et al.*, 2008: par. 3), also known as linear frequency transposition (Kuk *et al.*, 2006).
- **Frontal lobe:** Frontal refers to the anterior part of an organ or the body. The frontal lobe is the part of the brain before the central fissure and above the horizontal part of the lateral fissure (Brink, 1997:163).
- **Fundamental frequency:** The lowest component frequency of a periodic wave or quantity (Mueller & Hall, 1998:927).
- **Heschl's gyrus:** The areas of auditory reception are in the temporal lobes on both sides of the cerebral cortex in an area called Heschl's gyrus or also known as the superior temporal gyrus. It is the convolution of the temporal lobe believed to be the seat of language comprehension of the auditory system (Martin & Clark, 2000:365).
- **Insertion gain:** The difference in SPL produced by the hearing aid at a point in the ear canal and the SPL at the same point in the ear canal without the hearing aid. The difference between the two recordings (an un-instrumented equalization reference and an instrumented frequency response) is called the hearing aid insertion gain (Mueller & Hall, 1998:932).
- **Limbic system:** Complex system of brain nuclei and connections, including the hippocampus, amagdala, and fornicate gyrus, responsible for influencing endocrine and autonomic motor systems, affecting motivational and mood states (Stach, 2003:155).
- **Motor areas:** The part of the cerebral cortex that is involved with the central regulation of voluntary movement (Brink: 1997:312).

- **Musical scale:** A series of notes (symbols, sensations, or stimuli) arranged from low to high by a specified scheme of intervals, suitable for musical purposes (Mueller & Hall, 1998:941).
- **Music perception:** Music is defined as sounds that are put together in a pattern and performed by people who are singing or playing instruments (Collins, 1989:514) while perception refers to the recognition of physical phenomena by using one's senses (Collins, 1989:581). Music perception therefore refers to the recognition of music by using the hearing sense.
- **Non-linear frequency compression:** In hearing aid terminology non-linear refers to a hearing aid with overall gain and/or frequency-response change as a function of changing input signals (Mueller & Hall, 1998:943), therefore amplification of which the gain is not the same for all input levels (Stach, 2003:187). Non-linear frequency compression hearing aids therefore make use of non-linear amplification but are also equipped with a frequency compression algorithm to compress and shift otherwise inaudibly high frequencies into an adjacent lower frequency area and by doing this extend the audible range of hearing.
- **Octave:** The interval between two sounds having a basic frequency ratio of two, or, the pitch interval between two tones which is of such a nature that one tone may be regarded as duplicating the basic musical import of the other tone at the nearest possible higher pitch. One octave is equal to 1200 musical cents (Mueller & Hall, 1998:944).
- **Peak input-limiting level:** This refers to the most intense sound that can enter a hearing aid, and is typically implemented as a limiter immediately after the microphone at the 'front-end' of the hearing aid (Chasin 2006:22).
- **Perceptual smearing:** For normal hearing individuals, spectral selectivity derives from the different frequency components of the acoustic stimulus being separated into different auditory filters, with each component resulting in activity at discrete sites along the basilar membrane (Looi, McDermott, McKay & Hickson, 2008b:431). For hearing aid users, the auditory filters are broadened due to cochlear hearing loss with the perceptual consequence that the frequency selectivity is reduced and therefore smearing of the different frequency components occur (MacDonald, Pichora-Fuller & Schneider, 2010:1).
- **Pitch:** The subjective impression of the highness or lowness of a sound. The psychological correlate of frequency (Martin & Clark, 2000:66).
- **Planum temporale:** Temporal surface/side (Brink, 1997:383).

- **Primary auditory cortex:** The auditory cortical region, located on the superior plane and insula of the superior gyrus of the temporal lobe, which initially receives information from lower parts of the brain, such as the thalamus and brain stem.
- **Probe microphone:** A tiny microphone, often attached to a soft, small tube, placed within the external ear canal to measure sound intensity level near the eardrum. The probe microphone is connected to equipment for recording characteristics of sound (Mueller & Hall, 1998:950).
- **Recruitment:** A term commonly used in referring to abnormally rapid growth in loudness. A large increase in the perceived loudness of a signal produced by relatively small increases in intensity above threshold, symptomatic of some hearing losses produced by damage to the inner ear (Mueller & Hall, 1998:953).
- **Rhythm:** A regular movement or beat or a regular pattern of changes (Collins, 1989:683).
- **Severe hearing loss:** Mueller & Hall (1998:929) define a hearing loss as a problem with hearing that is characterized by decreased sensitivity to sound in comparison to normal hearing. A severe hearing loss refers to a loss of hearing sensitivity of 60 dB HL to 90 dB HL (Stach, 2003:240).
- **Sloping (configuration):** A term used in describing the configuration of a pure-tone audiogram, that is, how hearing loss varies as a function of test frequency. A sloping configuration shows progressively greater hearing loss for higher test frequencies (Mueller & Hall, 1998:959).
- **Speech perception:** Speech processing through sound detection, speech sound discrimination, word recognition and comprehension (Thibodeau, 2000:282).
- **Threshold knee-point (TK):** Also known as compression threshold. Knee-point in hearing aids refers to the intensity level at which compression is activated (Stach, 2003:147).
- **Timbre:** Characteristic feature of a sound or pitch (Brink, 1997:486). Attribute of auditory sensation in which a subject can judge that two sounds similarly presented and having the same loudness and pitch are dissimilar (Mueller & Hall, 1998: 965).
- **Tonal music:** Music composed of musical elements (e.g. tones and chords), which are arranged in a specific order. The selection and ordering of these elements result in the induction of a key, where music elements are associated with certain tonal functions. Tonal

functions are evoked by a sequence through its implied or accompanying harmony and are associated with varying levels of perceptual stability (Van Egmond & Boswijk, 2007:31).

- **Vent:** An opening (e.g. 1 mm or 2 mm diameter) coursing from the lateral face to the medial tip of an ear mould or hearing aid; used for pressure equalization and sound transmission.
- **Wide dynamic range compression (WDRC):** Hearing aid compression that is activated throughout most of the dynamic range, typically resulting in greatest gain for soft sounds and least gain for loud sounds (Stach, 2003:64)

1.5 ABBREVIATIONS

The text of this study contains discipline specific abbreviations. The following list of abbreviations and their meanings is provided:

Abbreviation/Acronyms	Full form
AMICI	Appreciation of Music in Cochlear Implantees Test
ANOVA	Analysis of variance
ASHA	American Speech Language and Hearing Association
dB	Decibel
dB HL	Decibel hearing level
dB SPL	Decibel sound pressure level
BTE	Behind-the-ear
CAMP	Clinical Assessment of Music Perception Test
CAT	Computerized-Adaptive Tests
CI	Cochlear implant/implantees
cm ³	cubic centimetre
daPa	deka Pascal
DPOAE	Distortion product oto-acoustic emission
DSL	Desired Sensation Level Method
dSC	Digital Super Compression

dWDRC	Digital Wide dynamic range compression
EBP	Evidence-based practice
HPCSA	Health Professions Council of South Africa
Hz	Hertz
kHz	Kilo Hertz
km/h	Kilometre per hour
MBEA	Montreal Battery for Evaluation of Amusia
MERT	Musical Excerpt Recognition Test
MPO	Maximum Power Output
MPT	Music Perception Test
ms	Millisecond
NAL	National Acoustics Laboratories Method
NDoH	National Department of Health
NFC	Non-linear frequency compression
OAE	Oto-acoustic emission
Par.	Paragraph
PMMA	Primary Measures of Music Audiation Test
PTA	Pure tone average
PTC	Psychophysical Tuning Curves
REM	Real-ear measurements
REAR	Real-ear aided response
REUR	Real-ear unaided response
SABS	South African Bureau of Standards
SAMA	South African Music Awards
SAT	Self-Adapted tests
SPL	Sound pressure level
TEN test	Threshold Equalizing Noise Test
TK	Threshold Knee-point
UP	Ultra Power
WDRC	Wide Dynamic Range Compression
WHO	World Health Organization

1.6 OVERVIEW OF CHAPTERS

This section entails a brief description of the chapters included in the current study.

- **Chapter 1: Orientation and problem statement**

This chapter provides an overview of the importance of knowledge regarding hearing loss as the initial step to appropriate service delivery. The high prevalence of hearing disorders as well as difficulties associated with a hearing loss is highlighted. Lastly, cochlear dead regions as well as hearing aid processing of speech and music stimuli are discussed. Through the above, the aim of the study, namely to determine the influence of non-linear frequency compression on music perception, is emphasized. The chapter concludes with definitions of terms as well as clarification of abbreviations and acronyms used throughout the study.

- **Chapter 2: Music perception**

The importance of suitable adjustments on hearing aids for musical stimuli is discussed and the researcher provides a summary of music perception. Furthermore, the researcher motivates the compilation of the music perception test that was designed for use in this study and presents an overview of the said test.

- **Chapter 3: Non-linear frequency compression in hearing aids**

In Chapter 3 detailed information regarding frequency lowering and specifically non-linear frequency compression is provided and placed within the context of evidence-based principles. Through this information the importance of appropriate hearing aid fittings as strategy for the improvement of the quality of life of persons with a hearing loss are emphasized.

- **Chapter 4: Method**

This chapter describes the operational framework that is implemented for the conduction of the empirical research. The framework dictates the scientific process that is implemented to determine the influence of non-linear frequency compression on music perception by stating the aims of the research and explaining the research design. Furthermore, selection of participants, as well as data collection and research procedures are described. A detailed account of the ethical considerations is also provided.

- **Chapter 5: Results**

In Chapter 5 the results that were processed by means of statistical analysis are presented.

- **Chapter 6: Discussion of results**

Results are discussed in accordance with the sub-aims presented in Chapter 4. After presentation of the results pertaining to each sub-aim its significance, meaning and implications are discussed with reference to the relevant literature.

- **Chapter 7: Conclusion and recommendations**

Chapter 7 presents a conclusion based on the findings and provides a framework of the value of the results and how they may contribute to current knowledge. The study is critically evaluated and recommendations for future research are made.

1.7 CONCLUSION

Satisfactory enjoyment of music depends primarily on the audibility of musical sounds for the person with a hearing loss. Conventional hearing aids are often unable to provide adults with a hearing loss with sufficient musical information in order to enjoy music. This may lead to numerous frustrations for music lovers. A modification of the output of hearing aids in the form

of non-linear frequency compression may improve the music perception abilities of some adults with a hearing loss. Non-linear frequency compression technology attempts to provide the listeners with better audibility of high frequency musical sounds by lowering high frequency information to lower frequencies where more residual hearing is present. This will enable music lovers to hear musical sounds that were previously missed and therefore may contribute to their enjoyment of music. Therefore, this study aims at determining whether non-linear frequency compression affects the musical perception abilities of adults presenting with a moderate to severe hearing loss, and if so, in which way.

1.8 SUMMARY

In this chapter the researcher aimed to provide relevant background information to clarify the theme of this study and to provide a holistic perspective of the importance of the rationale. Information regarding hearing loss in general and specifically a high frequency hearing loss is provided. Further information includes cochlear dead regions and an introduction to frequency lowering hearing aids. Lastly, the chapter focuses on music perception, differences between music and speech and the challenges presented to an audiologist confronted with the fitting of hearing aids for music lovers. The information in this chapter highlights a distinct need for appropriate audiological service delivery to persons fitted with hearing aids who also enjoys music, thereby emphasizing the importance of this study.