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The Performance of Music and Speech with Different Frequency Lowering Devices

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Abstract

Objective: Previous research studies have documented the benefits of both frequency transposition (FT) and non-linear frequency compression (NLFC) for patients with different degrees of hearing loss, however, very few studies directly compare the effect of two different frequency lowering (FL) techniques on the same population to investigate if superior performance in terms of speech and music perception exists.

Design and Sample: The aim of the study was to determine whether people with a moderate to severe hearing loss have improved music perception and speech intelligibility with the use of FL and if the benefits is dependent on a specific FL strategy. A parallel research design was implemented and a purposive sampling method was used. Participants (n=20) were experienced hearing aid users with bilateral, moderate to severe hearing losses and no FL experience. A music perception questionnaire were completed by participants to rate their perception of music and the Music Perception Test (MPT) were used to assess participants' musical performance. The Phoneme Perception Test (PPT) and Hearing-in-Noise Test (HINT) were used to assess participants' speech perception abilities. Two commercial hearing aid devices with different FL approaches (FT and NLFC) were used.

Results and Conclusion: Results indicate that participants distinguish high frequency sounds better with both FL strategies than without it resulting in better speech intelligibility in quiet and in noise. Greater speech scores with NLFC compared to FT was evident. Participants that used FT showed more confusion regarding speech perception. In terms of music perception the study shows that NLFC improves participants' pitch and melody perception whereas mostly no musical improvement was observed with FT. With the use of FT participants' ability to identify melodies decreased. A strong preference to listen to classical music with NLFC compared to FT was noted. Therefore it is evident that FL can improve speech and music perception for people with moderate to severe hearing losses but the perceived benefit seems to be dependent on the specific FL strategy implemented.

Keywords: Hearing aids; Frequency lowering; Non-linear frequency compression; Frequency transposition; Speech perception; Music perception

Abbreviations

FL: Frequency Lowering; FT: Frequency Transposition, NLFC: Non-Linear Frequency Compression, MPT: Music Perception Test, HINT: Hearing-in-Noise-Test, PPT: Phoneme Perception Test

Introduction

More than half of the world's hearing aid manufacturer's include FL techniques as an optimal feature in their hearing aids [1]. Frequency lowering algorithms aim to shift high frequency components of a signal into lower frequency regions to promote access to high-frequency information for those with high-frequency hearing loss in order to enhance speech perception and improve detection of environmental sounds [2,3].

Frequency lowering is considered an umbrella term that encompasses the different FL strategies present in commercially available hearing aids [1], of which linear frequency transposition, commonly referred to as frequency transposition (FT), and non-linear frequency compression (NLFC) has gained wide spread use among audiologists fitting patients with high frequency hearing loss [1,4].

Frequency transposition follows a "copy and paste" approach, where high frequency information is linearly transposed to lower frequencies preserving its harmonic structure and modulation ratio of the original signal and then mixing it with the lower non-transposed signal [1,4,5]. Non-linear frequency compression however can be termed a "squeeze" approach, where high frequency information above a certain cut-off frequency are compressed into a narrower output range according to a certain compression ratio. Low frequency parts are not affected by this algorithm [2,4].

Several research studies have documented the benefits of above mentioned FL strategies for patients with different degrees of hearing loss. Andersen [5] investigated the evidence for the effectiveness of FT and reported improved speech perception and production in children and adults across different studies. Improved consonant identification (immediately after fitting) as well as consonant and vowel recognition (with 3-6 weeks of acclimatization) was noted with children with sloping sensory neural hearing losses (SNHL) wearing FT devices [6-8]. Statistically significant improved fricative identification as well as clear but not statistically significant enhanced consonant recognition across different consonant classes in both quiet and noise

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was also reported in adults wearing hearing aids where FT was enabled [9-11]. Environmental sounds were also enhanced with the use of FT and Kuk and colleagues [12] reported that patients preferred listening to music with FT on rather than off 55% of the time. Ample evidence for benefits with NLFC is also reported with significantly enhanced speech perception pertaining to high frequency consonants in adults [13,14] and children [15]. Overall word recognition in quiet [2] and speech intelligibility in noise improved with the use of NLFC [16,17]. Short and long term benefits of using NLFC when listening to music also exists in terms of identifying melodies and musical instruments as well as rating the overall enjoyment and quality of music [16,18].

Although a specific FL strategy may result in different outcomes, a participant's degree of hearing loss may also influence the speech intelligibility and music perception [19]. Most research conducted addressing FT was conducted on subjects with severe to profound SNHL as well as patients with high frequency dead regions [7,10,11]. Research regarding NLFC has been performed on a wider range of hearing loss degrees including severe to profound SNHL, moderate to profound SNHL, steeply sloping hearing loss and high frequency hearing loss [13,14, 20-24]. From this research, subjects using both FT and NLFC performed better if a moderate to severe high frequency hearing loss with normal to mild low frequency hearing loss was present compared to subjects with a profound hearing loss [25].

The role of acclimatization to frequency lowered sound also need to be considered as the auditory sensations produced by FL algorithms are unfamiliar at first when perceived by the cochlea[25]. Multiple studies indicated a learning effect of FL for speech intelligibility and this may also be applicable to the perception of musical sound quality and musical detail [19].

As most people with a hearing loss express a need to understand speech but also require their hearing aids to be fitted optimally for listening to music [26] the above mentioned benefits of FL directly addresses these needs. Comprehensive evidence exists regarding the benefits of the different FL techniques but very limited research however directly compare the effect of two different FL techniques on the same population to investigate if superior performance in terms of speech and music perception with a specific FL strategy exists [27-29]. In 2008 Alexander and colleagues [30] compared NLFC and FT in 24 adults with mild to moderate hearing losses and found that subjects better perceived fricatives and affricatives with NLFC than with FT. In another study Salorio-Corbetto and colleagues [31] compared FT and NLFC but results from this study indicated no significant benefit in speech intelligibility with FL in general and unfortunately did not expand on the comparison with the two different FL strategies. The need for research that encompasses the above mentioned two techniques in the same study with common participants and common fitting strategies are thus necessary. Therefore the question arises if performance of music and speech perception is dependent on different FL techniques and whether the benefits of FL generalize to patients with moderate to severe hearing losses?

Method

Aims

The following aims were stipulated for the current study:

- To determine whether people with a moderate to severe hearing loss have improved music perception and speech intelligibility with the use of frequency lowering.
- To determine if the benefit is dependent on a specific frequency lowering strategy.

Study design

A parallel research design was implemented as each participant was tested with only one FL strategy. This is different from the approach followed by Salorio-Corbetto and colleagues [31] in which a cross over design was used as their participants were all exposed to FT and NLFC. The researchers in the current study selected a parallel design on purpose as they did not want participants to first get acclimatized to one FL strategy and then to another. The current study was partly single blinded as participants were unaware of the different FL strategy they were using and whether the FL algorithm was active or not. Another part of the study, the paired comparisons of musical clips, was double blinded as neither the participant nor the tester were aware of which setting were compared and the decoding of the results were conducted by an independent third person.

Participants

A purposive sampling method was implemented where participants (n=20) were chosen because they were representative to the topic of interest. They met the following criteria:

- Experienced hearing aid users with at least 3 years' experience with hearing aids
- No experience with frequency lowering hearing aids
- Bilateral, moderate to severe, sensory neural hearing loss
- Age: 18-65 years
- English language proficiency and literacy

The figure (Figure 1) below gives an indication of the average hearing loss for the included participants.

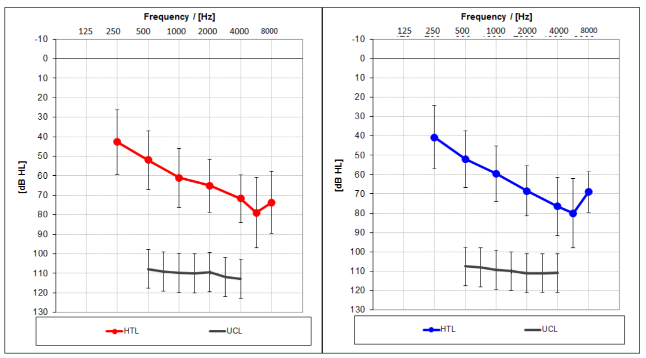

Figure 1: Average hearing loss (HTL and UCL) of participants for right and left ear.

Participants had a mean age of 53 years. All of the participants' native language was Afrikaans but they were proficient in English as a second language. This is important as the English version of the Hearing-in-Noise Test (HINT) was used during the speech testing and therefore all participants had equal opportunity to complete testing in their second language. No professional musicians were included although some participants had some formal musical training. Participants with musical training were grouped equally in both test groups.

Material and apparatus

Two commercial hearing aid devices with different FL approaches were used. Device #1 was a Phonak Audeo V90 hearing aid that compassed NLFC as frequency lowering strategy and device #2 was a Widex Dream 440 hearing aid that made use of FT. Both of the devices were receiver-in-the-canal (RIC) devices and were fitted with P receivers.

Participants were asked to complete a music perception questionnaire in order to obtain background information and give them the opportunity to rate their perception of music with the different hearing aids and hearing aid settings.

Procedure

Subjects were divided into two groups – each fitted randomly with one of the test devices. The groups were balanced according to participants' hearing loss, age and musical experience (Figure 2).

Group 1a	Switch from own device to device #1 (NLFC) with FL OFF then switch FL ON
Group 1b	Switch from own device to device #1 (NLFC) with FL ON then switch FL OFF
Group 2a	Switch from own device to device #2 (FT) with FL OFF then switch FL ON
Group 2b	Switch from own device to device #2 (FT) with FL ON then switch FL OFF

Figure 2: Group division of participants.

Participants completed three visits. They first underwent a hearing evaluation to determine their current hearing status which included otoscopic examination, pure tone and speech audiometry. The hearing aids were verified with the Audioscan Verifit and fitted according to the University of Western Ontario protocol [32] to ensure that they were optimized for listening to speech and accurately match the prescribed adult targets provided by the Desired Sensation Level 5.0 (DSL) algorithm. The hearing aids were programmed with a music and speech program and participants were asked to use the music program during the music perception evaluations and the speech program during the speech evaluations. All adaptive features of both programs were left on the manufacturer default settings. As a time of adaptation to frequency lowered sound, regardless of the type of FL, is advised to help users acclimatize to devices [25], measurements for all participants were taken before and after they adapted to the frequency lowered sound. This enabled the researchers to determine the effect of acclimatization for the different FL devices. A block diagram of participants' visits to the practice is displayed in Figure 3.

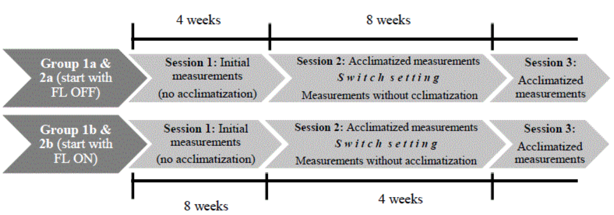

Figure 3: Block diagram of the protocol for participants' visits to the practice.

Initial measurements (MPT, PPT and HINT) were done after the fitting of the hearing aids. After the first visit, participants had to wear the hearing aids for a period of either four or eight weeks depending on the FL setting where after they returned for the second session. Four weeks were allocated for acclimatization to the new hearing aids (FL Off) and 8 weeks were allocated to acclimatize to FL. Literature [6,17] regarding acclimatization to FL technology indicated improved consonant and vowel recognition as well as improved sound quality over time and therefore it is important that participants receive the opportunity to acclimatize to FL in order to obtain optimal test results.

During the second visit the hearing aids were verified electro-acoustically to ensure that they were working properly [33]. The MPT and speech tests (PPT, HINT) were performed with the hearing aids on the same setting that participants used since their last visit. After the tests were performed, the hearing aid settings were switched – participants that had their hearing aids with FL active now had this algorithm deactivated and vice versa. Again participants were asked to wear the hearing aids for a period of either four or eight weeks (depending on the FL setting) before returning to the practice.

During participants' third visit to the practice the hearing aids were once again verified electro-acoustically and the same tests were performed with the addition of the paired comparison of music samples. This was only performed once, after participants acclimatized to the different FL strategies.

Sub-tests of the Music Perception Test (MPT) were used to assess participants' perception of music. This test is described in detail in Uys and Van Dijk [34] and a summary of the sub-tests that were used in the current study is available in Figure 4. Participants were also presented with different musical clips that were recorded on a KEMAR with the hearing devices programmed based on the average hearing loss and using the music program varying the different FL settings (FT On, FT Off, NLFC On, NLFC Off). Participants performed a complete paired comparisons listening to the recordings via headphones and had to indicate which musical clip they prefer to listen to. Musical styles included in these recordings were classical, pop and jazz.

To assess participants' speech perception abilities by determining the audibility of high frequency speech signals and the influence of acclimatization with different FL approaches, the Phoneme Perception Test (PPT) [35,36] and the (HINT) [37] were performed in both quiet and noise.

The following procedures were followed during conduction of the different tests:

MPT: The MPT were performed with the hearing aids using the music program. For testing, participants were seated in an audiometric booth, facing the loudspeaker at 45 degrees, at a distance of approximately one meter. A diagram of the setup is displayed in Figure 5. The stimuli were played on an 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. Those instructions were also presented acoustically via the loudspeakers before the onset of each sub-test. Participants did not receive any feedback after the test.

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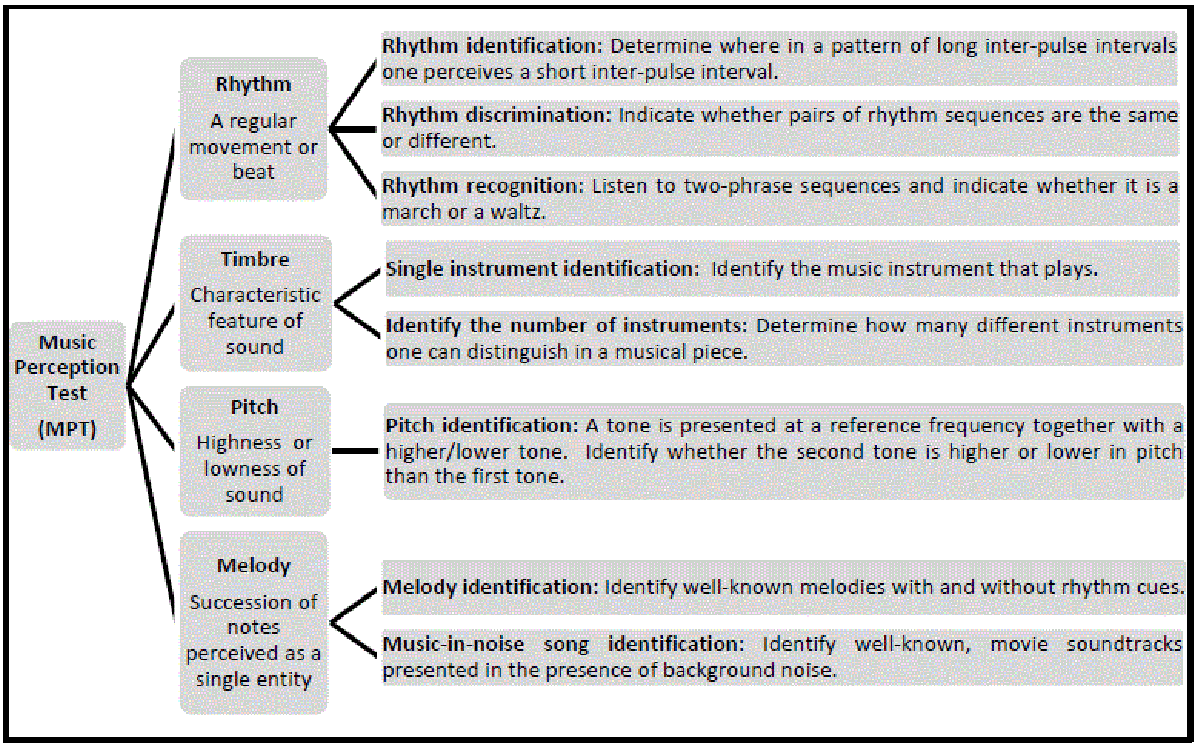

Figure 4: Block diagram of the sub-tests of the Music Perception Test (MPT) that were used.

Paired comparisons: The music samples were automatically presented via headphones with the musical style and the setting of the FL system completely randomized. The presentation level was adjusted individually at the beginning of the test so that the music samples had a comfortable loudness. This allowed a direct comparison of all settings with each other for all musical styles. Performance of this test was double blinded as neither the participant nor the tester were aware of which setting were compared and the decoding of the results were conducted by an independent third person.

PPT: The guidelines provided by the PPT manual were followed during testing [38] and the sound system was calibrated prior to testing. The detection, distinction and recognition tests were performed. The detection test detects the level at which a hearing impaired person begins to hear high frequency phonemes and the distinction test is conducted to reveal whether those high frequency phonemes can be distinguished. The recognition test was used to assess participants' ability to recognize high frequency speech sounds like /sh/ or /s/ embedded in a pair of vowels building logatomes. The setup for the PPT is visually displayed in Figure 5.

HINT: The test was performed according to the recommended protocol describe in the test manual [39]. Testing took place in a sound-isolated room where participants were seated one meter from the loudspeaker. A compact disc player was used to play the test material, output were routed to the two tape inputs of the Grason-Stadler GSI 61 audiometer. The speech was played through one channel and the noise signal through the other channel (presentation setup demonstrated in Figure 5). The sound room, audiometer and loudspeaker were calibrated before administration of any tests. For speech testing, an adaptive procedure was used to determine the absolute level (in quiet) or signal-to-noise ratio (in noise) at which the stimulus sentences were correctly identified 50% of the time. For the speech in noise test, the noise was presented at a fixed level (65 dB) and the level of the speech material was varied depending upon the performance of the listener's response. The presentation level of the following sentence was increased when the response to the previous sentence was incorrect and decreased when the response to the previous sentence was correct. Participants were asked to listen to each sentence and repeat aloud whatever was heard or understood. The same adaptive up-down strategy was followed for testing in quiet.

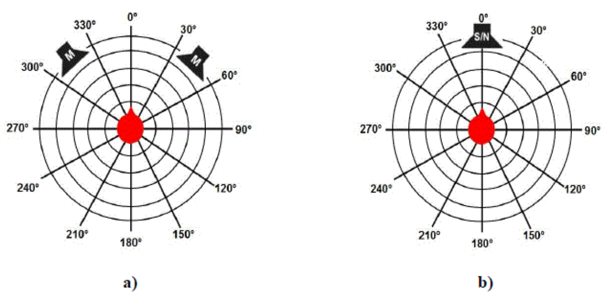

Figure 5: Setup for the a) Music Perception Test (MPT) and b) speech test in noise (HINT) and PPT.

Data recording: Test scores were directly written on the answer sheets of the MPT and HINT. The MPT answer sheets were hand scored because individual assessment was required as participants were

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only assessed on items familiar to them. Results from the PPT were directly entered into the computer while the participant was completing the test. The data from the answer sheets were coded into a Microsoft Excel worksheet.

Results

Music Perception Test (MPT)

Results from the MPT indicate that there was no real difference for rhythm, timbre and pitch with FT On compared to FT Off. Participants' ability to identify melodies did however decrease (10%) with the activation of FT. These results are displayed in Figure 6.

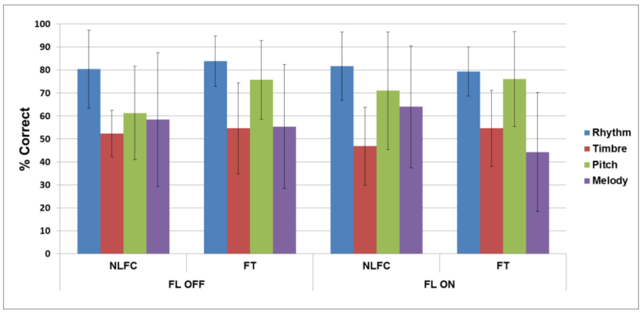

Figure 6: Results for the MPT with the different frequency lowering settings.

With regards to NLFC it is evident from the above mentioned figure that there was no difference for rhythm with the activation of this algorithm which confirms the results of a previous study by Uys [40] where the activation of NLFC also did not result in any difference in rhythm performance. A slight drop (5%) (not statistical significant) in participants' ability to identify musical instruments (timbre) with NLFC On was observed in the current study which differs from the results obtained by Uys and colleagues [18] where the activation of NLFC resulted in a significantly improved ability to identify musical instruments. With the activation of NLFC participants' ability to perceive pitch (10%) and identify melodies (6%) improved.

Results from the MPT indicate that participants did not perceive rhythm any different with NLFC than with FT. For timbre and pitch participants had a slight benefit (5-8%) with FT compared to NLFC but a definite improvement (20%) in melody identification is visible with NLFC compared to FT.

Paired comparisons of music sound samples

When pooling the data for conditions per musical style it can be observed that participants obtained a statistical significant benefit just for classical music using device #1 (NLFC) compared to device #2 (FT). For the other musical styles (pop and jazz) they performed slightly better with NLFC than with FT but these benefits were however not statistical significant.

Additionally it is interesting to observe the data according to different perspective. Table 1 shows an overview of the different comparison parts of the paired comparisons:

Definition	Conditions to be compared	Aspect to look into
NLFC	NLFC Off NLFC On	Influence of NLFC
FT	FT Off FT On	Influence of FT
OFF	NLFC Off FT Off	Music program with FL Off
ON	NLFC On FT On	Music program with FL On
Market	NLFC On FT Off	Default music programs settings of device#1 and device#2

Table 1: Definition of the different conditions used for the paired comparisons.

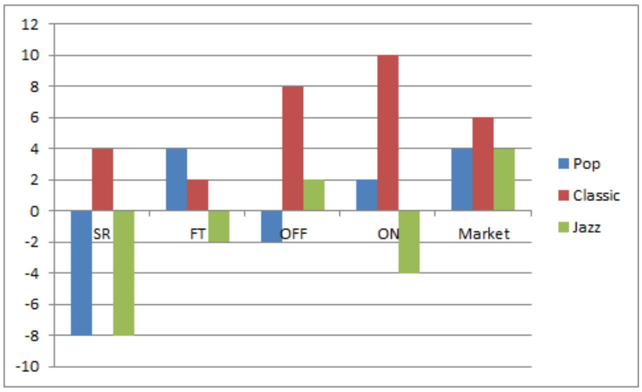

Figure 7: Results of the paired comparison separated to the comparison of the different conditions. (SR=SR Off ⊠ SR On, FT=FT Off ⊠ FT On, OFF=SR Off ⊠ FT Off, ON=SR On ⊠ FT On, Market=settings which are used by default in the market: FT Off ⊠ SR On).

The results displayed above show the following trends which are also displayed in Figure 7:

NLFC: If NLFC is switched on, it is beneficial only for classical music. For jazz and pop it seems to be better to switch NLFC off.

FT: The influence of FT is not as obvious as for NLFC and it seems that in music it is better to switch FT off although the difference in preference with and without FT is rather small.

OFF: When comparing the music programs of device#1 and device#2 when the FL algorithms are switched off it seems that device#1 performs much better with classical music. For both other styles the difference is only small.

ON: When comparing the FL techniques the results are depending on the musical style. For jazz music FT seems to be beneficial whereas NLFC seems to be beneficial for pop music. However these observations are as all the others described above not statistical significant. The only comparison that was found to be of statistical significance is the comparison of NLFC On and FT On when using classical music. In this case NLFC On is rated statistically significant better than FT On using binominal statistics ($p<0.05$). As this is the only part of the study where all participants compared all settings with each other it provides the biggest power with regards to musical stimuli.

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Market: Comparing the settings of the music programs which are used by default in the market (device #1 default with NLFC On; device #2 default with FT Off) demonstrates that the music program of device #1 tends to be better for all musical styles than the music program of device #2.

Phoneme Perception Test (PPT)

Figure 8 displays information of participants' phoneme detection thresholds with NLFC and FT as well as the effect of acclimatization to both FL strategies on participants' ability to detect phonemes.

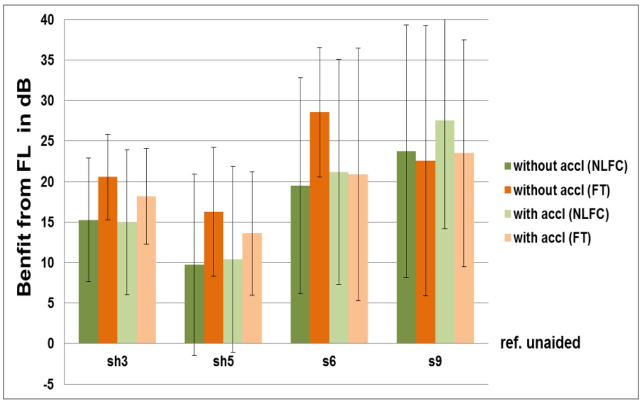

Figure 8: Phoneme detection thresholds, relative values related to FL Off for NLFC and FT.

NLFC *vs.* FT: From the figure above it is clear that with both FL devices participants detect sounds at lower thresholds with FL On compared to FL Off.

Acclimatization: With NLFC there is no acclimatization effect as results are almost constant for all frequencies with NLFC On and Off. A small improvement for s9 (9 kHz) with NLFC On was visible but however not statistical significant. With regards to FT On, a small deterioration (<4dB) in performance with acclimatization was visible at the middle frequencies (sh 3 kHz; sh 5 kHz) and a statistical significant deterioration (8 dB) for s6 (6 kHz) (Wilcoxon: $p<0.05$). This improvement with NLFC was expected as the improvement of the detection threshold is instantaneous and therefore logic but the opposite of the expected result was observed with FT as demonstrated by the deteriorated trend.

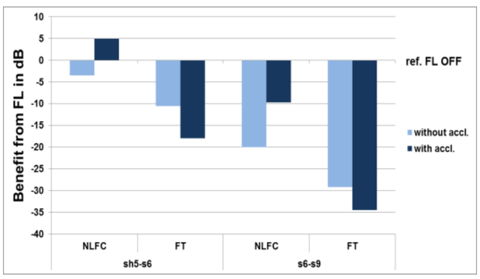

Figure 9: Relative results of the phoneme distinction test with NLFC and FT related to FL Off.

In Figure 9, results of participants' performance with the distinction test is displayed.

NLFC *vs.* FT: From the above mentioned figure it is obvious that NLFC provides less confusion and therefore better phoneme distinction that FT. But as only 10 subjects per group were included, the statistical power is not big enough to confirm these results statistically.

Acclimatization: With regards to the mid frequencies (sh5-sh6) it is evident that NLFC shows almost the same for FL On and Off without acclimatization but an improvement with FL On after acclimatization. FT on the other hand, demonstrates a clear decrease with FL On compared to Off, which worsen after acclimatization. With investigation of the high frequencies (s6-s9) a similar trend is seen as NLFC again shows a clear improvement with FL On compared to Off after acclimatization and FT again demonstrates a decrease for FL On compared to Off which deteriorates even further after acclimatization. These FT results are similar to the results obtained with FT in the detection test.

Figure 10 displays data of the phoneme recognition test in order to demonstrate possible phoneme confusions that participants experienced with FL On compared to FL Off.

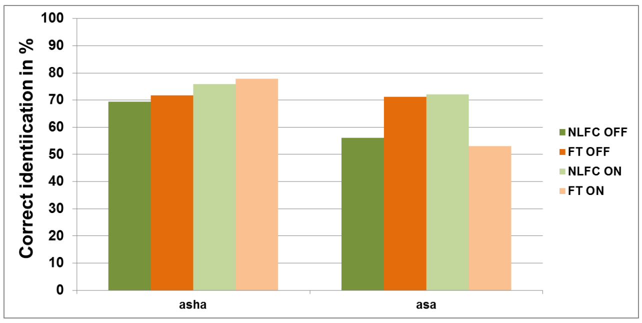

Figure 10: Phoneme recognition with NLFC and FT.

NLFC *vs.* FT: With both NLFC (+7%) and FT (+6%) On, participants recognized "asha" better compared to the FL setting being Off. With the recognition of "asa" the use of NLFC caused an increase of 16% while the use of FT resulted in a decrease of performance by 18%. These values are however not statistical significant but still indicates that participants hear and distinguish the /s/ sound better with NLFC than with FT.

Acclimatization: With regards to phoneme recognition, acclimatization had no influence for both FL devices so that the results are not shown.

Hearing-in-Noise Test (HINT)

Figure 11 shows the average HINT data when measured in quiet. It demonstrates an adhoc effect from FT directly when switched on (about 7 dB) and this effect keeps constant over time, therefore no acclimatization effect. In opposite the speech intelligibility is not directly improved with switching On NLFC but over time it reached the same value as FT. The observed acclimatization effect is statistically significantly confirmed using a Wilcoxon rang sum test ($p=0.05$).

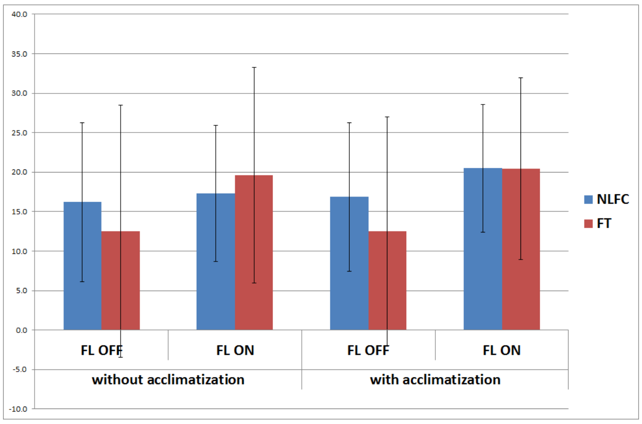

Figure 11: Averaged results of the HINT tested in quiet separated before and after acclimatization for FL On and Off.

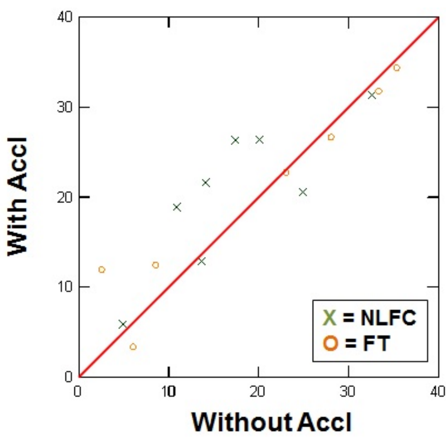

Figure 12: Individual data for HINT in quiet for NLFC and FT On.

When inspecting the individual data of the results for NLFC and FT On for the HINT in quiet (Figure 12), it confirms the findings of the average data and the result of the statistical test indicating that mostly no acclimatization effect with FT are seen (individual data are lying mostly on the diagonal line) but with NLFC scores are clearly increasing with acclimatization (individual data lying above the diagonal line with partly a rather huge distance of up to 12 dB from the diagonal line). A test of variance, using the Kruskal-Wallis-test, shows no influence of technology (NLFC ↔ FT).

Figure 13 displays information about participants' ability to perceive speech in noise when using the HINT with 65 dB constant background noise. The influence of acclimatization has not been looked at as there has been an intensive study looking especially at the influence of that parameter [16].

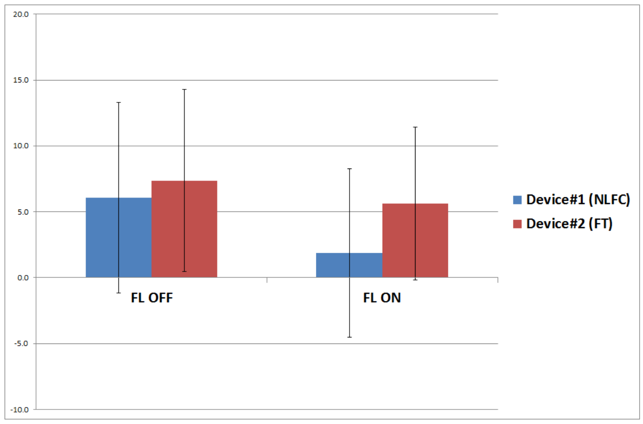

Figure 13: Averaged results of the HINT tested in noise separated for each of the FL techniques switched ON and OFF.

Looking only into the immediate effect of FL, the data show an improvement in speech understanding in noise by a clear reduction of the SRT (NLFC: - 4.2 dB; FT: - 1.8 dB). While the effect of NLFC was found to be statistical significant the effect of FT could not be confirmed using the Wilcoxon test (p=0.05).

A graph of the individual data confirms this trend as displayed in Figure 14.

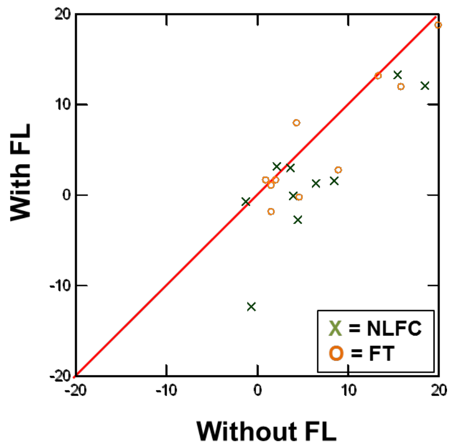

Figure 14: Individual data for HINT in noise.

From the above mentioned figure it can be seen that with FT On, participants had a slight improvement with the HINT in noise (values are laying below the diagonal line). With NLFC On a clear improvement in scores are visible as the individual data are lying far below the diagonal line.

Discussion and Conclusion

Results from the current study indicate that participants hear and distinguish high frequency sounds better with both FL strategies than without it resulting in better speech intelligibility in quiet and in noise. Although some previous research contradicts the benefit from FL [1], these results correlates with most research on this topic noting improved affricate detection, consonant recognition and plural recognition when employing FL strategies [25]. Superior speech scores with NLFC over FT was however evident in this study and correlates with a review of all English research studies published, where only 39% of adult patients using FT indicated an improvement in speech recognition tests as opposed to 53% of adult patients using NLFC, suggesting improved speech scores over time [25].

Participants from the current research study that used FT showed more confusions regarding speech perception, especially after acclimatization whereas participants that used NLFC tended to perceive speech better after acclimatization. The nature of FT may cause these confusions as an overlapping between high frequency transposed information and low frequencies may lead to an inability to recognize specific sounds [3]. For patients to gain benefit from FT devices it is suggested that training might be necessary [3]. No training was however given to participants during this study and only acclimatization was measured, possibly contributing to confusions of speech over time with FT. Hopkins and colleagues [2] noted that long periods of acclimatization were not necessary for patients to gain full benefit from NLFC whereas research by Uys and Latzel [16] indicated that NLFC results in better speech understanding after lengthy exposure. In this study, acclimatization contributed positively for NLFC participants but not for FT users.

As far as generalization to degree of hearing loss is concerned it should be noted that the research by Uys and Latzel [16] was conducted on subjects with severe to profound hearing losses. In the current study patients with moderate to severe hearing losses were evaluated and similar improvements in speech intelligibility for both NLFC and FT was present when speech was presented in noise. It does however seem that NLFC is more effective than FT. No difference was noted between different technologies with speech presented in quiet. Wolfe and colleagues [20] also investigated the effect of NLFC on speech recognition in adults with a moderate to severe hearing loss and similar improvements were noted. It can thus be concluded that people with a moderate to severe hearing loss will also benefit from FL in terms of improved speech understanding, especially in noise.

Frequency lowering technology generally facilitates improved speech understanding but not always improved sound quality of music [19]. With regards to music perception in the current study it is evident that NLFC improves participants' pitch and melody perception whereas mostly no musical improvement was observed with FT for pitch and melody. Despite the fact that NLFC actually changes the harmonic structure of music and in effect changes the naturalness of the signal which might affect pitch and melody identification [19], participants still performed better with NLFC On compared to NLFC Off. The improved ability to identify melodies correlates with previous studies by Uys and Latzel [16] and Uys et al. [18] where melody recognition improved with the use of NLFC, especially over time. The pitch perception benefit obtained in the current study do however differ from results of a previous study by Uys [40]which found no difference in participants' ability to perceive pitch with the activation of NLFC. Although Kirchberger and Russo [16] also examined how participants perceive music with NLFC, it is difficult to compare the results of the current study to their results due to the fact that the participants in their study evaluated music holistically and not specific attributes like melody or pitch. The results of the current research study are contradicting to those of Kuk and colleagues [9] who found that 65% of participants preferred FT On as opposed to Off when listening to music. With the use of FT in the current study, participants' ability to identify melodies actually decreased. This may be due to the overlap between transposed high frequency information and the unchanged lower frequencies [25] resulting in unclear identification of complex sound like melodies.

It can be deducted from this study that better melody recognition with NLFC generalized from individuals with severe-profound SNHL [16] to those with moderate to severe SNHL. In the current study, participants also have a strong preference to listen to classical music with NLFC compared to FT and perceived it significantly better with this algorithm.

To conclude, it is evident that FL technology can improve speech and music perception also for persons with a moderate to severe hearing loss. The benefit hearing aid users perceive is however dependent on the specific frequency lowering strategy implemented.

Declaration of Interest

The authors alone are responsible for the content and writing of the paper.

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