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Research Article
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The Influence of Non-Linear Frequency Compression on the Perception of Timbre and Melody by Adults with a Moderate to Severe Hearing Loss

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Abstract

Objective: To date, the main focus in frequency lowering hearing aid studies has been in relation to speech perception abilities. With improvements in hearing aid technology, interest in musical perception as a dimension that could improve hearing aid users' quality of life, however, grew. The purpose of this study was to evaluate the influence of non-linear frequency compression (NFC) on music perception with the use of a self-compiled Music Perception Test (MPT). Design & Sample: A quasi-experimental research design was implemented to fit participants (n=40) with NFC hearing aids. Test data was obtained with the hearing aids with NFC inactive and active.

Results: The use of NFC significantly improves hearing aid users' perception of timbre and melody.

Conclusion: The use of NFC can result in hearing users perceiving music more positively and does not influence music perception negatively.

Keywords: Hearing loss; Hearing aids; Non-linear frequency compression; Music perception; Timbre; Melody

Abbreviations: NFC: Non-linear Frequency Compression; MPT: Music Perception Test

Introduction

High frequency hearing loss is by far the most common audiometric configuration found in individuals fitted with hearing aids and affects speech comprehension adversely. Music and lyrics can however be difficult to detect or identify as well [1], which is problematic as music enhances the quality of a person's life. While enjoyment is certainly one of its main purposes, music also serves as a medium that models social structures and provides a medium for human interaction [2].

Some people may unknowingly present with cochlear dead regions and perceive high frequency amplification as distorted [3]. 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 [4]. Individuals with a cochlear dead region therefore may have different frequency-gain requirements than those without a dead region.

Many researchers have suggested the possibility of frequency lowering as a means of making speech sounds audible for patients with dead regions [5,6]. Therefore, various research projects had been conducted with frequency lowering hearing aids that focused on improved speech perception[1] [5,7]. An integral part of people's daily lives, however, consists of listening to music. Currently no studies have examined the influence of frequency lowering on music perception.

The majority of people wearing hearing aids complain of the reduced sound quality of music heard through their hearing aids, to such an extent that they often prefer to remove their hearing aids when listening to music [8]. This may be due to the fact that most hearing aids are designed with the focus on hearing speech and not music which is problematic as there are several differences between music and speech [9]. Furthermore, more people with a hearing loss are expressing an equal need for their hearing aids to be fitted optimally for listening to music [10].

To complicate matters more, music is highly complex [11] and therefore music perception with hearing aids is difficult to assess. This is because listening to music may give rise to a large variety of experiences that are based on individual interrelated emotional and cognitive processes in the brain [12] and numerous participative factors that influence enjoyment including personal preferences, listening environment and the listener's mood [13].

The effects of hearing aid processing on musical signals have received little attention in research, although evidence exists that the perception of fundamental aspects of Western musical signals, such as the relative consonance and dissonance[2] of different musical intervals, is significantly altered by a hearing loss [8]. The field of Audiology acknowledges the value of musical perception in quality of life [13]. Therefore, in the current consumer-driven era of health care, practitioners need to be able to demonstrate that the services they provide have a positive impact on their clients' functional status and quality of life. Currently, many service providers are unaware of the existence of frequency lowering hearing aids, while others fit these devices without proper knowledge or scientific evidence of their

[1]The study by Stuermann [7] made use of NFC which resulted in improved speech intelligibility for soft speech in quiet situations and provided significant improvement in noisy environments while the study by Bagatto et al. [5] revealed that participants' speech recognition improved significantly with the use of NFC.
[2]Musical consonance refers to a combination of notes that sound pleasant when played at the same time while musical dissonance is a combination of notes that sound harsh or unpleasant.

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efficacy. Therefore, there is a need to promote practitioners' ability to recognize the potential of promising new technologies, like non-linear frequency compression (NFC), and to apply it appropriately in order to provide accountable hearing aid fittings [14,15].

Methods

Aim

To determine the influence of NFC on the perception of timbre and melody by adults presenting with a moderate to severe, sensorineural hearing loss.

Study design

A quasi-experimental research design was implemented which involved the fitting of participants with NFC hearing aids. Test data was obtained with the hearing aids on conventional settings (NFC inactive) and with NFC active. A cross design was used to randomly assign subjects to different groups which implied that some participants were first fitted with NFC active, while for others this algorithm was first inactive. Furthermore, single blinding was used to remove any potential participant bias that could influence the results as participants did not know whether the NFC algorithm was activated or not.

Participants

A purposive convenient sampling method was implemented where participants were chosen on the basis of accessibility. The hearing aid users (n=40) met the following criteria:

- Bilateral, moderate to severe sensorineural hearing loss, with a pure tone average of 41-90 dB HL at the frequencies 500 Hz, 1000 Hz and 2000 Hz.
- Normal middle ear function, determined via tympanometry.
- Acquired hearing loss.
- Currently wearing bilateral digital hearing aids. Not used frequency lowering devices before.
- Be between the ages of 18 years and 64 years.
- English language proficiency and literacy.
- No musical background or experience level was required.

The average age of participants was 57.7 years (ranging from 18 to 64 years). Forty percent of the participants (n=16) received musical training ranging from one to 20 years.

Material and apparatus

The timbre and melody sections of the Music Perception Test (MPT) were used as assessment material. The MPT are described in detail in Uys and Van Dijk [16].

The prototype hearing aids that were used were Phonak Naida III Ultra Power behind-the-ear hearing aids. These hearing aids are digital and provide non-linear amplification in the form of multi-band compression. Furthermore, the hearing aid has an 80 dB of peak gain and 141 dB maximum output [16].

Procedure

Participants completed three visits. During the first visit they underwent a hearing evaluation to determine candidacy. This included otoscopic examination, immittance testing, oto-acoustic emissions, pure tone and speech audiometry. Prior to fitting the prototype hearing aids, participants' current hearing aids were verified with real-ear measurements to ensure that they were optimized to reflect the current best practice [17]. Real-ear measures were also performed to ensure accurate comparisons were made between the different technologies in order to ensure that positive changes could be contributed to NFC and not to optimization of the current hearing aids. If a participant's current hearing aids were not well fitted, extra time was provided to adjust to the optimized fitting without NFC and the study commenced after three weeks.

The prototype hearing aids were fitted with the Audioscan Verifit to accurately match the prescribed adult targets provided by the Desired Sensation Level 5.0 (DSL) algorithm. For listening to music, all automatic sound features such as noise reduction and adaptive directionality were turned off to prevent these systems from interpreting the music as noise or feedback [18]. Fine tuning adjustments were made according to the participant's preferences. There are two adjustable parameters of frequency compression that are programmable namely the cut-off frequency which determines the start of the upper band and secondly, the compression ratio, which determines the amount of frequency compression applied to the upper band. The cut-off frequency and compression ratio were determined on an individual basis using the Phonak fitting software [5] default setting and was only changed if participants had complaints about the sound quality.

Participants had to wear the hearing aids for four weeks after which they returned to the clinic. Four weeks were allocated for acclimatization because research with NFC indicates that benefits are best achieved with an acclimatization period of at least four weeks [7].

During the second visit the timbre and melody sections of the MPT was performed with the hearing aid on its original settings. For testing, participants were seated in an audiometric booth, facing the loudspeaker at 45 degrees, at a distance of approximately one meter. The stimuli were played on a Sony D-FJ041 audio player and presented via a Grason-Stadler GSI 61 two channel clinical audiometer to calibrated loudspeakers. The presentation level was 75 dB HL for the calibration tone. The sound level was averaged at 75 dB SPL and participants were permitted to adjust the volume on their hearing aids for maximum comfort. Participants held an answer sheet with a set of written instructions and instructions were also presented via the loudspeakers before the onset of each sub-test. Participants then completed the sub-tests and no feedback was given. On completion, the hearing aid settings were switched – participants that had their hearing aids with NFC active now had this algorithm deactivated and vice versa. Again participants were asked to wear the hearing aids for a period of four weeks before returning to the practice. During participants' last visit, the same sub-tests were performed (now with different NFC setting than previously).

Data recording

Test scores were directly written on the answer sheet of the MPT. The answer sheets were hand scored because individual assessment was required as participants were only assessed on items familiar to them. The data from the answer sheets were coded into a Microsoft Excel worksheet.

Results

Timbre

Results included responses to items from Section B of the MPT and specifically:

Sub-test 5: Timbre identification (Single instruments) where participants were presented with melodic sequences played by the

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cello, clarinet, piano, piccolo flute, saxophone, trombone, trumpet and violin. They were required to indicate which musical instrument produced each melodic sequence.

Sub-test 5: Timbre identification (Multiple instruments) where different combinations of the same instruments used in the previous test played the same melodic piece in unison and participants were asked to identify which instruments were playing together in each melodic sequence.

Sub-test 6: Number of instruments task which determined how many different instruments participants could distinguish in a short musical piece. They were presented with a cello, piccolo flute, snare drum, trumpet and xylophone which were selected to have timbres as different as possible. Participants did not have to name the instruments but only identify the number of instruments they heard in each melodic sequence.

Participants were asked to first indicate their familiarity with each of the instruments included in Sub-test 5 as they were only evaluated on the instruments with which they were familiar. The familiarity ratings of the musical instruments are displayed in Figure 1.

After participants indicated their familiarity with the instruments, they were asked to complete the timbre sub-tests. The scores for the three sub-tests were combined to determine whether there was an overall difference in participants' performance on timbre with NFC as displayed in Figure 2.

In total, 65% of the participants' (n=26) scores increased with the activation of NFC. Differences in scores were highly variable and no pattern could be established. Table 1 provides a summary of the statistical values for the perception of timbre and melody.

Melody

Results included responses to Section D of the MPT which consisted of:

Sub-test 9: Musicality perception where participants were presented with pairs of short melodic sequences. Some of the melodies in the pairs were random notes, making no musical sense, while others were musical pieces with a clear melodic structure. Participants had to indicate which of the melodic sequences were musical.

Sub-test10: Melody identification in which participants were requested to identify ten well-known melodies with and without rhythm cues.

Sub-test 11: Music-in-noise song identification in which participants were requested to identify famous movie soundtracks. The soundtracks were presented in the presence of background noise.

To ensure that it was identification abilities being assessed and not musical knowledge, participants' familiarity with the melodies was verified before testing [19]. Participants were given an alphabetical list of the melodies and were instructed to mark all the melodies that were familiar to them. The final score was reported as a percentage of correct responses on the melodies with which the listener was familiar. Those items missed on the test were cross checked with the list completed before hand. If an item was missed, and it was not listed as familiar, that item was eliminated from the analysis. To establish what the effect of NFC on melody perception was, the scores for the three melody sub-tests were calculated together and are summarized in Figure 3.

In total, 62.5% of the participants (n=25) had an increase in their score with the activation of NFC. Again results were characterized by high rates of variability as can be seen by the statistical data in Table 1.

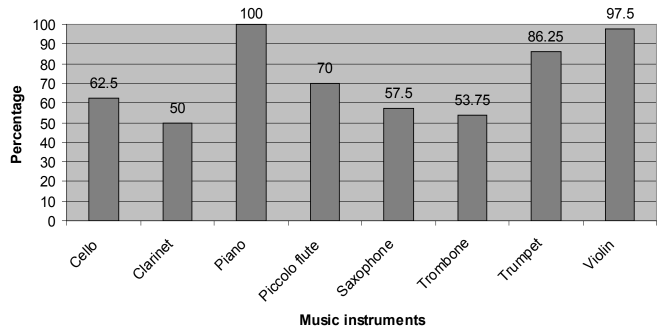

Figure 1: Participants familiarity with the musical instruments included in Sub-test 5 of the MPT (n=40).

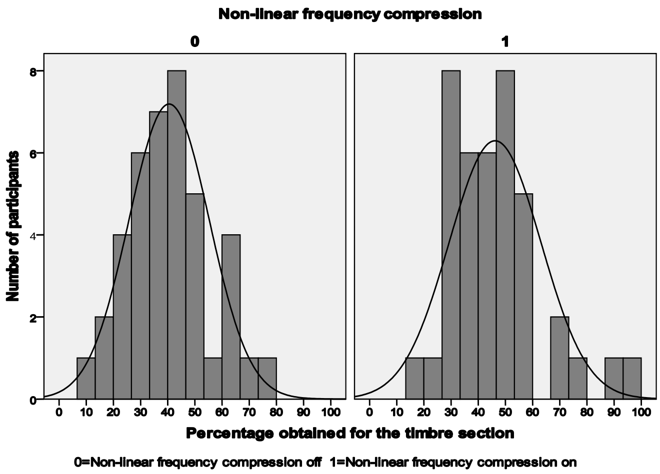

Figure 2: Participants' score for timbre with NFC off versus NFC on (n=40).

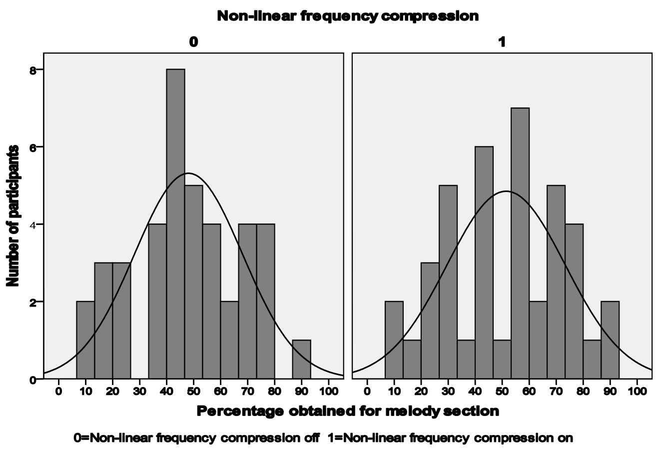

Figure 3: Participants' score for melody with NFC off versus NFC on (n=40).

TIMBRE		NFC OFF	NFC ON	MELODY		NFC OFF	NFC ON
Sub-test 5: Timbre identification (Single instruments)	Minimum	7.1%	31.3%	Sub-test 9: Musicality perception	Minimum	20%	10%
	Maximum	100%	100%		Maximum	90%	90%
	Mean	63.56%	67.89%		Mean	49.25%	49.25%
	Standard deviation	21.52%	20.34%		Standard deviation	20.18%	20.05%
	p-value	0.19			p-value	0.5	
Sub-test 5: Timbre identification (Multiple instruments)	Minimum	0%	0%	Sub-test 10: Melody identification	Minimum	0%	0%
	Maximum	100%	100%		Maximum	90%	100%
	Mean	17.15%	20.75%		Mean	45.76%	50.39%
	Standard deviation	19.78%	24.77%		Standard deviation	23.34%	20.86%
	p-value	0.25			p-value	0.22	
Sub-test 6: Number of instruments	Minimum	0%	0%	Sub-test 11: Music-in-noise song identification	Minimum	0%	0%
	Maximum	88%	88%		Maximum	100%	100%
	Mean	40.83%	49.95%		Mean	49.04%	54.77%
	Standard deviation	21.73%	21.65%		Standard deviation	37.59%	38.79%
	p-value	0.049*			p-value	0.28	
Timbre (Combined)	Minimum	12.3%	16.2%	Melody (Combined)	Minimum	11.4%	8.1%
	Maximum	73.8%	96%		Maximum	90%	93.3%
	Mean	40.52%	46.2%		Mean	48.09%	51.47%
	Standard deviation	14.77%	16.90%		Standard deviation	20.02%	21.94%
	p-value	0.01*			p-value	0.04*	

*Statistical significant benefit

Table 1: Statistical values for the perception of timbre and melody with NFC off versus NFC on.

Discussion

Timbre

Sub-test 5: The slight improvement in participants' score with NFC for the instrument identification tasks can be contributed to the activation of NFC which enables hearing aid users to hear more high frequency information than previously [20]. Although the majority of musical pitches exist in the lower half of the auditory spectrum, with corresponding fundamental frequencies at approximately 1 kHz and below, the perception of high frequency information is important for timbre related tasks as resonances occurring above the fundamental frequency of musical notes help the listener to distinguish the sound of one instrument from another [21]. The resonances of musical instruments are determined by fixed geometric properties of the instrument. This creates emphasis at one or several of the upper harmonics of a given note and although instrumental harmonic resonances may occur in that same range, they often extend much higher in frequency. For example the violin often has significant harmonics above 5 kHz [21]. If a participant is only able to hear the fundamental frequency of the musical notes, he/she will be able to hear the balance of one note against another, but will still have difficulty distinguishing between the sounds of instruments. Furthermore, it is well-known that tones falling into a dead region can have an abnormal timbre [4]. As it is assumed that all participants had high frequency dead regions, it implies that without NFC they would perceive the timbre of the musical instruments abnormally and therefore have increased difficulty (depending on the extent of the dead region) to correctly identify one instrument from another, resulting in decreased scores on the instrument identification tasks.

Result analysis confirmed that participants correctly identified the piano, violin, flute and trumpet most often and the trombone and clarinet least often. Confusion metrics showed that the clarinet (D4/293.7 Hz - C5/523.3 Hz), which produces a mid frequency sound, was most often confused with the flute (D7/2349 Hz - C8/4186 Hz) which produces a high frequency sound. The cello (D2/73.42 Hz - C3/130.8 Hz) was most often confused with the trombone (D1/36.71 Hz - C2/65.41 Hz) and vice versa – both of these instruments produce low frequency sounds. Participants performed significantly better at identifying single instruments than multiple instruments playing together as was also reported by Looi et al. [20] who compared this ability of cochlear implantees to that of hearing aid users.

Sub-test 6: For the number of instruments task, participants obtained statistically significant benefit with NFC on. This can again be explained by the fact that participants were able to hear more of the high frequency musical resonances with the activation of NFC as this algorithm provided them with additional high frequency information. Another aspect to consider is that when one listens to music, one groups together tones that are similar in timbre and separate out those whose timbres are substantially different [22]. Therefore when different types of instruments play in parallel one often forms groupings based on timbre, even when the tones produced by the different instruments overlap considerably in pitch. This was applicable to this task as the included instruments were selected to have timbres as different as possible. Generally, the snare drum and xylophone were more likely to be discriminated as the distinctive temporal envelopes of these instruments may have provided salient durational or rhythmical cues. Again, high error rates were seen on items with more instrument combinations.

Melody

Sub-test 9: One of the primary consequences of music's relational system is the creation of expectation in the listener based on a prior internalization of certain relational variables [23]. Most music listeners are accustomed to hearing musical notes that fit properly within the contextual musical reference, whether melodic, rhythmic, or harmonic. Corollary to the notion of musical expectancies is that of violations of musical expectancies for example, if a simple melody is played entirely within one key (e.g. G major), but the last note of the melody is out of key (e.g. G# instead of G natural), the listener detects an aberration within the melody as in Sub-test 9 of the MPT. To be able to perform this task, participants listen to differences in pitch [24]. If one considers that participants obtained basically the same score for the musicality perception task with both NFC settings and that participants had to rely on differences in pitch to perform this task, it might be assumed that NFC does not have a significant influence on the way hearing aid users perceive pitch.

Sub-test 10: With the activation of NFC participants performed slightly better when asked to identify melodies than without NFC. When trying to recognize familiar melodies, listeners depend on the exact pitch intervals of the melodies as well as rhythmic information that enhance recall and recognition [25]. A possible explanation for participants' improved melody recognition with the activation of NFC might be that the melodies were played in a range of A5/880Hz to 4186Hz and therefore contains relatively high frequency information. As the NFC cut-off frequency for most participants ranged between 2.5 kHz and 4 kHz one can assume that a substantial amount of frequency compression took thereby enabling listeners to hear more high frequency musical notes. As a hearing loss already influences melodic perception negatively [25], it is not surprising that participants experienced difficulty identifying melodies without rhythm cues as this is more complex due to the fact that they only have to rely on one source of information (pitch) instead of two. Error pattern analysis confirmed that participants (with both NFC settings) performed less accurately in the no-rhythm (56.4%) condition compared to the rhythm condition (79.5%) and further indicated that melodies with similar rhythmic patterns were confused more frequently than melodies with very different rhythmic structures.

It was not possible to compare the results of the present study with similar international studies as there is a high rate of variability in the results obtained by the different studies due to different methodological approached followed. Most of the other studies assessed the melody recognition skills of cochlear implantees [11,25,26]. The only study that included hearing aid users were done by Looi et al. [20] which compared the melody identification skills of hearing aid users to that of cochlear implantees and found that hearing aid users scored significantly higher for the task than cochlear implantees.

Sub-test 11: As cochlear hearing loss often involves damage to the outer hair cells [27] and consequences of outer hair cell loss include difficulty understanding speech especially in the presence of background noise [28], one could assume that participants would have difficulty with the identification of musical stimuli presented against the presence of background noise. This was confirmed by the low scores obtained for the music-in-noise song identification task. It is difficult to explain the slight benefit obtained with NFC in this task as there seems to be a discrepancy in the literature regarding the influence of NFC on stimuli presented against background noise. Moore [6] highlighted one of the potential problems of frequency lowering hearing aids as that when background noise is present, portions of the noise, which were previously inaudible, may be lowered to a frequency region where it is more audible. This might offset any advantage that would otherwise be gained from the lowering. Gifford et al. [29] however found that patients benefit from digital frequency compression when speech was presented against background noise. As a slight benefit with NFC was also seen for the melody identification task one can assume that NFC could also benefit the identification of melodies in the presence of noise. The identification of music-in-noise is, however, more complex and therefore participants' scores were substantially lower than for the identification of melodies without noise. These results could not be compared to other studies as no similar music-in-noise task could be found in the literature.

Conclusion

Results of the present study indicate that hearing aid users perceive timbre and melody significantly better with the use of NFC. Furthermore it seems that the musical perception abilities of hearing aid users are highly variable irrespective of using NFC technology or not. As a hearing loss clearly effects the enjoyment of music further research with regards to music perception and NFC are warranted.

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