High-Frequency Amplification and Sound Quality in Listeners With Normal Through Moderate Hearing Loss

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Purpose: One factor that has been shown to greatly affect sound quality is audible bandwidth. Provision of gain for frequencies above 4–6 kHz has not generally been supported for groups of hearing aid wearers. The purpose of this study was to determine if preference for bandwidth extension in hearing aid processed sounds was related to the magnitude of hearing loss in individual listeners.
Method: Ten participants with normal hearing and 20 participants with mild-to-moderate hearing loss completed the study. Signals were processed using hearing aid–style compression algorithms and filtered using two cutoff frequencies, 5.5 and 9 kHz, which were selected to represent bandwidths that are achievable in modern hearing aids. Round-robin paired comparisons based on the criteria of preferred sound quality were made for 2 different monaurally presented brief sound segments, including music and a movie.
Results: Results revealed that preference for either the wider or narrower bandwidth (9- or 5.5-kHz cutoff frequency, respectively) was correlated with the slope of hearing loss from 4 to 12 kHz, with steep threshold slopes associated with preference for narrower bandwidths.
Conclusion: Consistent preference for wider bandwidth is present in some listeners with mild-to-moderate hearing loss.

KEY WORDS: hearing aids, sound quality, high frequency, amplification

Perceived sound quality depends in part on the audible frequency bandwidth and smoothness of frequency response of the reproduction or amplification system, both of which, if degraded, have a significant negative effect for listeners with normal hearing (e.g., Gabrielsson, Hagerman, Bech-Kristensen, & Lundberg, 1990; Gabrielsson, Lindström & Till, 1991; Moore & Tan, 2003; Toole, 1986a, 1986b). The preference for a wide, audible bandwidth appears to be most important for signals containing frequency information across the entire audible bandwidth, as evident in some music and environmental signals, but also for band-limited signals such as speech. For example, Moore and Tan (2003) reported that perceived sound quality of music was rated highest for the test condition with the widest tested bandwidth of approximately 16.5 kHz. Similarly, for speech signals, a significant degradation in sound quality was noted when the upper cutoff frequency was decreased below 10.8 kHz and when the lower cutoff frequency was increased from 123 to 208 Hz.

Most modern hearing aids do not provide useful gain above about 6 kHz. However, the ability to achieve a much wider bandwidth in hearing

aids was demonstrated more than 2 decades ago (e.g., Killion & Tillman, 1982). Although transducer limitations do exist, speech recognition data, particularly for those listeners with high-frequency hearing thresholds in excess of 55 dB HL and those with high-frequency "dead regions," have been used to support bandwidth limitations (Amos & Humes, 2001; Baer, Moore, & Kluk, 2002; Ching, Dillon, Katsch, & Byrne, 1998; Hogan & Turner, 1998; Byrne & Murray, 1986; Turner & Cummings, 1999; Villchur, 1973). In summary, these studies suggest that for some listeners, little or no additional speech recognition or sound quality benefit is found when increasing the high-frequency cutoff frequency beyond 3–4 kHz. However, these studies also revealed that for many other listeners, particularly those without high-frequency dead regions, improvements in speech recognition can be associated with increasing the high-frequency cutoff.

Improved speech recognition with increasing bandwidth has also been shown more recently in listeners with high-frequency hearing thresholds as poor as 85 dB HL. Specifically, Hornsby and Ricketts (2006) reported small incremental improvements in speech recognition performance as the audible high-frequency energy was extended from 3.2 kHz up to approximately 7 kHz. Other research has shown that adult listeners with mild-to-moderate hearing loss demonstrate speech recognition benefit from high-frequency information, at least through approximately 6 kHz (Skinner & Miller, 1983; Vickers, Moore, & Baer, 2001). Emerging data suggest that high-frequency speech information, up to approximately 8 kHz, may be necessary for optimal speech and language development of hearing-impaired children (Stelmachowicz, Pittman, Hoover, Lewis, & Moeller, 2004). Given the data supporting small improvements in speech recognition as a function of increased bandwidth, it is of special interest to examine how this extension affects sound quality. Even slight improvements in sound quality and speech recognition in listeners with mild-to-moderate hearing loss would appear to support extension of high-frequency cutoff frequency beyond commonly used limits.

Only a few studies to date have systematically examined how sound quality preference, as a function of hearing loss, is affected by extending the bandwidth beyond the limits set by the majority of current hearing instruments. These data are especially lacking for adult listeners having mild or mild-to-moderate hearing loss. The few studies that have examined sound quality judgments as a function of high-frequency extension have generally been limited to frequencies below 6.5 kHz (e.g., Versfeld, Festen, & Houtgast, 1999). One notable exception is the work of Franks (1982). Results from that study revealed an improvement in perceived sound quality as the hearing aid bandwidth was increased from 4 to 10 kHz for a group of normal-hearing listeners but no

change in average preference in 20 listeners with hearing loss. The results of that study were interpreted as evidence that extended bandwidth does not affect sound quality in listeners with mild-to-moderate hearing loss. However, it is unclear whether this conclusion can be broadly generalized because listeners with a fairly wide range of hearing thresholds were included (ranging from 10 to 85 dB HL for frequencies of 1000 Hz and above). Although individual threshold data were not provided by the author, the reported mean threshold values of 57 and 60 dB HL for 4 and 8 kHz, respectively, suggest that a relatively high percentage of these participants had greater than moderate hearing loss at these frequencies. Based in part on this large range of thresholds and the fact that listeners with normal hearing usually prefer wider bandwidths, we propose an alternative hypothesis that may also be used to account for these data. Specifically, it may be that listeners with mild-to-moderate hearing loss are not a homogenous group with regard to sound quality. Instead, it is proposed that some listeners will prefer wider bandwidths, others will have no preference, and still others will prefer narrower bandwidths, and the pattern of preference will be based on audiometric factors.

Given the potential improvement in sound quality with extended bandwidth and the limited data on bandwidth preference for individual listeners with mild-to-moderate hearing loss, the need for additional study in this area appears clear. This need is highlighted further by survey data collected from hearing aid wearers who ranked sound quality as the second most important area in need of improvement, behind speech understanding (Kochkin, 2002).

The purpose of the current study was to determine if preference for a high cutoff frequency in hearing aid processed signals is related to hearing thresholds in individual listeners with normal hearing to moderate hearing loss. The cutoff frequencies were selected to represent a range that encompassed those frequencies that can readily be achieved in modern hearing aids, including 5.5 (common in modern hearing aids) and 9 kHz. Because potential hearing aid wearers were of interest, sound quality preference, as measured using paired-comparison techniques, was examined for two short sound segments after applying two types of multichannel compression schemes that can be implemented in commercial hearing aids. The use of two separate compression schemes allowed us to examine the robustness of any identified relationships. Paired comparisons were chosen given that the goal of this study was to identify the presence and direction (wider vs. narrower bandwidths) of potential preference differences. The paired-comparison method has the advantage of high sensitivity to such differences; however, it is limited in that the strength of preference is not measured.

Method

Sound quality comparisons for two different signals (described below), processed using two different types of compression processing (fast Fourier transform [FFT] and Warp, described below) and two different low-pass filter cutoff frequencies (5.5 and 9 kHz) were made by 10 listeners with normal hearing and 20 listeners with mild-to-moderate hearing loss. The test order of signal type, filter conditions, and compressor were randomly selected, without replacement, for each participant. Sound quality was evaluated using a round-robin, paired-comparison technique. Listeners were instructed to concentrate on sound quality and choose the preferred interval. Specifically, participants were instructed as follows:

> You will hear the same short sound segment twice. Your task is to compare the sound quality of the two segments and pick the one you like best by telling me "number 1" or "number 2." There is no right or wrong answer. We are simply interested in the sound that you think has the best quality. If you can't tell the difference, you must still pick one or the other.

Although time consuming, the paired-comparison technique provides a rank ordering of preference for all evaluated conditions. None of the signals were subjected to high-pass filtering. Therefore, the low-pass filter cutoff frequencies will be referred to as *bandwidth values* throughout the remainder of this article. Bandwidth comparisons (within the same compressor condition) were evaluated in a single session. The trials included comparisons in which the compressor type was held constant (either FFT or Warp), and the two bandwidths were compared (5.5 vs. 9 kHz) for each of the two signal types. Comparisons across compressor type within the same trial were made in a single session that preceded the bandwidth comparison and are reported elsewhere (Dittberner, Ricketts, & Bondy, 2006). To obtain a reliable comparison, each distinct pair was presented eight times, and the order of presentation was reversed for half of the eight trials (e. g., Kiedser, Dillon, & Byrne, 1995). The stimuli were processed (i.e., via compression and frequency shaping) prior to every trial and then presented with an interstimulus interval of 500 ms.

Participants

Participants included two groups of adult listeners: one group of 10 listeners with normal hearing and one group of 20 listeners with hearing loss. All hearing sensitivity thresholds were measured at octave frequencies of 0.25 through 8 kHz (inclusive) as well as at 10 and 12 kHz, using a high-frequency calibrated audiometer (Madsen Orbiter 922) and headphones (Sennheiser HDA-200). The reference equivalent threshold SPL assumed

in this calibration was 21.5 and 27.5 dB for 10 and 12 kHz, respectively. The measurement of high-frequency thresholds through these earphones and insert earphones has been shown to be as reliable as the measurement of the frequencies traditionally used in clinical audiometry (Schmuziger, Probst, & Smurzynski, 2004). Participants with normal hearing exhibited hearing sensitivity thresholds better than 15 dB HL at all audiometric frequencies (through 12 kHz) via a hearing screening. There were 6 women and 4 men in the group with normal hearing.

The participants with hearing loss were selected to ensure a distribution of thresholds across the mild-to-moderate range, as it was expected that these listeners would be the most likely to prefer wider bandwidth signals. Hearing thresholds for the group with hearing loss are shown in Table 1. Specifically, 10 listeners with pure-tone average (PTA) hearing thresholds (500, 1000, 2000 Hz) between 20 and 35 dB HL and 10 listeners with PTAs between 36 and 60 dB HL were included. Listeners with hearing thresholds poorer than 70 dB HL at any audiometric frequency tested (0.25 through 12 kHz) were excluded. For those participants with *symmetrical hearing loss* (defined as exhibiting no more than a 5-dB difference in pure-tone thresholds at any octave frequency from 250 Hz through 4000 Hz), the right ear was arbitrarily selected for testing. For those participants with threshold asymmetry, the ear with the better hearing sensitivity (lowest pure-tone average threshold) was selected for testing. The group with hearing loss included 10 men and 10 women.

The mean age of participants was 27 years (*SD* = 4.5) and 56 years (*SD* = 13.5) for listeners in the normal and hearing loss groups, respectively. Participants exhibited no significant air–bone gap (<10 dB) at any frequency, and they exhibited normal *tympanometry,* defined as compensated static admittance between 0.35 and 1.65 mmho measured from the positive tail with tympanometric peak pressure between –75 and +100 daPa in their test ear.

Stimulus Material Preparation

Paired comparisons were made separately for each of two recorded sound samples. These included a short segment of bluegrass music ("The Lucky One" as performed by Alison Krauss [AK]) and a popular movie (both voices and a ringing musical triangle from the movie *Seabiscuit* [SB]). The music sample was from a commercial CD, and the movie sample was from a commercial DVD. Both segments were approximately 5 s in length. Both segments were specifically chosen because they included high-frequency content and exhibited sound energy through at least 12 kHz over at least a 500-ms duration of the sample.

Table 1. The individual, frequency-specific hearing thresholds (in dB HL) of the 20 study participants with hearing loss.

Subject #	Age	Frequency (Hz)								PTA
		250	500	1000	2000	4000	8000	10000	12000	
11	32	20	25	45	40	20	10	10	20	36.7
12	59	15	20	15	40	60	25	40	65	25
13	67	30	25	25	35	45	55	55	60	28.3
14	71	20	35	35	45	40	25	30	55	38.3
15	74	30	35	30	30	15	30	40	50	31.7
16	49	30	35	25	25	20	30	30	20	28.3
17	64	20	25	30	35	35	35	50	60	30
18	33	30	25	20	25	50	40	35	40	23.3
19	42	15	15	15	25	45	10	10	20	18.3
20	45	35	40	35	30	15	25	35	55	35
21	68	15	15	15	60	60	60	60	70	30
22	53	30	40	35	30	60	55	55	65	35
23	59	40	35	35	40	40	55	55	55	36.7
24	64	15	20	35	55	45	50	55	60	36.7
25	68	25	40	40	50	50	50	55	75	43.3
26	44	30	30	40	60	50	50	55	60	43.3
27	41	30	40	40	60	55	20	60	80	46.7
28	69	15	25	40	50	60	40	35	40	38.3
29	46	40	50	50	50	55	60	60	60	50
30	72	25	35	50	45	45	30	40	50	43.3
M	56	25.5	30.5	32.8	41.5	43.3	37.8	43.3	53	34.9
SD	13.5	8.3	9.4	10.8	12	15.1	16	15.4	17.3	8.2

Note. Pure-tone-average (PTA) hearing loss was calculated as the average hearing threshold at 0.5, 1.0, and 2.0 kHz.

Stimulus Processing and Presentation

All test signals were recorded at ear level using a low-noise microphone (Etymotic ER 10 B+) at the usual listening position of an 8 m × 4.5 m × 3 m home theatre. The home theatre equipment consisted of eight Definitive Technologies loudspeakers in a Dolby 7.1 configuration (one pair of BP-30 and a single C/L/R 2000 in the front of the room; one pair of BPVX and one pair of ProMonitor 200 serving as side surround and back surround, respectively; and a TL200 subwoofer in the front of the room), a Denon 1703 DVD player, and a Denon AVR 3805 receiver. The music signal was played in stereo mode using only the BP-30 loudspeakers and TL200 subwoofer, whereas the movie signal was played using all eight loudspeakers. The recording microphone was taped on the side of the head (approximate behind-the-ear microphone location) of an acoustic manikin (Knowles Electronics Manikin for Acoustic Research; KEMAR). The KEMAR was placed approximately two-thirds of the way from the front in the home theatre and was 5.7 m away from the BP-30 loudspeakers. The output of the microphone was routed to a laptop computer for recording through the use of a Sound Blaster Audigy 2 ZS sound card. All signals were sampled at 16 bit, 44.1 kHz. The digital samples were then transferred to a desktop computer for processing and delivery to the participants.

After recording but prior to further processing and presentation to the participants, the two test stimuli were matched in terms of overall root-mean-square (RMS) level using a commercial sound editing package (Adobe Audition, Version 1.5). All sound quality comparisons were based on these same two prerecorded signals. These stimuli were presented using software provided by Great Nordic Research Group. The software algorithms were used in conjunction with Tucker Davis Technology (TDT) System 3 hardware to accomplish all filtering and signal processing. All signals were delivered to participants monaurally through an Etymotic ER-2 earphone after processing. This earphone was chosen because it has a relatively flat frequency response through approximately 12 kHz. The ER-2 was coupled to the ear using a soft probe tip that also included a low-noise microphone (ER 10 B+) used for real-time ear level recording of each signal presentation. The maximum output for the ER-2 earphones is somewhat limited; however, the RMS level of the amplified signal as measured in an artificial ear (IEC 711) did not exceed 103 dB SPL for any of the tested participants. To further evaluate the potential for earphone distortion, the test equipment was programmed

to provide an output at each frequency that was greater than that provided to any of the participants. Specifically, National Acoustics Laboratory–Nonlinear1 (NAL-NL1; (Dillon, 1999) targets were derived for a hypothetical participant who had hearing thresholds 5 dB poorer than those exhibited by any of the participants at each audiometric test frequency. These target values were used to program the test equipment, and the output of each of the two test signals was then recorded using the artificial ear coupled to the Sound Blaster Audigy 2 ZS sound card. Visual inspection of these recorded signals revealed no clipping of the waveform. The output level of 103 dB SPL was also well below the unshaped test signal output of 112 dB SPL, which led to visually evident clipping.

The signals were subjected to amplitude compression prior to delivery. Low threshold amplitude compression (<60 dB SPL compression threshold) is commonly used in commercial hearing aids in an attempt to improve audibility over a wide range of input levels while minimizing the potential for overamplification (see Souza, 2002, for review). Furthermore, recent surveys suggest that between 90% and 92% of the hearing aids dispensed in 2005 used compression processing (Kirkwood, 2006; Strom, 2006). Two side-branch digital compressors were evaluated, one of which was frequency warped. The two compressor designs have been described previously (Kates 2003, 2005; Kates & Arehart, 2005). The compressor systems operated at a 32-kHz sampling rate and were simulated in MATLAB (Version 7.3; The MathWorks, 1994) using floating-point arithmetic. To adjust the bandwidth of an input signal, a Parks-McClellan optimal equiripple finite impulse response (FIR) filter (Okudda, Ikehara, & Takahashi, 2006) was designed to low-pass filter each input signal to the desired pass-band edge frequency of either 5.5 or 9 kHz and the corresponding stop-band edge of either 6 or 9.5 kHz. Filter coefficients were selected for a pass-band ripple of 0.01 dB and a stop-band attenuation of 100 dB. The input signal power level was normalized before processing by the individual compressor strategies (100 dB SPL equivalent to an RMS value of 1.0).

The FFT-based compressor used a block size of 112 and an FFT size of 256 samples, whereas the Warp-based compressor used a block size of 32 and an FFT size of 64 samples. The block size affects the overall system processing delay, and there is a desire to minimize this to prevent perceptual disturbance such as negative perception of the end-user's own voice. The processing delay in the FFT-based compressor is constant across frequencies (5 ms), whereas in the Warp-based compressor, there is a greater delay at low frequencies (~6 ms) than at high frequencies (~3 ms).

The Warp-based compressor used frequency warping to approximate the Bark frequency scale. The FFT-based compressor had a 125 Hz linear frequency resolution.

In the FFT-based compressor, the FFT compression bands were formed by summing FFT analysis bins to give bands that overlap by approximately 50%. This resulted in 16 compression bands. The Warp-based compressor realizes compression bands from the positive frequency FFT bins, and the band overlap formed by combining FFT bins was not needed. The Warp-based band overlap is produced by the length of the warped FFT and the windowing applied to the data sequence prior to computing the FFT. The effective FIR filter length is equivalent to 81 filter tap coefficients for the FFT-based compressor. The Warp-based compressor filter length is equivalent to 63 filter tap coefficients. Quantization noise for both compressor types was estimated at about 60 dB signal-to-noise ratio (Kates & Arehart, 2005).

The FFT- and Warp-based compressors had many of the same general attributes. Specifically, both included adjustable gain at 10 audiometric frequencies (0.25, 0.5, 1, 2, 4, 6, 8, 10, 12, and 14 kHz) via two gain handles at 50 and 80 dB SPL and a low threshold compression knee point of 45 dB SPL in each band. In addition, both systems had a high threshold compression knee point of 90 dB SPL (infinite compression) and attack times of 5 ms across the 10 audiometric frequencies and release times of 70 ms for all frequencies but 250 and 500 Hz, which were valued at 125 ms.

After processing, the output from the TDT System 3 was routed to the ER-2 Earphones via a Madsen Auricle Audiometer that was used to provide desired gain to the processed and frequency-shaped signals. Frequency-specific gain shaping for the hearing-impaired participants in response to 50 and 80 dB SPL input levels was calculated using the NAL-NL1 prescriptive method (Dillon, 1999). This procedure is currently the most popular nonlinear prescriptive method in the United States for adult hearing aid candidates. Target real-ear insertion gain for 50- and 80-dB inputs was then applied to the compressor algorithms prior to verification. Verification of target output values was accomplished using recordings made in a Zwislocki coupler—that is, ear simulator targets were verified for gain that was adjusted based on each individual participant's hearing loss. Although this methodology limited fitting accuracy for individual listeners, it was chosen because of the difficulty in obtaining accurate, high-frequency output values measured in the ear using probe microphone techniques as a result of the presence of standing waves. Specifically, with increasing frequency, placing the tube opening nearer the tympanic membrane is necessary to reduce the influence of standing waves on the measured sound level (e.g., Dirks & Kincaid, 1987).

The presentation system was first calibrated so that the signals were input as if they were presented to the compressor at an overall level of 65 dB SPL. The compressors were designed to provide identical gain and

frequency responses, regardless of bandwidth, so that increasing bandwidth in all cases slightly increased the overall output level of the signal in the ear. A decision had to be made regarding appropriate high-frequency gain because the NAL-NL1 method does not provide targets beyond approximately 6 kHz and only considers thresholds up to 8 kHz. Given that the optimal target gain for frequencies above approximately 6 kHz remains unknown, a somewhat arbitrary method of gain assignment was used. Specifically, for 8-kHz gain targets, the prescribed target values were assigned by extending the target slope observed from 3 to 6 kHz, out to 8 kHz. The threshold at 12 kHz was then input to the NAL-NL1 software as if it were a 4-kHz threshold, and the resulting targets for that frequency were then applied to the compressors at 12 kHz. The gain at 10 kHz was set to the average of the gains at 8 and 12 kHz. For example, if target gain for a 50-dB SPL input was 20 dB at 8 kHz and 30 dB at 12 kHz, the gain handle at 10 kHz was adjusted to 25 dB.

Although sound quality was of primary importance, it is clear that frequency-specific audibility of the test signals could affect interpretation of the test results. Examination of output at the tympanic membrane using a probe microphone is commonly considered optimal for assessment of audibility. However, the reliability of such measures is suspect, especially in the higher frequencies because of standing waves. Therefore, rather than measuring levels in the ear, the average RMS output of the two test signals (over the entire duration) and the audiometer output required for threshold for each individual participant were measured using an artificial ear (IEC 711) mounted within a KEMAR. The output spectral level for the 9-kHz low-pass test signals after applying the gain of each individual participant in turn was first measured, as was the output level of the pure-tone level necessary to obtain threshold for each participant at each frequency. The spectral levels for the test signals were then used to calculate the output in each equivalent rectangular bandwidth (ERB_N). The ERB_N is assumed to reflect auditory filter bandwidth in listeners with normal hearing (Glasberg & Moore, 1990; Moore, Glasberg, & Vickers, 1999). Therefore, the dB SPL per ERB_N of the test signals was calculated to provide a signal that was perceptually relevant to the measured threshold level.

It was of interest to test participants with normal and impaired hearing under similar compression conditions, rather than using a compression ratio of 1:1 for participants with normal hearing. This was done to ensure that any between-group differences in sound quality were not due to the use of linear processing in the listeners with normal hearing. Listeners with normal hearing do not exhibit loudness recruitment; therefore, the use of compression does not reflect a natural listening situation. However, the decision was made to use compression processing for all groups so that any artifacts generated by the specific processes would be introduced to all listeners. For participants with normal hearing, the system was calibrated to provide a compression ratio of 2:1 for inputs above 45 dB SPL (in all channels), and the input of the system was again assumed to be 65 dB SPL. This was accomplished by setting compressor gains to 30 and 15 dB for 50- and 80-dB SPL inputs, respectively. For presentation to participants with normal hearing, the output of the earphones was then reduced using the audiometer so that the overall real-ear RMS level of the signal was between 61.3 and 64.7 dB SPL, depending on the bandwidth presented. Although these small differences in level may have been detectable, they were not expected to affect sound quality.

Data Analysis

The sound quality data were first converted to percentage values for data analysis. Given that there were eight repetitions of each condition (all signal type, compressor type, and bandwidth combinations), the step size was limited to 12.5 percentage points for each individual condition. Specifically, if there was no preference (each condition selected four times), the percentage preference would be 50%. These values were then arcsine transformed prior to data analysis so that the range of scores more closely approximated a normal distribution (Studebaker, 1985). Data analysis was based on two separate goals. The first goal was to examine if significant sound quality preferences were present within groups for the purpose of comparison to past data. The second, and primary, goal of data analysis was to test the hypothesis that bandwidth preferences may be related to individual audiometric data.

To address the first goal, the percentage preference sound quality data were first subjected to analyses of variance (ANOVAs) testing. The purpose of the ANOVAs was to determine any overall effects of signal type, bandwidth, and compression within each group. Given this purpose, the fact that the data were ordinal in nature was not considered problematic. For each of the two groups, the within-subjects factors were the two bandwidths (5.5 and 9 kHz), the two signal types (AK and SB), and the two compressors (Warp, FFT). Statistical significance was defined at the $\alpha = .05$ level, and Tukey's honestly significant difference testing was used for post hoc analyses of the data.

Consistent with the second goal of data analysis, a number of threshold factors including PTA, individual threshold values at each frequency, averaged high-frequency thresholds (4, 8, and 12 kHz), and threshold slope (from 4 through 12 kHz) were compared to derived bandwidth preference values for all participants with
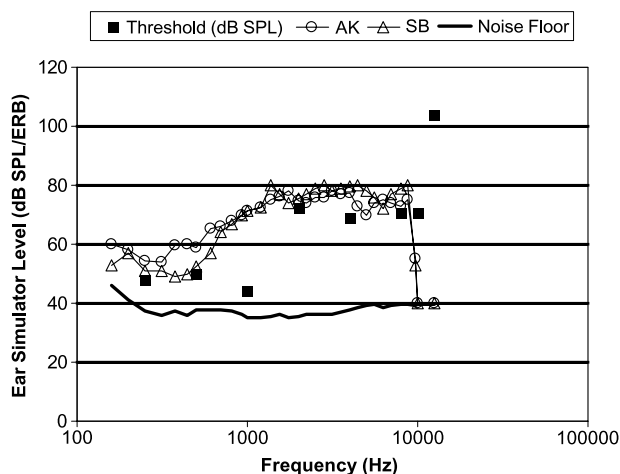
hearing loss using correlation techniques. A total of 10 correlations were calculated; therefore, the significance level was adjusted to α = .005 (Bonferroni adjustment) to account for the fact that the high number of correlations increased the probability of obtaining a significant correlation by chance. Further, those audiometric factors that were the most highly correlated with bandwidth preference differences were subjected to partial correlation analysis to quantify the independent contributions of each of the factors (Kendall & Stuart, 1976).

Results
Audibility of the Test Signals

The decibel SPL per ERB_N (dB SPL/ERB_N) of the two test signals and the frequency-specific output necessary for audiometric threshold for 1 theoretical participant, as measured in the artificial ear, are shown in Figure 1. This theoretical participant was based on Subject 27 with one modification: Subject 27 was selected as a model because she exhibited the poorest threshold at 12 kHz and the second poorest PTA. Because Subject 27 had unusually good thresholds at 8 kHz, we chose to use a threshold of 60 dB HL and apply gain based on this threshold instead for our theoretical participant, given that out greatest interest was to examine high-frequency audibility. A threshold of 60 dB HL was chosen because it represents the poorest 8-kHz threshold measured across all study participants. This figure

suggests that both of the amplified test signals were generally above the thresholds of this theoretical participant through 9 kHz. As this measurement was based on assumed hearing thresholds that were among the poorest of all participants, it is not surprising that, using this technique, it was estimated that the two test stimuli were generally above absolute thresholds through 9 kHz for all 30 participants.

Group Comparisons

The preferences for bandwidth (5.5 and 9 kHz) for each signal and compressor type are shown for participants with normal hearing in Figure 2. Statistical analysis revealed no significant differences between the two compressors or the two signal types and no significant interactions. These results suggest that the same bandwidth preference judgments were made independent of the signal and compressor type. A highly significant main effect of bandwidth was identified, $F(1, 9) = 377,374$, $p < .0001$, revealing that the 9-kHz bandwidth was preferred significantly more often than the 5.5-kHz bandwidth.

The preferences for bandwidth (5.5 and 9 kHz) for each signal and compressor type for participants with hearing loss are shown in Figure 3. An ANOVA revealed

Figure 1. The relationship between pure-tone signals presented at audiometric thresholds and the amplified signal levels for a single theoretical participant measured using an artificial ear mounted in the Knowles Electronics Manikin for Acoustic Research (KEMAR). The levels of the two signal types are expressed as decibel sound pressure level per ERB_N (dB SPL/ERB_N). AK = Alison Krauss music segment. SB = *Seabiscuit* movie segment.

Figure 2. The percentage of time that the 5.5- and 9-kHz bandwidths were preferred based on eight trials for each of the compressor types (W = Warp-based; F = fast Fourier transform–based) and signal types, averaged across all participants with normal hearing. The 50% point on the x-axis indicates no preference. The percentage of times each of the two bandwidths was preferred, for each of the two test conditions necessarily adds up to 100%. Error bars represent standard error of measure.
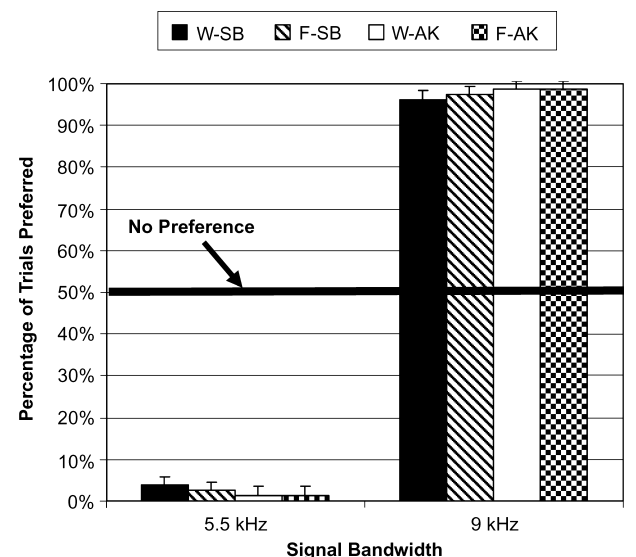
Figure 3. The percentage of time that the 5.5- and 9-kHz bandwidths were preferred based on eight trials for each of the compressor and signal types, averaged across all participants with hearing loss. The 50% point on the *x*-axis indicates no preference. The percentage of times each of the two bandwidths was preferred, for each of the two test conditions necessarily adds up to 100%. Error bars represent standard error of measure.
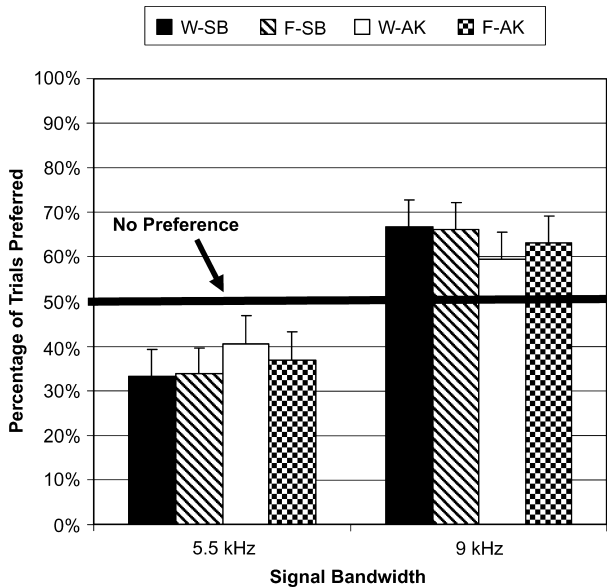
a pattern similar to the results for participants with normal hearing with no significant differences between the two compressors or the two signal types and no significant interactions. Again, a significant main effect of

bandwidth was identified, $F(1, 19) = 25.8$, $p < .0001$, revealing that the 9-kHz bandwidth was preferred significantly more often than the 5.5-kHz bandwidth.

Relationship Between Preference and Audiometric Data

Further analysis was completed to examine if some aspect of hearing threshold was correlated with bandwidth preference. Because of the lack of significant effects of stimulus and compressor type, and because it was of interest to focus on general preference across signals, the data from the two compressor comparisons and across both the AK and SB stimuli were averaged before completing this analysis. Analysis of the potential relationship between bandwidth preference and PTA, overall average thresholds across all tested frequencies, averaged high-frequency thresholds (4, 8, and 12 kHz,) and thresholds at 8 kHz all revealed nonsignificant correlations of $r = .08$ or less. Correlations based on the threshold slope from 0.25 through 12 kHz, 4 through 8 kHz, 2 through 4 kHz, and 2 through 12 kHz were also not significant. Data comparing thresholds at 8 and 12 kHz and bandwidth preferences are shown in Figure 4. This figure demonstrates the lack of correlation between 8-kHz thresholds and bandwidth preferences as well as a trend toward a borderline (nonsignificant) correlation between the thresholds at 12 kHz and the bandwidth preference, $r = .58$, $F(1, 18) = 9.17$, $p < .008$. Threshold slope from 4 through 12 kHz is compared to bandwidth preferences in Figure 5. Correlation analysis of these data revealed a significant moderately strong

Figure 4. The individual bandwidth percentage preference scores for 20 listeners with impaired hearing as a function of hearing threshold at 8000 and 12000 Hz. The 50% point on the ordinate indicates no preference, whereas higher and lower percentage values are associated with increasing preference for narrower and broader bandwidths, respectively.
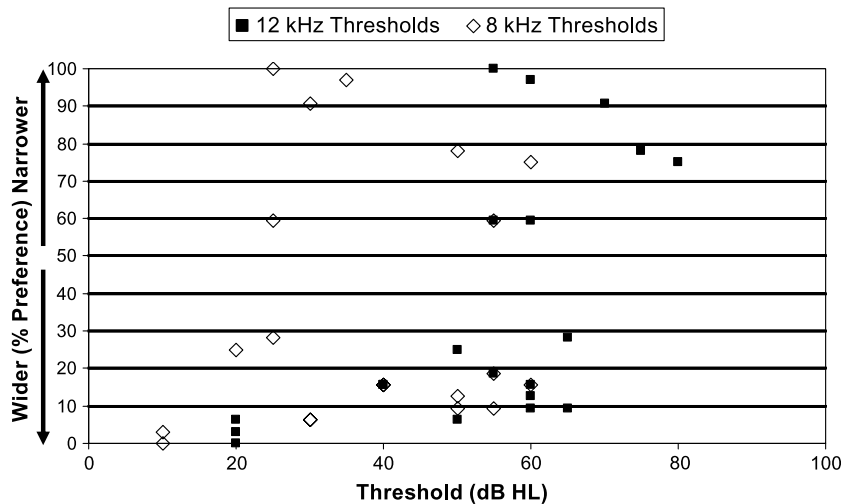
Figure 5. The individual bandwidth percentage preference scores for 20 listeners with impaired hearing as a function of high-frequency hearing loss slope (4 kHz through 12 kHz). The 50% point on the ordinate indicates no preference, whereas higher and lower percentage values are associated with increasing preference for narrower and broader bandwidths, respectively.
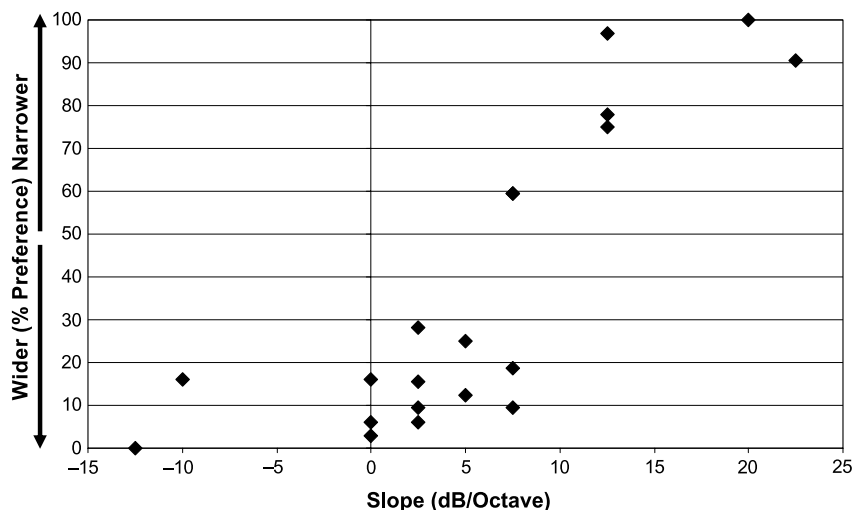
relationship, $r = .81$, $F(1, 18) = 35.3$, $p < .0001$. The bandwidth preference data presented in Figures 4 and 5 reveal that 17 of the 20 participants with hearing impairment chose either the wider or narrower bandwidth on at least 70% of the trials, demonstrating a relatively consistent preference. Partial correlations quantifying the independent contributions of the 12-kHz threshold and high-frequency threshold slope for the prediction of bandwidth preference revealed that only threshold slope was significantly correlated with bandwidth preference (see Table 2)—that is, threshold slope was still significantly correlated with bandwidth preference, even after controlling for the 12-kHz threshold. In contrast, no relationship was found between 12-kHz threshold and bandwidth preference.

Table 2. The results of partial correlation analysis of 12-kHz threshold and high-frequency threshold slope values (predictors) and the outcome of the percentage of the total trials in which the wider bandwidth signal was preferred.

Predictor	β	Partial correlation	R^2	$t(17)$	p level
12-kHz threshold	.1816	0.2588	.3141	1.1048	.2846
High-frequency slope	.7122	0.7245	.3141	4.3338	.0005

Note. Beta indicates the standardized regression coefficients for each predictor. The partial correlation indicates the correlation between each predictor and the percentage of the total trials in which the wider bandwidth signal was preferred after removing the effect of the other predictor.

Discussion

The results revealed that listeners with normal hearing found the sound quality provided by the narrowest bandwidth inferior to that of the wider bandwidth across all signal types. These data are generally in good agreement with past data (e.g., Gabrielsson et al., 1990, 1991; Moore & Tan, 2003) with few exceptions (e.g., Versfeld et al., 1999). However, it should be noted that the stimuli used in this study had considerably more high-frequency content (see Figure 1) than the speech materials used by Versfeld et al. (1999). Versfeld and colleagues argued that this limited high-frequency content did, in fact, influence sound quality differences between the two highest cutoff frequencies.

Recall that audibility estimates were used in an attempt to confirm that the pattern of results was not due to limited audibility. These data, as exemplified in Figure 1, support our contention that the signals were audible throughout the bandwidth of interest for all participants. In addition, the fact that all but 3 participants with hearing loss preferred either the wider or narrower bandwidth on at least 70% of the trials provides additional support that the stimuli were audible well above 5.5 kHz for all hearing-impaired listeners.

The significant bandwidth preferences within the group of participants with hearing loss are in contrast to the data of Franks (1982). The wide range of results exhibited in Figures 4 and 5 supports our hypothesis that there is a lack of homogeneity in listeners with

mild-to-moderate hearing loss with regard to bandwidth preferences. Therefore, it is speculated that these significant differences would be eliminated if the test population included a larger portion of listeners with poorer hearing thresholds. The correlation between individual listeners' preferences for either wider or narrower bandwidth and high-frequency hearing threshold slope (see Figure 5) supports our hypothesis that the pattern of bandwidth preference is related to audiometric data. The hypothesis that there are individual differences in bandwidth preference is further supported by the similarity between the preference ratings for the two stimulus types. Specifically, when collapsed across the two compressor types, individual participants' preference scores for the two stimuli were well correlated with each other ($r = .72$, $F = 19.82$, $p < .001$). The lack of significant correlation between 12-kHz thresholds and bandwidth preferences appears to have been mainly due to the pattern of results for the 10 participants with hearing thresholds at 12 kHz between 50 and 70 dB HL. Specifically, bandwidth preference in this group spanned the entire range, from consistent preferences for the narrower bandwidths to consistent preferences for the wider bandwidths. However, the high-frequency threshold slope (4–12 kHz) could be used to differentiate the bandwidth preferences expressed by these 10 participants. Specifically, of the 10 participants with thresholds between 50 and 70 dB SPL, both participants who primarily chose the narrower bandwidth exhibited high-frequency (4–12 kHz) threshold slopes of 12.5 dB per octave or more. In contrast, the other 8 participants exhibited high-frequency threshold slopes of 7.5 dB/octave or less. The remaining 10 participants also followed this pattern of greater slopes associated with preference for narrower bandwidth and lower slopes associated with preference for wider bandwidths, leading to the significant correlation.

The correlation and partial correlation analyses suggest that high-frequency hearing threshold slope was the primary factor related to bandwidth preference judgments in the current study. Some segments of the data shown in Figure 4 suggest that 12-kHz thresholds may have contributed to bandwidth preference despite the fact that these thresholds were not a primary factor based on the partial correlation analysis. Specifically, all 3 participants with 12-kHz thresholds of 70 dB HL or worse exhibited a preference for the narrower bandwidth. Further, all 7 participants with hearing thresholds at 12 kHz of 50 dB HL or better exhibited a preference for wider bandwidths. We speculate, on the basis of these data, that using the threshold slope for prediction of bandwidth preference may be limited by very high or low 12-kHz thresholds (e.g., a wider bandwidth may not be preferred when the 12-kHz threshold exceeds 70 dB SPL, regardless of threshold slope). However, further data collection is needed over a wider range of high-frequency

hearing thresholds to determine if the relationship between 12-kHz threshold and bandwidth preference is just an artifact resulting from the link between 12-kHz thresholds and high-frequency threshold slope in the current participants as supported by the partial correlation analysis.

On the basis of our data to date, a preliminary hypothesis can be posited relating high-frequency hearing threshold slope to sound quality preference for 5.5 kHz versus 9 kHz cutoff frequencies. Specifically, those participants who exhibit a high-frequency threshold slope of less than 8 dB per octave are likely to prefer extended high frequencies (or show no preference), and those with greater slopes will prefer a narrower bandwidth. Obviously, more data are needed from a larger sample, especially from those listeners with 12-kHz thresholds poorer than 70 dB HL and those with high-frequency threshold slopes of between 5 and 15 dB/octave before the strength of this potentially predictive relationship can be verified. However, data from the current study show promise in predicting sound quality preferences for bandwidth extension in hearing aids based on audiometric data.

Although these data suggested a preference for the 9-kHz bandwidth over the 5.5-kHz bandwidth in some of the listeners identifiable by their high-frequency hearing threshold slopes, at least two additional factors limit generalization of these data to a larger population. First, our limited choice of test signals (i.e., one music sampling and one movie sampling) reduces the strength of these findings to some degree—that is, it is unknown whether these preferences would be maintained for other signals with substantial high-frequency energy. For example, speech presented in a background of realistic broadband competing signal with a relatively flat spectral slope through 9 kHz would be an important signal to examine. In this example, the additional bandwidth is expected to provide little additional speech energy while providing more competing energy. It is unclear whether increased bandwidth would lead to improved or poorer sound quality in such conditions—that is, bandwidth extension in this case would increase the overall level of the noise while providing little additional speech audibility. In addition, other signals with increased energy above 9 kHz warrant evaluation to determine whether even broader bandwidths may be preferred for specific stimuli.

The second limitation of this study relates to the assignment of gain for frequencies above 4 kHz—that is, it seems possible that the somewhat arbitrary method of gain assignment in this study was not optimal. For example, one might speculate that those listeners with the greatest hearing loss preferred the lower cutoff frequency because of overamplification of the high frequencies resulting from our arbitrary gain rule. However, such

speculation is not supported by the results. Specifically, an identical pattern of results was found for the two stimuli. Even though the same gain rule was applied to these two signals, the output (dB per ERB_N) was approximately 2–8 dB greater for the SBE stimuli for frequencies above 5 kHz (see Figure 1). This difference in output across signal type, along with the fact that listeners with similar 8- to 12-kHz thresholds did not demonstrate homogenous results (some preferred a lower cutoff and some a higher), suggests that the pattern of results was not the result of the gain rule. Finally, although the gain rule applied can certainly be questioned, audibility—at least well into the 5.5- to 9-kHz bandwidth for the two stimuli—appears assured given that significant differences between the 5.5- and 9-kHz cutoff frequencies were found. However, additional work is needed to develop optimal prescriptive targets now that evidence supports improved sound quality as a function of increased high-frequency cutoff in some listeners with hearing loss.

The underlying mechanism for these data is not yet known. However, if the correlation between audiometric data and sound quality with extended bandwidth is accepted, the mechanism is expected to be peripheral in nature. Interestingly, the range of 12-kHz thresholds over which a change in bandwidth preference was noted (55–65 dB SPL) and the threshold above which narrower bandwidths were preferred (70 dB SPL) are consistent with estimates of thresholds for which reduced inner hair cell integrity usually begins (Moore, 2004; Moore & Alcántara, 2001; Moore & Glasberg, 2004; Moore, Huss, Vickers, Glasberg, & Alcántara, 2000). Furthermore, compromised inner hair cell integrity, as defined by the identification of dead regions, has been associated with reduced pitch perception accuracy (Huss & Moore, 2005b), reduced tonality of pure tones (Huss & Moore, 2005a), and reduced utility of high-frequency speech information in speech recognition (e.g., Baer, Moore, & Kluk, 2002; Vickers, Moore, & Baer, 2001).

Given these findings, a reasonable first hypothesis is that inner hair cell integrity may be the main factor influencing extended high-frequency cutoff preference. It has been suggested that only a small number of functioning inner hair cells are necessary for sound detection; however, speech recognition may be negatively affected when the loss of inner hair cells exceeds 50% (Schuknecht & Gacek, 1993). It is speculated that sound quality might be even more sensitive to inner hair cell integrity than speech recognition. An alternative hypothesis might be that sound quality is reduced when there is a complete loss of outer hair cells near the frequency region in question—that is, a number of authors have suggested that it is expected that there are no functioning outer hair cells for hearing losses greater than about 60 dB

(e.g., Moore & Glasberg, 2004; Oxenham & Plack, 1997). Further work is needed to examine these questions, given the plausibility of the conflicting hypotheses.

Conclusion

These data indicate a preference for wider bandwidths than those typically used in current commercial hearing aids in some listeners with hearing loss. This preference is important because it is possible that perceived poor sound quality resulting from limited bandwidth might be a factor contributing to the limited use of hearing aids by listeners with mild-to-moderate hearing loss. These data also suggest that preference for high-frequency information above 5.5 kHz is related to high-frequency threshold slope.

Acknowledgments

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