Title: The effect of frequency compression on front-back localization and speech recognition in noise

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Introduction

Although the concept of frequency lowering has been around for at least four decades[1], it has recently seen a resurgence as a "hot topic" in amplification and over the last couple of years has seen increased mainstream commercial success since being implemented in several products by two of the major hearing aid manufacturers (Phonak and Widex). The goal of frequency lowering is to shift high-frequency sounds that cannot be adequately amplified by a hearing aid, or used by the corresponding region of the cochlea, to lower frequencies where the information can be better amplified or utilized. In particular, the feature is expected to assist in making available such important information as high-frequency speech sounds (e.g. /s/, /f/, /θ/), and frequencies between 2 – 5 kHz which are uniquely shaped by the pinna depending on their angle of origin to assist with front-back (F-B) discrimination.

The frequency lowering technique implemented in Phonak's Naida product range (non-linear frequency compression, hereafter called frequency compression) affects only the frequency range above the frequency compression threshold and is permanent. The compressed input range is consistently mapped to the output range, so wearers may be better able to adapt to the change in auditory stimulation than if the frequency lowering was transient. Extensive research was performed in the development of Naida's frequency compression and post release using predominantly speech in quiet [2-6]. However its effect on horizontal localization and possible synergy with high-frequency directionality, a feature that has been demonstrated to improve F-B discrimination in users of behind-the-ear (BTE) hearing aids[7], has not been investigated. The study reported in this article was therefore designed to explore the effect of frequency compression, high-frequency directionality, and the combination of the two on horizontal localization and speech recognition in noise.

Methodology

Twenty-three bilaterally aided, sensorineurally hearing impaired volunteers aged 69 – 88 years of age (mean age 78.7 years) participated in the study. The participants' average hearing loss can be seen in Figure 1. Their bilateral 3FA (average threshold at 0.5, 1 and 2 kHz) ranged from 42 – 75 dB HL.

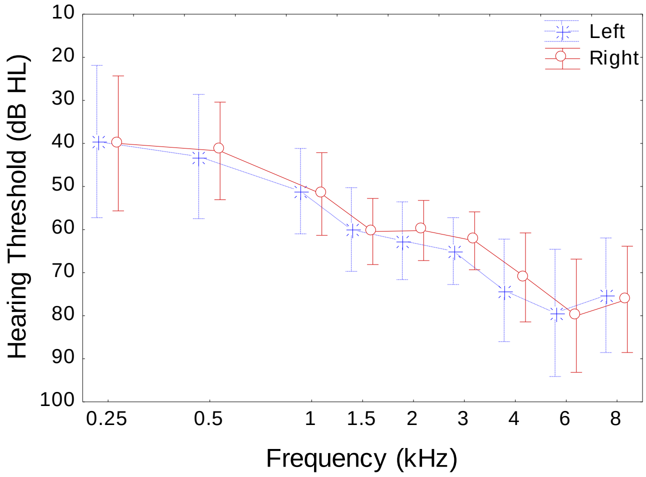


Figure 1. Average audiometric thresholds in dB HL for participants' left and right ears. Vertical bars indicate ± one standard deviation. Left/right ear data are shown shifted for clarity.

The test devices were Phonak Naida V SP BTE hearing instruments set to the NAL-NL1 prescription minus 3 dB[8] for all except 2 participants with more severe loss who were fitted to the full NAL-NL1 targets[9]. The fitting was verified using real ear insertion gain (REIG). Checks were made to ensure that mid-level sounds were comfortable, that the volume was balanced between the ears and that the Maximum Power Output (MPO) was appropriate.

Half the participants had frequency compression enabled for the first 8 weeks of the study and disabled for the second 8 weeks; for the remaining participants this order was reversed. Throughout the study participants had access to two test programs that differed only in the microphone input; one program was omni-directional in all channels and the other was omni-directional below ~ 1.3 kHz and directional above ~ 1.3 kHz. The order of microphone mode assignment to each program was balanced across participants. Noise reduction was disabled in the test programs and wind-noise reduction was set to "light". The feedback cancellation was set to moderate (the default). Participants were instructed to spend alternating days in P1 and P2 to ensure as far as possible that they were evenly exposed to omni-directionality and high-frequency directionality.

The frequency compression control, which simultaneously adjusts the frequency compression threshold and the frequency compression ratio, was set such that the effect was audible when listening to the sentence "She sells sea shells by the sea shore", but not bothersome. A further check was made to ensure that frequency compression was audible in each ear, which resulted in seven participants with different frequency compression strengths in each ear. All but one participant required stronger frequency compression settings than prescribed in at least one ear to hear an effect of frequency compression (Figure 2).

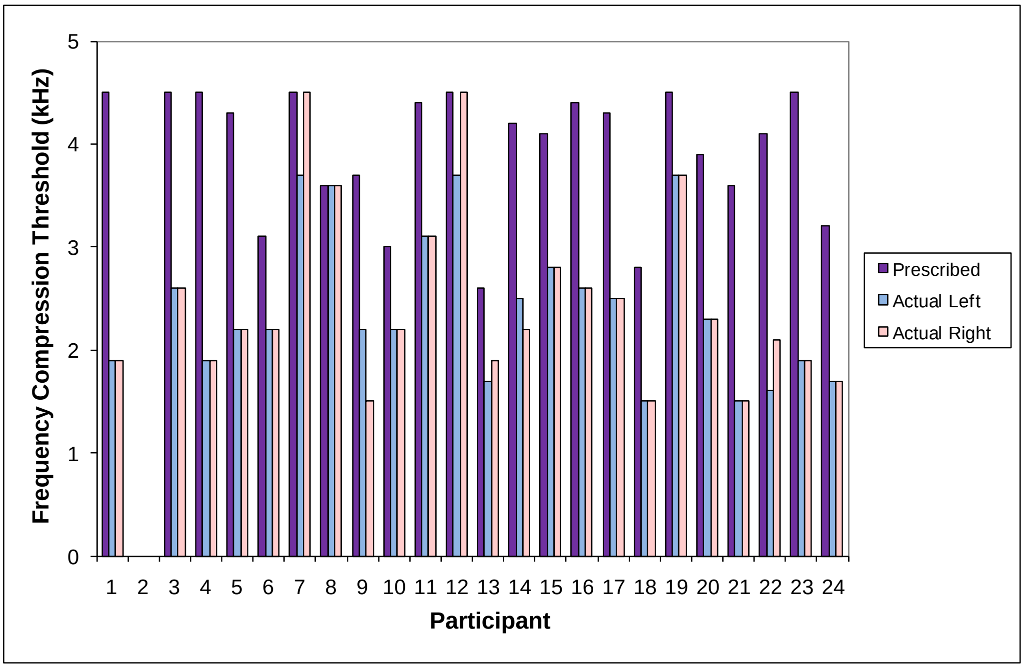


Figure 2. Prescribed (purple) versus actual frequency compression threshold in left (blue) and right (pink) ears for each participant.

Horizontal localization performance was tested in a medium sized anechoic chamber using a 360º array of 20 loudspeakers separated by 18 degrees (see Keidser et al[10] for more details). Localization testing was performed aided using a broadband pulsed pink noise stimulus, presented at 70 dB Leq. For each test condition the stimulus was presented twice from each loudspeaker in a random order. A ± 3 dB variation was randomly applied to the presentation level.

Aided speech recognition in noise was assessed in a sound treated test booth using lists of 50 monosyllables presented at each participant's most comfortable level from a loudspeaker located at 0˚ azimuth. Eight-talker babble noise was presented from either the same loudspeaker as the speech (N0) or from a second loudspeaker located at 180˚ azimuth (N180). The level of the 8-talker babble was varied adaptively in 1 dB steps to determine the Speech Reception Threshold Signal to Noise Ratio (SRT SNR) - the SNR at which each participant identified 50% of phonemes correctly.

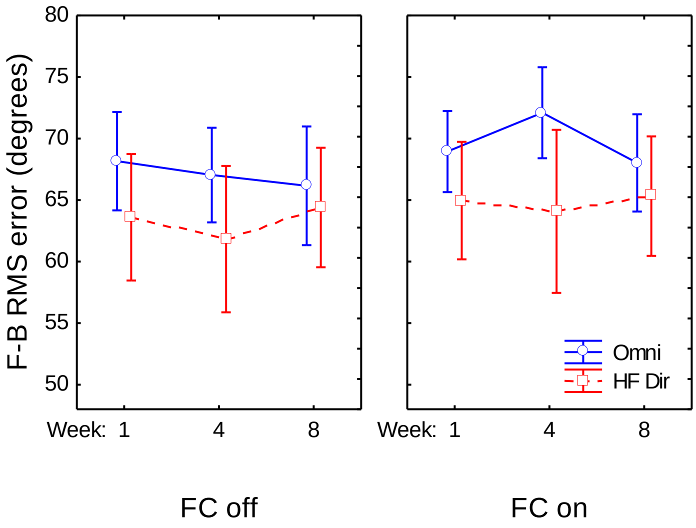
The Speech, Spatial and Qualities of Hearing (SSQ) questionnaire[11] was used to investigate how participants rated the two test schemes in their real-life environments. An exit interview was used to elicit information on how they rated the hearing instruments.

Aided horizontal localization and speech recognition in noise data were collected after one, four and eight weeks with each frequency compression scheme. At each appointment testing was performed with both omni-directional and high-frequency directional microphone modes. The SSQ and exit interview data were collected after eight weeks with each scheme.

Results

Horizontal localization

The responses to the localization test were analyzed for F-B RMS errors[7]. To explore the effect of frequency compression and high-frequency directionality on F-B localization, a repeated measures ANOVA was conducted using aided F-B RMS errors as observations, and frequency compression (on/off), time (1, 4, 8 weeks with scheme) and microphone mode (omni-directionality, high-frequency directionality) as repeated measures. This analysis showed a significant effect of microphone mode ($F_{1,22}$=16.04, p=0.0006), with high-frequency directionality reducing F-B RMS errors by, on average, 4.5˚ (Figure 3). The effect of frequency compression neared significance ($F_{1,22}$=4.21, p=0.052), with performance with frequency compression on approximately two degrees poorer than with it off. There was no significant effect of time, indicating that participants did not benefit from time to adapt to frequency compression or microphone mode; nor were there any significant interactions involving frequency compression, microphone mode or time (p>0.19).



FC off

FC on

Figure 3. F-B RMS error over time for frequency compression off and on, with omni-directionality and high-frequency directionality. Vertical bars indicate 95% confidence intervals.

Speech recognition in noise

To investigate the effect of frequency compression and microphone mode on speech recognition in noise, a repeated measures ANOVA was conducted using SRT SNRs as observations and frequency compression (on, off), time (1, 4, 8 weeks with scheme), microphone mode (omni-directionality, high-frequency directionality) and noise direction (0˚, 180˚ azimuth) as repeated measures. Although a lower (better) SRT SNR of about one dB was produced, on average, when frequency compression was on, this analysis found no significant effect of frequency compression ($F_{1,22}$=1.18, p=0.29), or microphone mode ($F_{1,22}$=1.83; p=0.19). There was, however, a significant main effect of noise direction ($F_{1,22}$=4.91, p=0.04) and a significant interaction between microphone mode and noise direction ($F_{1,22}$=7.72, p=0.01) with high-frequency directionality improving SRT SNR when noise was presented from 180˚ by, on average, 1.3 dB; i.e. high-frequency directionality provided spatial release from masking but omni-directionality did not (Figure 4).

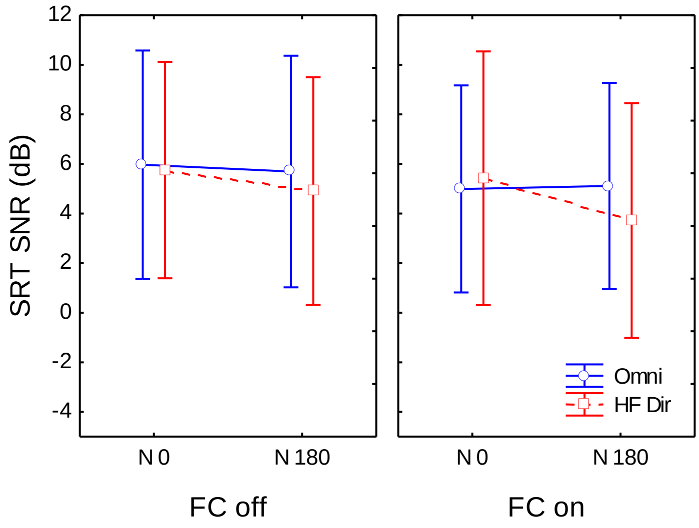


Figure 4. SRT SNR averaged across time with frequency compression on/off for omni- and high-frequency directional modes with noise presented from 0˚ and 180˚ azimuth. Vertical bars indicate 95% confidence intervals.

There were near-significant interactions between time and noise direction ($F_{2,44}$=2.86, p=0.07) and frequency compression, time and noise direction ($F_{2,44}$=2.88, p=0.07; Figure 5). Tukey's post hoc analysis showed that the SRT SNR for noise from 180˚ azimuth was significantly higher at week 1 than at week 8 with frequency compression off (p<0.04). This indicates that despite initially poorer speech recognition in spatially separated noise with frequency compression disabled, after eight weeks listeners had learned to benefit from the spatial separation of speech and noise such that their performance was similar to when frequency compression was enabled. No such adaptation over time was observed with frequency compression enabled or for either condition when noise was presented from 0˚ azimuth. No other interactions were significant (p > 0.09).

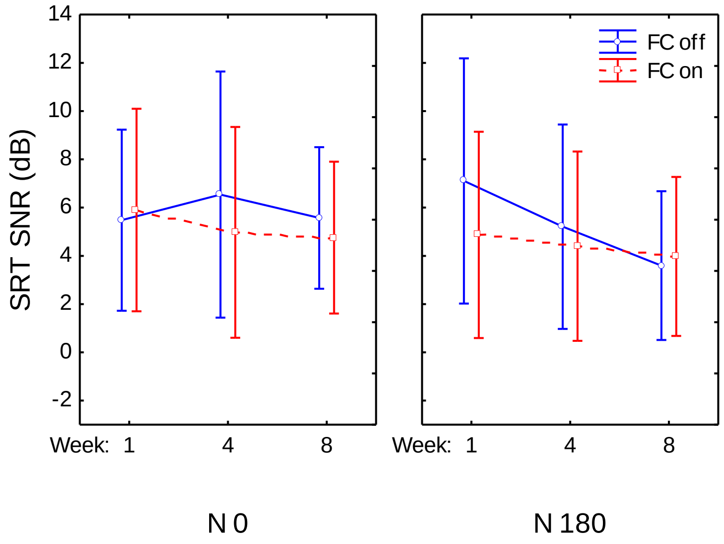


Figure 5. Average SRT SNR over time (averaged across microphone modes) with frequency compression on and off, for noise from 0˚ and 180˚ azimuth. Vertical bars indicate 95% confidence intervals.

For both the localization and speech recognition tests, the group's performance was quite homogenous. Specifically, across appointments, none of the participants consistently produced a difference value between F-B RMS error with frequency compression on and off that exceeded the standard deviation of all participants' difference values as calculated for each specific test condition (microphone mode, stimulus). Using the same criterion for SRT SNR performance, only one participant consistently performed better across appointments and conditions (microphone mode, noise direction) with frequency compression on while another performed better with frequency compression off. Consequently, candidacy for this feature was not further explored.

Subjective evaluation of schemes

The SSQ rating scale ranged from zero (greatest handicap) to ten (perfect ability). The participants' ratings for each item were clustered and averaged according to ten domains described in Gatehouse and Akeroyd[12].

To investigate whether there was any difference between frequency compression on or off, an analysis of variance was conducted using the rating for each SSQ sub-scale as observations, and amplification (frequency compression on/off) and sub-scale (Speech 1–4, Spatial 1-2 and Qualities 1-4) as repeated measures. This analysis showed a significant effect of sub-scale ($F_{9,198}$=40.07, p<0.000001), indicating that participants experienced varying degrees of handicap depending on the sub-scale in question. However there was no significant effect of frequency compression ($F_{1,22}$=0.08, p=0.78), nor a significant interaction between frequency compression and sub-scale ($F_{9,198}$=0.87, p=0.55). Frequency compression therefore did not make a noticeable difference to participants' perceived handicap for the speech, spatial or qualities of hearing domains evaluated.

In the exit interviews, participants were asked to rate the performance of each microphone mode for each test scheme from one (extremely poor) to seven (excellent), excluding in very loud or noisy situations. The average rating across amplification schemes and microphone modes was just under six (very good), indicating a high degree of satisfaction with the hearing aids. To examine more closely whether any of the combinations of frequency compression and microphone mode influenced performance ratings, a Friedman ANOVA was conducted using frequency compression (on, off) and microphone mode (omni-directionality, high-frequency directionality) as the dependent variables. This showed no significant interaction between frequency compression and microphone mode (df=3, p=0.15; Figure 6).

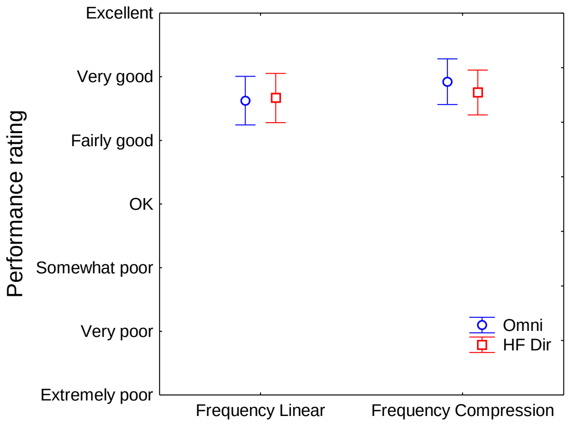


Figure 6. Average performance rating for frequency compression on/off with omni-directionality and high-frequency directionality. Vertical bars indicate 95% confidence intervals.

Discussion

While high-frequency directionality significantly improved F-B localization, frequency compression did not. It is speculated that even if frequency compression increased audibility of monaural high-frequency F-B localization cues between 2 – 5 kHz, the fact that they were spectrally compressed may have made them less useable. Data from Keidser et al[7], collected using the same localization test set-up, suggests that hearing aid users are able to utilize mid-frequency information for F-B discrimination in the horizontal plane. It is therefore possible that the information in the mid-frequency region above ~ 1.3 kHz (the starting frequency for high-frequency directionality) and below ~ 2.5 kHz (the frequency compression threshold of most participants), *replaced* rather than supplemented the traditional high-frequency cues used for F-B discrimination. This 1.3 – 2.5 kHz frequency range is substantially smaller than the available (non-compressed) mid-frequency range in the Keidser et al[7] study, in which improved F-B localization was demonstrated with high-frequency directionality above 1 kHz. The comparatively small frequency range may account for the smaller magnitude of improvement in the current study (4.5˚ compared with ~ 10˚).

High-frequency directionality improved speech recognition in noise when the noise was spatially separated from the speech. Frequency compression provided some benefit initially when listening to speech in spatially separated noise; however this advantage diminished over time as participants' performance improved with frequency compression turned off. There was no significant benefit of frequency compression when listening to non-spatially separated speech in noise. The effectiveness of the frequency compression in re-introducing audibility of high-frequency speech sounds was not tested, so it is possible that at positive SNRs participants with better high-frequency hearing may have heard all phonemes even with frequency compression disabled or, conversely, that participants with poorer high-frequency hearing may have found high-frequency phonemes inaudible even with frequency compression enabled. This is consistent with anecdotal experiences of the researchers that participants did not notice a striking difference between frequency compression on/off when the frequency compression strength was being fine-tuned. It is also possible that participants gained access to some speech sounds but lost reliable discrimination of others; e.g. /s/ became audible but was indistinguishable from /ʃ/[13]. Ensuring discrimination between /s/ and

/ʃ/ has since become a recommendation when fitting frequency compression (Scollie et al, in[14]). Finally, although frequency compression has been found to assist speech detection/discrimination in quiet[2,4,6], our findings suggest it is less beneficial for understanding speech in noise. It should, however, be noted that the NAL-NL1 fitting prescription used in the current study tends to prescribe less high-frequency gain than the fitting prescriptions used in at least two of the aforementioned studies, and that this could play a role in the audibility of both frequency compressed and uncompressed high-frequency information.

Additionally, the monosyllabic speech material used intentionally denied participants any supportive context (apart from lexical knowledge) which forced them to rely on the bottom-up processing of acoustic information in the presence of 8-talker babble. Given older listeners in difficult listening situations rely more on supportive context than younger listeners[14], it may be that this was an overly difficult task for our participants whose average age was 78.7 years, even if frequency compression provided some ease of cognitive loading (which was not measured). Supporting this are other, unpublished, data collected at NAL on 25 volunteers with a similar average age (75.5 years). These participants' average aided SRT SNR for sentence material spoken by a male and presented in 24-talker babble was about 7 dB better, which is likely due at least in part to richer contextual information in the sentence material.

Consistent with the objective measurements, subjective evaluations of the test schemes in the field showed that although the participants rated the hearing instruments very well, there was no significant difference between ratings with frequency compression on or off.

It may be instructive for further work in this area to explore the effect of prescribed gain on benefit from frequency compression, and whether frequency compression eases cognitive loading in challenging listening situations.

Clinical implications

1. In older adults with hearing loss similar to those configurations used in this study, fitted with NAL-NL1, frequency compression neither harms nor helps front-back discrimination, speech recognition in noise or satisfaction with amplification.

2. Where possible, omni-directionality should be replaced with high-frequency directionality in BTE fittings as it offers small but significant benefit for both front-back localization and speech recognition in noise, without detriment to satisfaction with amplification.

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