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The Effect of Digital Phase Cancellation Feedback Reduction Systems on Amplified Sound Quality

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Abstract

The effect of feedback reduction (FBR) systems on sound quality recorded from two commercially available hearing aids was evaluated using paired comparison judgments by 16 participants with mild to severe sloping hearing loss. These comparisons were made with the FBR systems on and off without audible feedback and while attempting to control for differences in gain and clinical fitting factors. Wilcoxon signed rank test analyses showed that the participants were unable to differentiate between signals that had been recorded with the FBR systems on and off within the same hearing aid. However, significant between-instrument differences in sound quality were identified. The results support the activation of the FFT-phase cancellation FBR systems evaluated herein without concern for a noticeable degradation of sound quality.

Key Words: Feedback reduction system, hearing aid, paired comparison, sound quality

Abbreviations: FBR = feedback reduction; FFT = fast Fourier transform; LMS = least mean square; NAL-NL1 = National Acoustic Laboratories Non-linear 1; RMS = root mean square

Sumario

Se evaluó el efecto de los sistemas de reducción de la retroalimentaciñn (FBR) sobre la calidad del sonido registrado por medio de dos auxiliaries auditivos disponibles comercialmente, utilizando juicios de comparación en pares, de 16 participantes con una hipocusia leve a moderada de pendiente pronunciada. Estas comparaciones se realizaron con los sistemas FBR apagados y encendidos, sin retroalimentación audible y tratando de controlar las diferencias en cuanto a ganancia y a factores clínicos de adaptación. Los análisis de pruebas de rango certificados por Wilcoxon mostraron que los participantes no podian diferenciar entre señales que habian sido registradas con los sistemas de FBR encendidos o apagados dentro del mismo auxiliar auditivo. Los resultados apoyan la activación de los sistemas de FBR de cancelación de fase FFT, aqui evaluados, sin preocupaciones por una degradación identificable en la calidad del sonido.

Palabras Clave: Sistema de reducción de la retroalimentación, auxiliar auditivo, comparación en pares, calidad de sonido

Abreviaturas : FBR = reducción en la retroalimentación; FFT = transformación rápida de Fourier; LMS = cuadrado medio mínimo; NAL-NL1 = Laboratorios Nacionales de Acústica No lineal 1; RMS = media de la raíz al cuadrado

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The presence of audible, acoustic feedback is a major concern as annoyance caused by feedback can drastically reduce patient satisfaction (Kochkin, 2003). In fact, 24% of hearing aid wearers reported dissatisfaction with a hearing aid due to audible noise generated by the hearing aid or "whistling," a common complaint associated with feedback (Kochkin, 1997). A hearing aid will start to feedback once the gain of the hearing aid has been increased at a frequency where the amplitude of the feedback loop response is greater than 0 dB at a phase multiple of 360 degrees (Hellgren et al, 1999), where a feedback loop response refers to the frequency, amplitude, and phase characteristics of the pathway from the receiver to the microphone. In addition, aspects of both hearing aids and hearing loss exacerbate acoustic feedback problems.

Used in almost all current hearing aids (Dillon, 2001), the aim of low threshold compression (often referred to as "wide dynamic range compression," or "WDRC") systems is to maximize audibility of speech by placing the acoustic speech cues within a reduced dynamic range. Thus, compression systems provide increasing gain for decreasing inputs down to the compression threshold. As a result of increased gain for low inputs, feedback is more likely to occur for low intensity inputs in compression systems. Furthermore, approximately 90% of hearing losses in adults are downward sloping from 500 Hz to 4 kHz (Dillon, 2001), and prescriptive targets for sloping hearing losses accordingly apply more gain for higher frequencies than lower frequencies. In addition, the amplitude of the feedback loop response is greatest between 2 and 5 kHz, and therefore, feedback is most likely to occur in this frequency range (Kates, 1999).

COMBATING THE PROBLEM OF FEEDBACK

Given how common and deleterious the presence of hearing aid feedback is, it is not surprising that a number of methods have been proposed to reduce the likelihood of feedback occurring. As described below, some of these methods are quite effective at reducing feedback levels; however, concerns related to potential side effects remain. Specifically, it is unknown whether the positive impact of reduced feedback might be offset by concomitant reductions in sound quality related to this processing.

Solutions for Feedback

One traditional method for reducing the likelihood of feedback is to increase the microphone and receiver separation by increasing the size of the hearing aid product worn by the user. Through the use of larger hearing aids, the feedback loop response must be more intense due to the increased distance separation from the receiver and microphone to yield audible oscillations. Decreasing the residual diameter of the vent or the selection of a fully occluding vent are other techniques that will decrease the likelihood of audible feedback (Kuk, 1994). However, one negative side effect of reducing the vent size is the increasing presence of the occlusion effect, which results in reduced sound quality for the hearing aid wearer's own voice (Wimmer, 1986). Given the trading relationship between the occlusion effect and acoustic feedback as a function of vent size, it is of considerable interest to reduce the occlusion effect while limiting feedback.

A number of algorithms have been introduced using advanced digital signal processing in modern hearing aids in an attempt to reduce audible feedback, while also allowing for greater amounts of gain with larger vent sizes that reduce problems with the occlusion effect. Most of the FBR (feedback reduction) systems in new hearing aid models are classified as a continuous method feedback reduction system (Chung, 2005). A continuous method means that the system constantly monitors for the presence of feedback and updates the cancellation parameters without interrupting output of the hearing aid processed signal. This type of system contrasts earlier implementations of noncontinuous FBR systems that introduced an audible probe tone to estimate cancellation parameters to reduce detected feedback. Two implementations of the continuous and noncontinuous methods of FBR systems are notch filtering and phase cancellation.

While not assessed in the current study, the operation of adaptive notch filter systems may be described simply as those that reduce gain within a frequency band where feedback is occurring (Agnew, 1996). The notch filter in these systems was designed so that it may exist within one channel over a small frequency range or within concurrent frequency bands over a broader frequency range. In addition, some systems have been designed to incorporate two or more narrow notches simultaneously. This type of system is now less commonly used by hearing aid manufacturers as a means of long-term digital feedback reduction in comparison to the next type of FBR system discussed.

The FFT (fast Fourier transform)-phase cancellation method of FBR system implementation attempts to reduce feedback by generating a signal of equivalent amplitude 180° out of phase with the estimated feedback pathway frequency response. This estimated response is then processed in parallel with incoming signals. The continuous digital, FFT-phase cancellation method continually adjusts adaptive filter weights while processing signals and tracking changes in the feedback loop response utilizing a least mean squares (LMS) adaptation (Widrow et al, 1976) or other similar techniques. After several recursive iterations of estimating the feedback pathway, optimal filter weights best reflecting the actual feedback pathway, as determined by the LMS differences between the estimated and actual pathway, are used (Maxwell and Zurek, 1995). Feedback is alleviated by filtering the hearing aid output with this approximation of the feedback path transfer function, which may be established during the initial processes in the hearing aid fitting session (static pathway) and/or while monitoring the feedback pathway during actual hearing aid use (dynamic pathway). The details related to deriving the feedback pathway transfer function are hearing aid specific. Accordingly, performance of FBR systems might be expected to vary between two hearing aid products with FFT-phase cancellation FBR processing implemented differently.

Evaluation of Electroacoustic FBR Systems

The performance or effectiveness of an FBR system is often only evaluated by measuring additional gain before feedback. This is often termed "gain margin" or "gain headroom." Depending on the effectiveness of the FFT-phase-cancellation-based FBR system, gain headroom can be as large as 20 dB before onset of feedback without loss of any of the high-frequency response; however, when measured in real ears, it is generally between 8 and 15 dB (see Kates, 1999, for review).

In contrast to simply measuring gain headroom, Maxwell and Zurek (1995) suggested that both gain headroom and inadvertent side effects of processing be measured when assessing FBR systems after finding reduced sound quality for signals processed with feedback reduction techniques. These authors suggested that due to processing of all methods of digital FBR algorithms, signals of interest can be corrupted or possess other annoying features. That is, all signals subjected to FBR system processing have potential negative characteristics compared to unprocessed signals, (e.g., spectral dips, phase distortions, or other distortions). However, since 1995 there has been much advancement in digital processing related to feedback reduction processing, and these artifacts may be less notable than before. For example, a study of a laboratory-based hearing aid feedback reduction system utilizing a continuous phase cancellation method yielded no significant effect on the pleasantness and intelligibility of speech using speech-quality ratings (Greenberg et al, 2000). However, no known published study has evaluated the effect of continuous FBR systems on perceived sound quality by listeners with hearing impairments with commercially available, digital hearing aids.

In these commercial systems, the allocation of processing power is spread across multiple digital signal processing tasks in the hearing aid (e.g., noise reduction, data logging, etc.) and may limit estimation accuracy of the feedback loop response and/or production of the feedback cancellation signal resulting in audible artifacts. Additionally, prior sound-quality evaluation of FBR systems has mostly concentrated on speech inputs without much attention to other important signals such as music. Both speech and more tonal music signals are of interest, as they represent commonly heard sounds in the daily lives of persons with hearing loss; however, it is unclear if FBR systems will have differing effects on sound quality of these two signal types. For example, signals such as the musical notes from a flute may be inadvertently classified as feedback due to their tonal nature, and unintentionally subjected to FBR system processing.

The purpose of this experiment was to examine the effect of two commercially implemented continuous, FFT-phase cancellation FBR systems on perceived sound quality by listeners with sensorineural hearing impairments. FBR systems similar to those selected are increasingly becoming standard in digital hearing aids (Chung, 2005). Paired comparisons of overall sound quality were made on speech and music signals recorded at the output of the hearing aids with FBR activated and deactivated. Recorded signals were used to allow for matching of frequency response and amplitude level both across and within instruments.

METHOD

Participants

A total of 16 participants that ranged in age from 58 to 84 years (mean = 75) made sound-quality comparisons monaurally of hearing aid-processed speech and music recordings. Pure-tone air-conduction hearing thresholds were measured on all participants indicating sloping hearing losses in the borderline normal/mild to severe range from 250 to 8000 Hz. Comparisons with previous clinical records reaffirmed this finding and ensured that hearing losses were sensorineural in nature. The average audiogram for the participants' ear used in the study is shown in Figure 1. This wide range of hearing loss was included to represent the range of hearing losses that may be fit with a BTE hearing aid that utilizes FBR processing.

Signal Preparation

Hearing Aids

Two commercially available BTE hearing aids were selected for this study. Each hearing aid was coupled to a single participant's ear using a skeleton earmold with a 3 mm vent (Westone style 12). This earmold was selected to increase the likelihood of feedback requiring engagement of the hearing aid FBR systems. The first hearing aid (HA1) utilized an FFT-phase canceller for reducing feedback. The second hearing aid (HA2) was a product that combined both FFT-phase cancellation and adaptive notch filters for the reduction of feedback; however, the FFT-phase cancellation portion of the system was responsible for the long-term cancellation feedback in the static

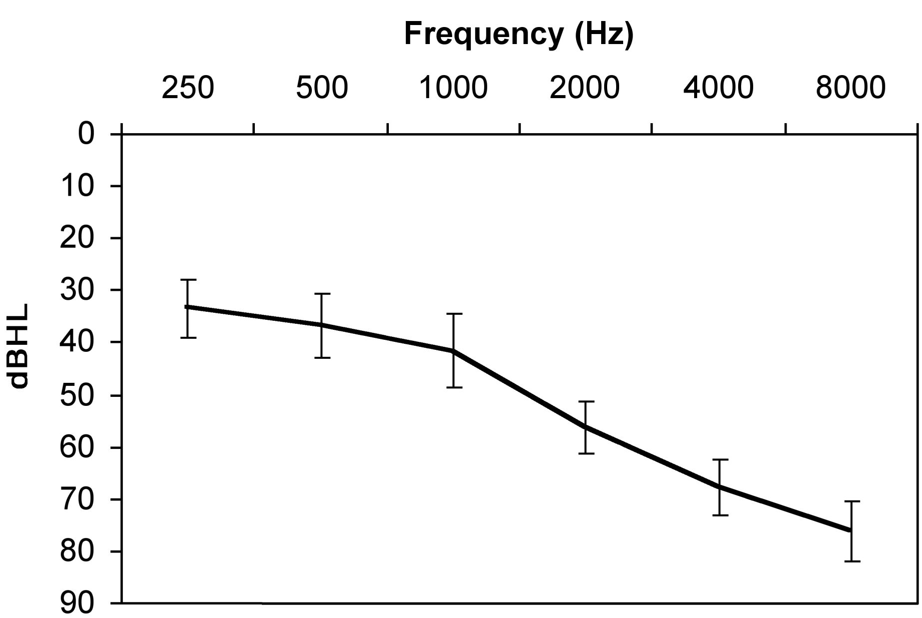

Figure 1. Average audiogram for the test ears used from the study participants with 95% confidence interval bars.

feedback pathway assessed in this experiment as it should have engaged after 5–10 sec of use given this system's feedback reduction time constants.

The feedback system for HA1 utilized the continuous method of feedback reduction and has been described in two stages: feedback detection and suppression (Chung, 2005). First, the feedback path was estimated by internally generating a noise burst and analyzed for level and frequency at the microphone input. Quantitatively, the noise burst was a known signal by the hearing aid system, and thus, the feedback pathway loop response is estimated by examining the difference of the known noise burst and the composition of the noise burst at the input of the microphone. A signal generated 180° out of phase with the estimated feedback pathway of equivalent amplitude is then processed in parallel with incoming signals of interest to somewhat negate the feedback pathway. Secondly, the system adaptively monitored incoming signals for feedback. Adaptation times for the feedback system in this system were proprietary (Chung, 2005). This specific FBR system was constrained, thus meaning it does not adapt to signals that deviate significantly from the initial estimated feedback pathway (Kates, 1999). That is, this system was deliberately designed to not cancel environmental tone-like or transient signals that were not feedback.

HA2 was a continuous method FBR system that has been described in three steps. Like HA1, a noise was internally generated and analyzed at the microphone input to set the baseline for the slow-acting component of the feedback reduction system. A signal 180° out of phase with the estimated feedback pathway was then processed in parallel with incoming signals for suppression of static pathway feedback. A series of tonal-like signals were generated for setting the baseline for the fast acting component that monitored feedback in the dynamic pathway. Adaptation times have been reported at less than 1 sec for the fast-acting component and 5 to 10 sec for the slow-acting component (Chung, 2005).

Stimuli Preparation

Two different test signals were recorded as processed by the hearing aids with one participant. The test signals were two sentences (approximately 7 sec in duration) from the lemon passage of the Speech Intelligibility Rating Test (Cox and McDaniel, 1989) and 7 sec of Mozart's Flute Concerto no. 2 in D. These signals are herein referred to, respectively, as speech and music. The spectral characteristics of the signals are shown in Figure 2. In the figure, the tonality of the music signal is apparent

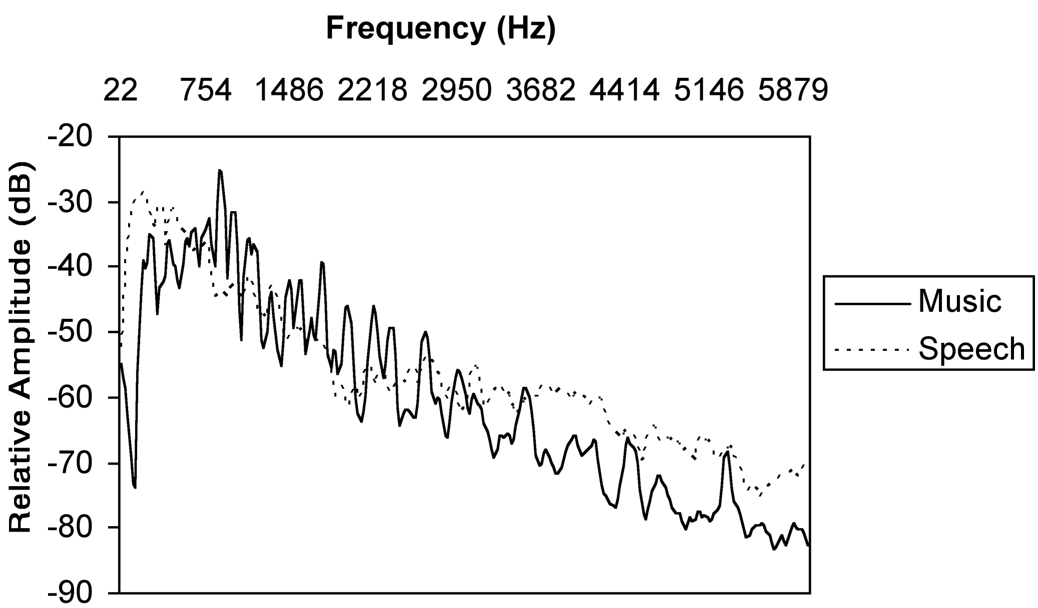

Figure 2. Long-term average frequency spectrum of the music signal (excerpt from Mozart's Flute Concerto no. 2 in D) and speech signal (sentence excerpt from the Lemon passage of the Speech Intelligibility Rating Test).

in contrast to the speech signal. The signals were presented at a level of 50 dBA in the sound field to the participant who wore the hearing aids programmed to insertion gain NAL-NL1 (National Acoustic Laboratories Non-linear 1) prescriptive targets for a 50 dB input. Hearing thresholds and insertion gain targets for this participant are shown in Figure 3. The speech and music stimuli were output from an Echo Darla soundcard on a Pentium 4 computer routed through a Grason-Stadler GSI-61 audiometer to provide amplification and presented in the sound field from a point-source, forward-firing loudspeaker (Tannoy System 600™) located at a 0° azimuth 1 m from the participant. In addition to a hearing aid, the participant wore an earhook, on which the reference and measurement microphone for the Fonix 6500-CX system was placed, as well as a low-noise recording microphone (Etymotic Research, ER-7). The amplified test signals were recorded in the ear canal using the ER-7 microphone and a second Echo Darla soundcard.

Due to a default manufacturer setting, HA2 initially limited its gain to 6 dB below hearing aid detected feedback providing one reason why HA2 provided less gain headroom than HA1. Thus, HA1 was first programmed to match HA2's maximum output before feedback in both the FBR system off and on recordings of the speech and music signals in the static feedback pathway. Thus, for both hearing aids the gain levels at the time of recordings were well below a level to cause feedback. Frequency matching across aids was verified with the Frye 6500CX creating conditions with similar gain headroom for the two aids. These recordings are referred to herein as "Lower" conditions. For the Speech Lower and Music Lower gain condition recordings, the gain headroom for both HA1 and HA2 was 2.4 dB and 2.23 dB, respectively. Given a change from the manufacturer default of 6 dB to 1 dB for the feedback margin setting, maximum gain headroom for HA2 would be expected to be 5 dB greater than the gain headroom utilized in these experimental conditions.

Additional recordings of the signals were made with HA1 at the hearing aid output level deemed (1 dB) below audible feedback. For these recordings, only HA1 was programmed to maximum gain without audible feedback to create "Higher" gain experimental conditions. This second condition was evaluated so that the effect on sound quality of the FBR system in HA1 could be examined in an experimental condition that required substantial effectiveness of the system unlike the lower gain conditions. In the Speech Higher and Music Higher conditions, gain headroom corresponded to 15.75 dB and 13.1 dB. For both the Lower and Higher gain conditions, increases in gain for the FBR-on conditions were performed while maintaining the general frequency response shape of the prescribed NAL-NL1 frequency response.

It is important to consider that variations

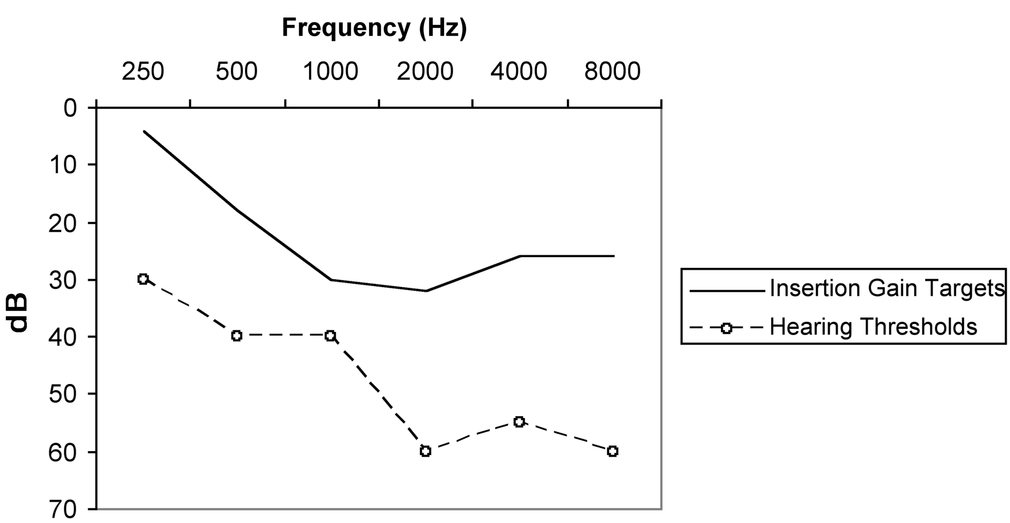

Figure 3. Audiogram in dB HL for the participant and insertion gain targets in dB for the hearing aid used when recording experimental stimuli.

in frequency shaping and gain during the recording of a signal and at the time of signal presentation may supersede small distortions of the FBR processed signals and, thus, dominate the rating of sound quality. Consequently, it was important to equate hearing aid conditions (e.g., FBR-off versus FBR-on) for both amplitude and frequency response to determine the effect of FBR system processing in isolation. Thus, following the recording process, all speech and music files were shaped offline using Adobe Audition 1.5 FFT frequency shaping to match the frequency response prescribed by the NAL-NL1 prescriptive method (Byrne et al, 2001) for the participant with the poorest hearing thresholds at octave frequencies 250–8000 Hz (Figure 4). These shaped stimuli were presented to all study participants at the same output levels. While this gain and shaping provided greater than normal audibility for most participants, shaping to this participant's prescriptive targets was chosen to further increase the audibility of any potential negative attributes in the FBR processed signals for study participants. Thus, the audibility of these attributes was at least equivalent to or greater than recordings that could have been made at individual specific NAL-NL1 prescriptive target that are known not to provide complete audibility. The shaped speech and music files were individually presented via an ER-2 earphone to verify correct shaping in a Zwislocki coupler connected to a Larson Davis 814 sound-level meter. An analysis of output sound pressure level through 6 kHz showed good agreement between the prescribed output and shaped output of the speech and music files with an average RMS (root mean square) difference of 2.19 dB.

Procedures

Participants completed round robin paired comparisons of the recorded test stimuli monaurally. The paired comparison method was chosen over other methods (e.g., category rating and magnitude estimation) of accessing sound quality as it is a more sensitive and effective technique for differentiating small differences in sound quality (Eisenberg et al, 1997), as we hypothesized that, if present, any differences in sound quality as a byproduct of FBR processing would be small. Certainly, more realistic of real-world use, the hearing aids could have been fit individually to the patients for a period of time to compare sound-quality differences. However, this method is grossly less adequate for differentiating small reliable differences in sound quality than the paired comparison method.

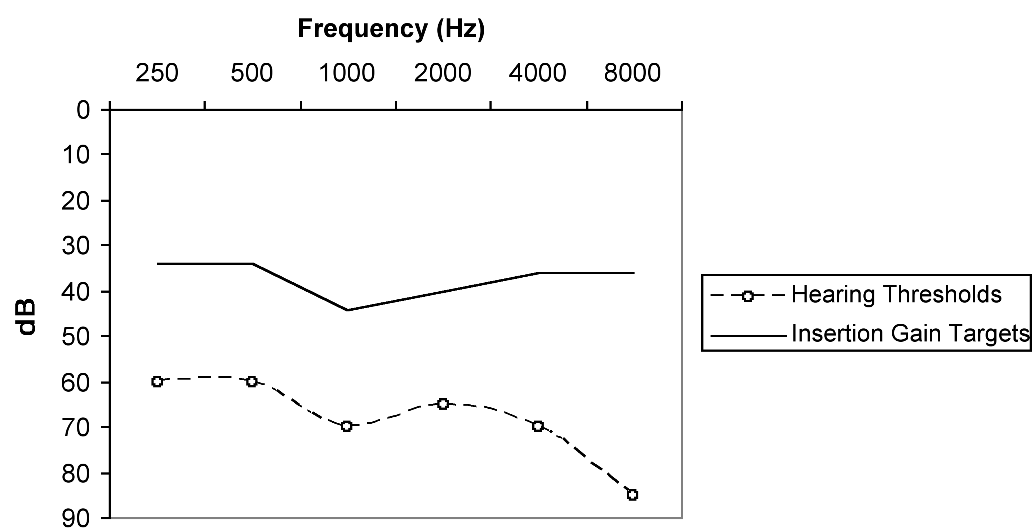

Figure 4. Audiogram in dB HL for the participant and insertion gain targets in dB used when shaping experimental stimuli to the frequency response presented to all participants.

The paired comparison method requires that the two items of interest remain in memory for the length of time required to make direct comparison between the items (Thurstone, 1927a, 1927b; Edwards, 1957). The length of the stimuli (i.e., 7 sec) was chosen over longer duration stimuli (e.g., 1 min or longer) as shorter signals, of a few seconds in duration, are more appropriate than longer signal segments for paired comparison testing as the listener needs to recall the sound quality of both signals in short-term memory when making a preference judgment. In addition, short signal segments are preferred for timeliness as judgments need to be made multiple times for each experimental condition to obtain a reliable preference (Punch and Parker, 1981).

Of the 16 participants, ten made sound-quality assessments with their right ear while six used their left ear. Ten paired sound-quality comparisons of the recordings included the FBR-on and FBR-off conditions within each hearing aid, as well as FBR-on across both hearing aids and FBR-off across both hearing aids. Note that not all possible sound-quality comparisons were included as comparisons of FBR-off versus FBR-on across aids were not of interest and not examined (e.g., HA1 FBR-off versus HA2 FBR-on, etc.). All comparisons were presented a total of eight separate times to establish a more reliable account of the sound-quality differences in the pair (Punch and Parker, 1981). Thus, each participant made 80 total comparisons. The actual presentation order of the pairs was randomized within each experimental condition block (Speech Lower, Music Lower, Speech Higher, and Music Higher). The presentation order of the experimental conditions was counterbalanced within a subject and across subjects.

Each of the participants made an overall sound-quality preference judgment for each pair of shaped recordings (e.g., HA1 FBR-on versus HA1 FBR-off, etc.). A strength of preference rating scale was added to accentuate the magnitude of the difference in the overall sound-quality preference for each pair (Keidser et al, 1995; Ricketts and Hornsby, 2005). The strength of preference rating scale used "Much Better," "Moderately Better," and "Slightly Better." Number values should not represent this scale as the distance between numbers may not reflect the amount of difference between ordinal rankings (Speaks, 1992; Howell, 2002). Thus, numerals of 1, 2, and 3 corresponding respectively to "Little Better," "Moderately Better," and "Much Better" were used to reflect ordinal distances for the strength of preference rating scale. For each comparison, the preferred signal according to its strength of preference was assigned a numeral, and the non-preferred signal was assigned a zero.

Results

Nonparametric statistics (i.e., sign test and Wilcoxon signed rank test) were chosen over more commonly used parametric statistics (e.g., matched pairs t-test) due to the ordinal versus interval nature of the data. The overall preference judgment results without the rating scale were analyzed with the sign test and refer to the frequency count of one processed signal preferred over another processed signal in each comparison. The same comparisons with the strength of preference rating were also analyzed with Wilcoxon signed rank test. As expected, use of the strength of preference rating increased the likelihood of observing a significant difference in paired comparisons in almost all cases. In cases where the likelihood was not increased using the strength of preference ratings, significant differences were not shown using the overall preference rating either. Results are presented based on the analyses with the overall preference and strength of preference ratings.

Planned, a priori comparisons of main interest paired the same hearing aid in its FBR-on and -off state. These pairings addressed the study's main purpose of determining an FBR system's effect on sound quality. For these six comparisons, an alpha level of significance was defined at .05. None of these experimental condition pairings yielded a significant sound quality preference (see Table 1 for details). Additionally, the lack of observed differences using both the speech and music signals suggests no effect of the signal types examined with these systems either.

In addition to within-hearing-aid differences, it was also of interest to determine if differences existed between hearing aids

Table1. FBR-Off versus FBR-On Comparisons for All Experimental Conditions

		Sign test α = .05	Wilcoxon signed rank test α = .05
Speech Lower Condition			
HA1 FBR-on	HA1 FBR-off	Z = -.265, p = .791	Z = -1.863, p = .062
HA2 FBR-on	HA2 FBR-off	Z = -1.503, p = .133	Z =-1.762, p = .078
		Sign test α = .05	**Wilcoxon signed rank test α = .05**
Speech Higher Condition			
HA1 FBR-on	HA1 FBR-off	Z = -.088, p = .930	Z = -.291, p = .771
		Sign test α = .05	**Wilcoxon signed rank test α = .05**
Music Lower Condition			
HA1 FBR-on	HA1 FBR-off	Z = -.972, p = .331	Z = -964, p = .335
HA2 FBR-on	HA2 FBR-off	Z = -.088, p = .930	Z = -.201, p = .841
		Sign test α = .05	**Wilcoxon signed rank test α = .05**
Music Higher Condition			
HA1 FBR-on	HA1 FBR-off	Z = -.088, p = .930	Z = -.201, p = .841

Note: Statistical values for the Sign test relate to the frequency count of the preferences and the Wilcoxon signed rank test relate to the strength of the comparison preferences for all participants. Bolded α values represent the significant alpha level used to determine significant preferences of sound quality. No asterisk is present to indicate a preference as the comparisons did not yield a significant finding.

when the FBR system was deactivated and activated (Table 2). This comparison was completed to confirm matching of the two hearings aids. Although the two hearing aids could not be matched exactly, the rate of recurrence for sound-quality differences between the two was unexpected. Post hoc comparisons across hearing aids based on an alpha level as defined by .05/4 or 0.0125 to control for an increase in familywise error rate demonstrated significant differences in three out of four paired comparisons.

When significant differences were noted, HA1 was less preferred than HA2. Representative of this trend, in the Music Lower gain condition, HA1 was less preferred than HA2 ($p < .001$). A paired comparison of the HA1 FBR-off versus HA1 FBR-off recordings for a measure of presentation order rating bias was also analyzed. Thus, the HA1 FBR-off recording was presented in both the first and second intervals to determine if participants chose a given interval more often. The comparison yielded a nonsignificant difference in perceived sound quality ($p = .256$), suggesting that the listeners' preferences were not related to the ordering of the paired comparisons.

To represent the data visually to the reader, albeit in an interval scale, Figure 5

Table 2. Hearing Aid Comparisons in Lower Gain Conditions

		Sign test α = .0125	Wilcoxon signed rank test α = .0125
Speech Lower Condition			
HA2 FBR-on	HA1 FBR-on	Z = -1.149, p = .251	Z = -.943, p = .346
HA2 FBR-off	HA1 FBR-off	Z = -2.563, p = .010*	Z = -3.697, p < .001*
Control comparison			
HA1 FBR-off	HA 1 FBR-off	Z = -1.326, p = .185	Z = -1.137, p = .256
		Sign test α = .0125	**Wilcoxon signed rank test α = .0125**
Music Lower Condition			
HA2 FBR-on	HA1 FBR-on	Z = -3.977, p < .001*	Z = -5.129, p < .001*
HA2 FBR-off	HA1 FBR-off	Z = -5.038, p < .001*	Z = -6.024, p < .001*

Note: Statistical values for the Sign test relate to the frequency count of the preferences and the Wilcoxon signed rank test relate to the strength of the comparison preferences for all participants. Bolded α values represent the significant alpha level used to determine significant preferences of sound quality. The asterisks indicate pairings in which a significant preference for a hearing aid was present.

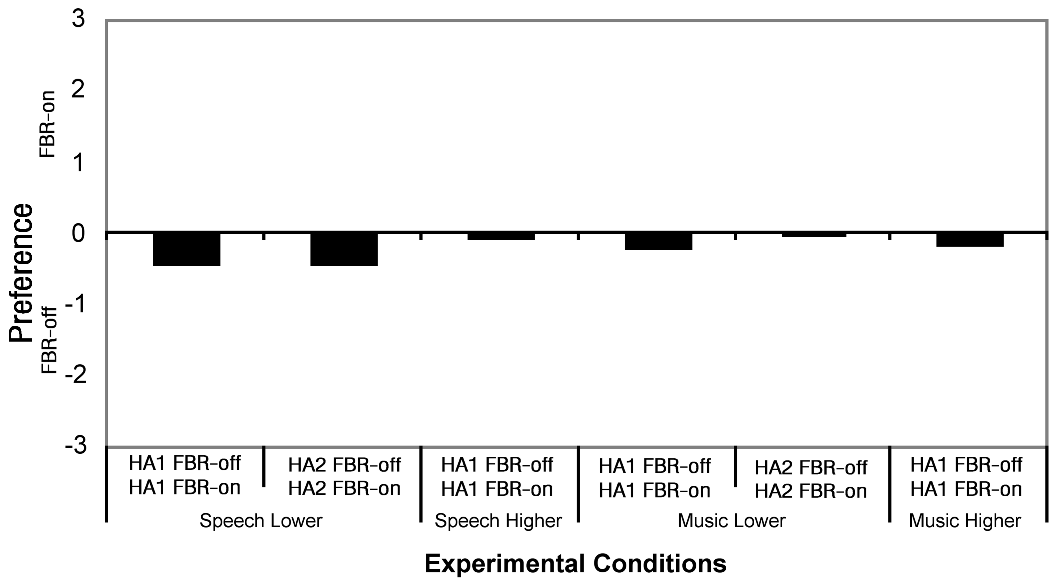

Figure 5. Mean strength of preference rating difference in FBR-off versus -on conditions for all experimental conditions across all subjects. Note that HA1 had greater gain headroom capabilities than HA2, and only HA1 was assessed in the "Higher" gain headroom conditions.

demonstrates the effect of activating the FBR system, showing the difference in the mean rating of the FBR-off and -on comparison preferences for each of the two hearing aids. Recall that only HA1 was examined in the Speech Higher and Music Higher conditions. Figure 5 is presented such that a positive difference indicates more preference for FBR-on processing and a negative difference indicates more preference for FBR-off processing. Figure 6 is presented such that a positive difference indicates more preference for HA2 and a negative difference indicates more preference for HA1 with the exception of the control comparison. In creating these figures, the preferred signal chosen by the participant was assigned a value of 1 to 3 corresponding to the strength of preference rating scale and a negative 1 to 3 for the nonpreferred signal. Thus, for each experimental condition, an average value of near zero for the eight repeated preference judgments by all participants presumes no preference. It is of note that when the data was viewed as interval in nature, matched pairs t-tests on the data showed the same pattern of nonsignificant and significant findings as the Wilcoxon signed rank tests. Thus, an asterisk, if present in Figures 5 and 6, indicates a paired comparison for which a significant sound-quality preference was established.

Discussion

Recall that the primary purpose of this investigation was to determine if FBR system processing significantly affected the perceived sound quality of a signal when compared to a signal not subjected to FBR system processing. Activation of the FFT-phase cancellation FBR systems used in the two test hearing aids did not lead to significant changes in sound quality for any of the six tested conditions that paired the same hearing aid with the FBR system on and off. Two of these six comparisons were with HA1's FBR system on while providing substantial gain headroom of 13.1 dB and 15.75 dB at the time of recording in the Music Higher and Speech Higher experimental condition, respectively. Thus, clinically, the benefit of additional gain afforded to listeners with hearing impairments by this FBR system is not expected to be offset by degraded sound quality, at least for the implementation of FBR system processing used in the test devices. These results are in good agreement with previous work on a laboratory-based hearing aid system with a continuous FBR system, which also showed no effect on intelligibility or pleasantness of sound using speech-quality ratings (Greenberg et al, 2000).

That said, a closer visual examination of

Figure 5 showed a slight trend of the FBR-on recordings being preferred less than the FBR-off recordings across all conditions, even though no difference reached statistical significance. More statistical power in the experimental design can always increase the likelihood of identifying small but real differences, but this small trend, if real, may not be of clinical significance. That is, patients would be unlikely to notice decrements in sound quality of this magnitude during the everyday use of their hearing aids given that no preference was established in this study using repeated measures with sequential comparisons. Moreover, if real, the trend may be explained by increased equivalent input noise occurring as a byproduct of the gain headroom provided by the FBR system and not a processing artifact of the FBR processing. An analysis of the overall RMS level of equivalent-input noise for the FBR-on and -off recordings showed a difference of 2.3 dB and 7 dB for the lower and higher gain conditions, respectively, at the time of recording. Recall that at the time of recording the amplitude of the FBR system off and on recordings varied by the amount of gain headroom but that the FBR system off and on recordings were later equated for overall RMS level when shaped to the NAL-NL1 prescriptive targets for the participant's hearing thresholds with the worst hearing sensitivity. Thus, the increased gain headroom could have slightly negatively biased the signals recorded with the FBR system on due to increased equivalent-input noise of the hearing aid at the time of recording. It is of note, however, that paired comparisons did not reach statistical significance even with this potential bias.

While not the focus of this investigation, the observed differences in preference across the different hearing aids in FBR-off versus FBR-off and FBR-on versus FBR-on recordings were of note. These differences were not expected, particularly given the matched gain settings and the fact that the two tested hearing aids utilized the same method of long-term feedback reduction. These differences between aids, however, cannot be solely attributed to the effects of the FBR systems as other differences in each hearing aid's unique digital signal processing were still present, and these differences existed with the FBR system deactivated. Other aspects of the hearing aids' signal processing were present, including compression time constants, differences in compression implementation, and other unknown differences in signal processing, which may have altered moment-to-moment gain in the amplitude varying speech and music signals. Equivalent-input noise was not different between the two aids by more than a few tenths of a dB and

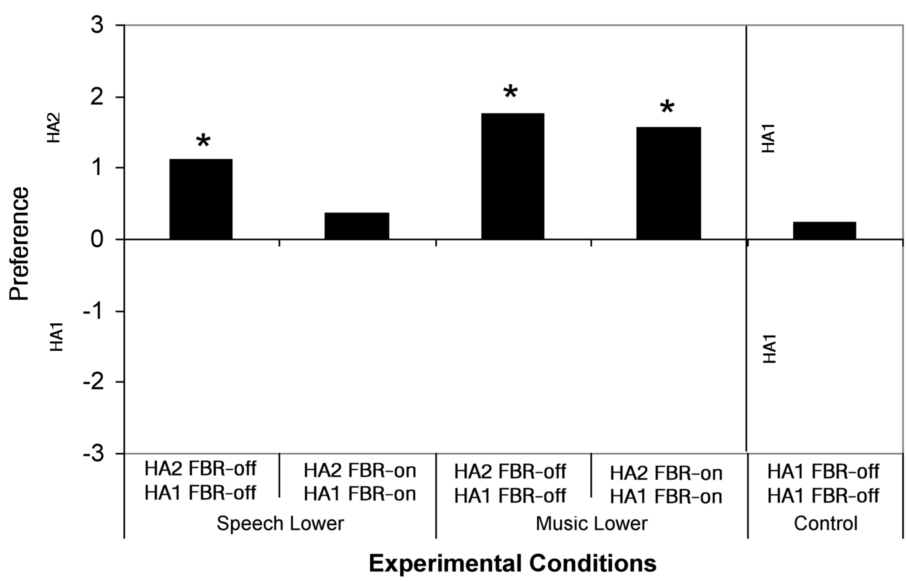

Figure 6. Mean strength of preference rating difference in FBR-off versus FBR-off and FBR-on versus FBR-on conditions between the two test hearing aids across all subjects.

was not higher for the nonpreferred aid; thus, it is not the expected cause of sound-quality differences between aids either. Finally, the sound-quality differences between aids may not be present when these products are fit clinically to individual specific prescriptive targets as these sound-quality results were from recordings that had been shaped to the NAL-NL1 prescriptive targets for the participant with the worst hearing thresholds. Collectively, these issues may explain a part of the observed differences across aids and complicate the exact causes of differences between HA1 and HA2. These differences are not considered important given the focus of this study but are included anyway to highlight the sensitivity of the methodology used for identification of differences in sound quality. Given the sensitivity of the paired comparison technique used, these data are viewed as strong evidence that the FBR processing used in the two hearing aids evaluated does not effect sound quality.

SUMMARY

Within the methods employed to evaluate the two hearing aid FBR systems, no significant effect on sound quality was observed as a result of activating the FBR system in either device for short segments of a speech and music signal. This was even the case in the presence of 13.1 dB and 15.75 dB of additional gain for both the music and speech signal, respectively, with HA1. The method of paired comparisons utilizing a strength of preference rating to demonstrate significant sound-quality differences in the experiment was shown effective as differences were consistently shown in comparisons between HA1 and HA2. Thus, clinically, the benefit of additional gain afforded to listeners with hearing impairments by the continuous phase cancellation FBR systems examined is not offset by degraded sound quality.

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