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Sound Quality Ratings of Amplified Speech and Music Using a Direct Drive Hearing Aid: Effects of Bandwidth

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Objective: To determine sound quality for extended bandwidth amplification using a direct drive hearing device.
Study Design: Prospective double-blind within-subjects repeated measures study.
Setting: University hearing research laboratories.
Patients: Fifteen experienced hearing aid users with symmetric mild-sloping-to-severe sensorineural hearing loss.
Intervention(s): Sound quality ratings of speech and music passages were obtained using the Multiple Stimulus with Hidden References and Anchors (MUSHRA) protocol after wearing a direct drive hearing aid for at least 4 weeks. Passages were processed to filter out low-frequency (below 123 and 313 Hz) and high-frequency (above 4455, 5583, 6987, and 10,869 Hz) energy.
Main Outcome Measure(s): Comparison of sound quality ratings for speech and music between low and high-pass filter frequencies measured from 0 to 100, where 0 represents ‘‘bad’’ and 100 represents ‘‘excellent.’’
Results: Wider bandwidth stimuli received higher sound quality ratings compared with narrower bandwidth stimuli. Conditions with more low-frequency energy (full-band and 123 Hz cut-off) were rated as having higher sound quality. More low-frequency energy in the 123 Hz condition was rated as having higher sound versus the 313 Hz condition (mean difference: 11.2%, $p = 0.001$). Full-band conditions with more low- and high-frequency energy were higher than the other high-frequency cutoff conditions (mean difference range: 12.9–15%, $p < 0.001$).
Conclusions: The direct drive system provides higher sound quality of both speech and music compared to narrowband conditions. Sound quality improvements were mainly attributable to low-frequency sound, but stimuli with specific high-frequency content were rated with higher sound quality when additional high-frequency energy was present.
Key Words: Acoustics—Adult—Direct drive—Hearing aids—Hearing loss—Humans—Music—Personal satisfaction—Sound quality—Speech perception—Technology.

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Hearing aids traditionally improve hearing and communication by processing and amplifying sound. Improving speech communication for adults with hearing loss mainly requires increased audibility in the mid-frequency range, as reflected in the widely-available Speech Intelligibility Index (SII) (1). The SII weights speech importance in the mid frequencies, and is highly correlated with subjective speech intelligibility (2–4). However, it is possible to have a good SII score associated with poor sound quality (5,6). This suggests that improving speech intelligibility is a core outcome of many hearing aid fittings but is not expected to be the only driver of user satisfaction. In fact, studies throughout the last decade have shown that hearing aids improve hearing-related quality of life (7), speech audibility, and intelligibility, as well as demonstrate an increase in

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hearing aid user satisfaction; yet, many users continue to be dissatisfied with their devices (8,9).

Many dissatisfied hearing aid users attribute this to poor device sound quality (9). Sound quality has been described as the overall fidelity and enjoyability of sound (10), and for hearing aid purposes, has been defined across a range of descriptors, some of which include ''fullness,'' ''sharpness,'' ''loudness,'' and ''naturalness'' (11). Maintaining tolerable sound quality and comfortable amplification has been considered an important part of hearing aid fittings (9,12,13).

Extended high- and low-frequency bandwidth has been associated with superior sound quality for speech and music. Moore and Tan (14) measured normal hearing listeners' perceived naturalness ratings for jazz music, a male-spoken sentence and a female-spoken sentence processed using a wide range of bandwidth limitations. Highest naturalness ratings for speech were associated with a bandwidth between 123 and 10,869 Hz and highest naturalness ratings for jazz music were associated with a bandwidth between 55 and 16,845 Hz. Some literature has investigated extended-bandwidth sound quality in only the high or low frequencies. In the high-frequency range, listeners with flat audiograms have preferred stimuli containing energy above 5000 Hz compared with listeners with steeper audiograms (15,16). In the low-frequency range, Franks (17) presented listeners with hearing loss with music passages processed using low-frequency cut-offs between 50 and 500 Hz. Listeners preferred passages containing more low-frequency energy. More recently, Vaisberg et al. (18) evaluated hearing aid music sound quality ratings with listeners with hearing loss. Listeners preferred a wider high- and low-frequency bandwidth hearing aid compared with narrower bandwidth hearing aid. Collectively, the results above encourage the fitting of extended bandwidth amplification in both the high- and low-frequency ranges for hearing aid users when preferable sound quality is the objective.

Many hearing aids provide bandwidth that, while sufficient for speech intelligibility, may not be ideal for sound quality. Kimlinger et al. (19) investigated the effective high-frequency bandwidth of eight hearing aids from leading manufacturers. They found that the average high-frequency cut-off was approximately 7000 Hz (standard deviation [SD] $=$ 870 Hz) for a flat, moderately-severe hearing loss, and approximately 3680 Hz (SD $=$ 70 Hz) for a normal-sloping-to-profound hearing loss; both falling below the high-frequency cut-offs (10,869 and 16,854 Hz for speech and music, respectively) exhibiting higher naturalness ratings (14).

Minimal research has investigated the effective low-frequency bandwidth of commercial hearing aids. One reason may be due to hardware limitations in hearing aid coupling configurations. Hearing aid users often complain of the occlusion effect (OE) (20), in which their voice sounds ''hollow'' or ''boomy'' (21). The OE occurs when low-frequency energy is trapped in the ear canal due to occluded hearing aid couplings, but is often mitigated by introducing a vent in the hearing aid or earmold. The vent allows for low-frequency energy to leak from the ear canal and is typically accompanied by a reduction in the OE. However, low-frequency leakage implies that less energy will be transmitted to the auditory system, making it challenging for clinicians to provide meaningful low-frequency amplification. This may limit the sound quality of the aided signals.

A direct drive hearing device (22,23) may overcome low-frequency and high-frequency sound quality limitations. The device consists of a lens that resides deep in the ear canal and makes direct contact with the umbo of the malleus on the surface of the tympanic membrane. A behind-the-ear processor is worn behind the ear to house external microphones, batteries, and signal processing hardware. The external device encodes sound and emits non-acoustic infrared or low-power radio frequency induction signals from an ear-tip residing in the ear canal. The signals are received by the lens, which converts the signal into appropriately scaled vibrations of the umbo, which propagate through the middle and inner ear system causing sound to be perceived (23). Useable gain provided via the direct drive hearing aid has been shown to meet Cambridge Method for Loudness Equalization 2-High-Frequency (CAMEQ2-HF) prescriptive targets from 125 to 10,000 Hz (24–26). Struck and Prusick (27) compared the effective bandwidth of the direct drive hearing aid to traditional open-fit receiver-in-the-canal hearing aids from six leading hearing aid manufacturers. They found a mean effective bandwidth of 890 Hz to 4.4 kHz across all six acoustic hearing devices, compared with an effective bandwidth of 125 to 10,000 Hz for the direct drive hearing aid. These findings demonstrate that the direct drive hearing aid, when fitted to a wideband prescriptive target, provides an effective bandwidth exceeding that of traditional hearing aids when fitted to proprietary defaults. This suggests that the direct-drive system may deliver sound quality benefits compared with traditional hearing aids, when fit accordingly to clinical procedures.

The purpose of the current study was, therefore, to compare sound quality preferences for speech and music processed using a variety of high- and low-frequency cut-offs in individuals wearing a direct drive hearing system. We used a quasi-experimental, within-subjects design, and double-blinded measures of sound quality.

MATERIALS AND METHODS

Participants

A total of 15 adult listeners (eight men, seven women) between the ages of 66 and 86 years (mean $=$ 72.2 yr) were recruited to participate in this study. Participants were enrolled in a trial of the Earlens Contact Hearing Solution (Earlens Corporation, Menlo Park, CA) direct drive hearing system as part of a larger study.

Participants were experienced hearing aid users, recruited from a participant database at the National Centre for Audiology, University of Western Ontario, London, Ontario, Canada. All participants met Food and Drug Administration indication criteria for the device (23) and presented with mild sloping to severe sensorineural hearing loss. Figure 1 illustrates air-conduction

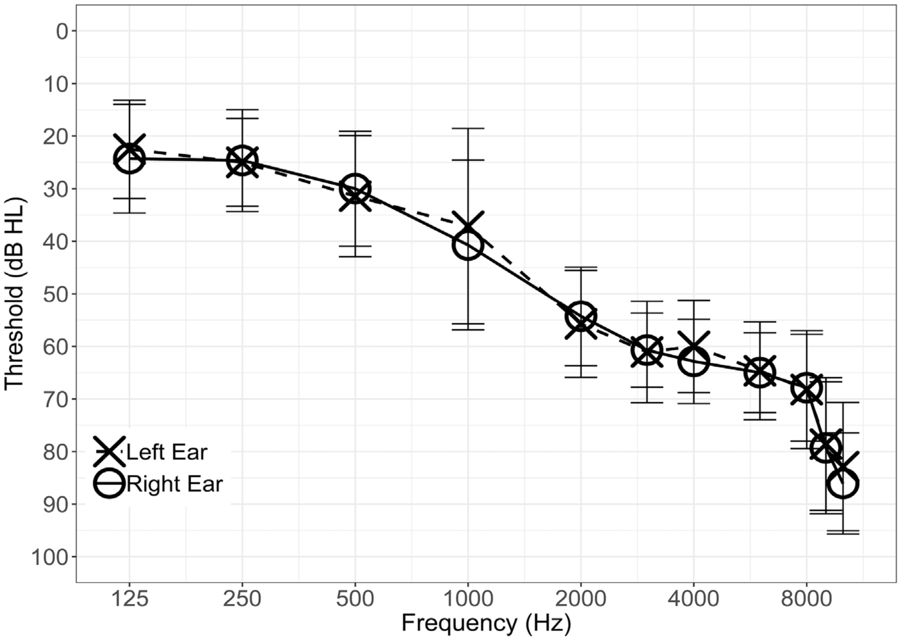

FIG. 1. Mean air-conduction thresholds in dB HL for participants' left ears (*dashed*, X) and right ears (*solid line*, O). Error bars represent one standard deviation.

thresholds for both ears for all participants. Participants wore the devices for a minimum of 4 weeks before completing the sound quality outcome measurements. The devices were fitted using the manufacturer's recommended protocol to a modified version of the CAM2 prescriptive method (24,28) based on participants' hearing loss and in-situ light calibration, with fine tuning to participant preference. This study was approved by the Western University Human Research Ethics Board (109433) and Lawson Health Research Institute (R-18–057).

Sound Quality Ratings

Sound quality ratings were obtained using the MUltiple Stimuli with Hidden Reference and Anchors (MUSHRA) listening test (29). The MUSHRA protocol is a standardized subjective sound quality evaluation method which uses multiple comparisons with reference stimuli. Listeners rate the overall sound quality of each signal processing condition on a sliding scale from 0 to 100, where 0 represents ''bad'' and 100 represents ''excellent'' (25 = ''poor'', 50 = ''fair'', 75 = ''good''). Listeners were instructed to use this software to play the reference signal, and then to play one test signal. After this, the listener would use the software slider to rate the test stimulus in comparison to the reference stimulus. The process was repeated until each test stimulus was rated, and listeners could revisit the test stimuli to revise their ratings if desired. The task was repeated for four stimulus types: female speech, male speech, pop music, and jazz music. Each stimulus type was rated under a variety of bandwidth conditions, as described below.

Stimuli and Bandwidth Conditions

The study stimuli consisted of male and female speech samples, and jazz and pop music samples. These stimuli, which vary in bass/treble content, have been used in hearing aid sound quality evaluations. The speech stimuli were two Institute of Electrical and Electronics Engineers (IEEE) (30) sentence pairs that have been used previously in hearing aid sound quality studies (31). The specific sentences pairs were: ''Would you please give us the facts? He arrived home every other night,'' spoken by a female talker, ''Raise the sail and steer the ship northward. A cone costs five cents on Monday,'' spoken by a male talker. The music stimuli, purchased from the Apple iTunes store, consisted of a 6-second sample from Dave Brubeck's ''Take Five,'' representing a jazz genre and an 8-second sample from The Beatles' ''With a Little Help from My Friends,'' representing a pop genre. Impacts of hearing aid processing have previously been shown to be sensitive to different music genres (32,33).

The sound quality rating software presented the listener with several screens each evaluating one stimulus between seven different processing conditions: the reference condition, two anchor conditions, and four restricted bandwidth conditions (Table 1). The reference was the original unprocessed, full-bandwidth version of the stimulus. The anchors were selected to represent poor sound quality and consisted of: 1) a low-pass filter cut-off of 2000 Hz and 2) 10% center clipping. In the MUSHRA procedure, a hidden copy of the reference and two anchor conditions are included and not labeled for the listener, such that the listener has unbiased representations of the high (reference) and low (anchor) perceptual endpoints of the rating scale. These ''hidden'' stimuli encourage the listener to make use of the full rating scale when rating the experimental restricted bandwidth conditions.

The experimental conditions consisted of several high-pass filter/low-pass filter combinations (selected to approximate those used by Moore and Tan (14)). The high-pass filter cut-offs were 123 and 313 Hz and were each combined with one of four low-pass filter cut-offs:4455, 5583, 6987, and 10,869 Hz for a total of eight experimental conditions. The restricted bandwidth conditions were parsed into two groups of four to provide a manageable set of stimuli per software screen for the listeners. Therefore, two separate screens for the 123 and 313 Hz high-pass filter cutoff screen were used to independently gather ratings comparing the four low-pass filter cut-offs. The reference and anchor filter conditions were held constant across the two screens so that the rating endpoints were common.

TABLE 1. *Summary of experimental conditions used in the 16 tasks used during a sound quality measure*

Tasks (16)	Stimuli (7)		
Stimuli	Low-Frequency Cut-off	High-Frequency Cut-off	Reference (R) and Anchors (A)
Female IEEE sentence (60 dB SPL) ×2	123 Hz	4455 Hz	Full Bandwidth (R), 2 kHz low-pass (A), 10% center clip
Male IEEE sentence (60 dB SPL) ×2		5583 Hz	
Pop (Beatles) music (60 dB SPL) ×2		6987 Hz	
Jazz (David Brubeck) music (60 dB SPL) ×2		10,869 Hz	
Female IEEE sentence (60 dB SPL) ×2	313 Hz	4455 Hz	Full bandwidth (R), 2 kHz low-pass (A), 10% center clip
Male IEEE sentence (60 dB SPL) ×2		5583 Hz	
Pop (Beatles) music (60 dB SPL) ×2		6987 Hz	
Jazz (David Brubeck) music (60 dB SPL) ×2		10,869 Hz	

Each task included seven stimuli: four filtered versions, one reference unfiltered stimulus, and two anchor stimuli that were either low-passed or center clipped.

The procedure totaled 16 screens (stimulus [4] × screens per stimulus [2] × test-retest [2]) consisting of a total of 112 sound quality ratings (screens [16] × sliders [7]) per participant. The protocol was double-blind, so that neither the participant nor experimenter was aware of the stimulus or condition. Screen order was randomized between participants, as were slider-condition assignments between each screen.

Test Procedures

Listeners completed sound quality ratings in a sound-attenuated booth in front of a computer monitor displaying the MUSHRA software (Western University, London, ON, Canada), SPSS v24 (UNICOM Global, Mission Hills, CA). A loudspeaker located at 0 degree azimuth presented the stimuli at 60 dB SPL.

During the speech evaluations, the devices were set to the default program worn during the field trial with advanced digital signal processing features (i.e., adaptive microphones, automatic noise reduction etc.) disabled. During the music evaluations, the devices were set to the default music program with the bandwidth matched to that of the default field program.

RESULTS

Reliability

MUSHRA reliability was assessed by comparing the first and second repetition using the intraclass correlation coefficient (ICC). The ICC analysis was implemented in RStudio version 1.0.132 (34) using the ''ICC'' software package (35). Resulting ICC values were 0.79 and 0.79 for female and male speech, and 0.57 and 0.56 for pop and jazz music, suggesting good to moderate reliability (36) across stimuli. These ICC are also comparable to past hearing aid MUSHRA sound quality ratings as rated by listeners with hearing loss (31).

Sound Quality Ratings

Sound quality ratings are illustrated in Figures 2 and 3 for speech and music stimuli, respectively. Ratings were averaged across repetitions for statistical analysis. A repeated measures analysis of variance (RM-ANOVA) was conducted with stimulus (four levels: male and female speech, pop and jazz music), low-cut frequency (123 and 313 Hz), and stimulus condition (reference stimulus plus four high-cut frequencies: 4455, 5583, 6987, and 10,869 Hz). Greenhouse-Geisser epsilon corrections were applied to adjust the degrees of freedom for departures from sphericity. Statistical analyses were completed using SPSS v24.

The results revealed significant effects of low-cut frequency (mean difference: 11.2%, F [1,14] = 17.88, $p = 0.001$, $\eta^2 = 0.56$) and stimulus condition (F [2.16, 30.2] = 31.81, $p \leq 0.001$, $\eta^2 = 0.69$). Stimulus type interacted with low-cut frequency condition (F [1.9, 27.1] = 3.75, $p < 0.038$, $\eta^2 = 0.21$), and low-cut frequency condition interacted with stimulus condition when collapsed across stimuli (F[1.7, 24.3] = 26.4, $p < 0.001$, $\eta^2 = 0.65$).

Pairwise contrasts compared the sound quality ratings for the reference signal (i.e., unfiltered bandwidths) and the high-cut stimuli, when collapsed across both low-cut conditions. Results revealed the reference signal to have better ratings than the high-cut stimuli (mean differences ranged from 12.9 to 15%, $p < 0.001$ for all contrasts). Ratings between high-cut conditions were not significantly different from one another.

Low-cut frequency interacted with stimulus type. In the 313 Hz condition, no significant differences were observed between any stimuli (mean differences were all <2.5%, $p > 0.05$). In the 123 Hz condition, differences were observed between male and female speech (mean difference: 6.7%, $p = 0.004$) and between female speech and pop music (mean difference: 7%, $p = 0.007$). These effects may be idiosyncratic to the specific stimuli overall, but increased low-frequency energy clearly supported the listeners in discerning between-stimulus quality differences.

Low-cut frequency also interacted with high-cut frequency. In the 313 Hz condition, no significant differences were observed between any high-cut frequencies, although the full-band reference was rated higher than any high-cut frequency conditions (mean differences ranged from 23 to 23.8%, $p < 0.001$ for all contrasts). In the 123 Hz condition, the full-band reference was rated higher than the 4455, 5583, and 6987 Hz high-cut frequency conditions (mean differences ranged from 4.6 to 6.5%, $p < 0.03$ for all contrasts). The full-band reference

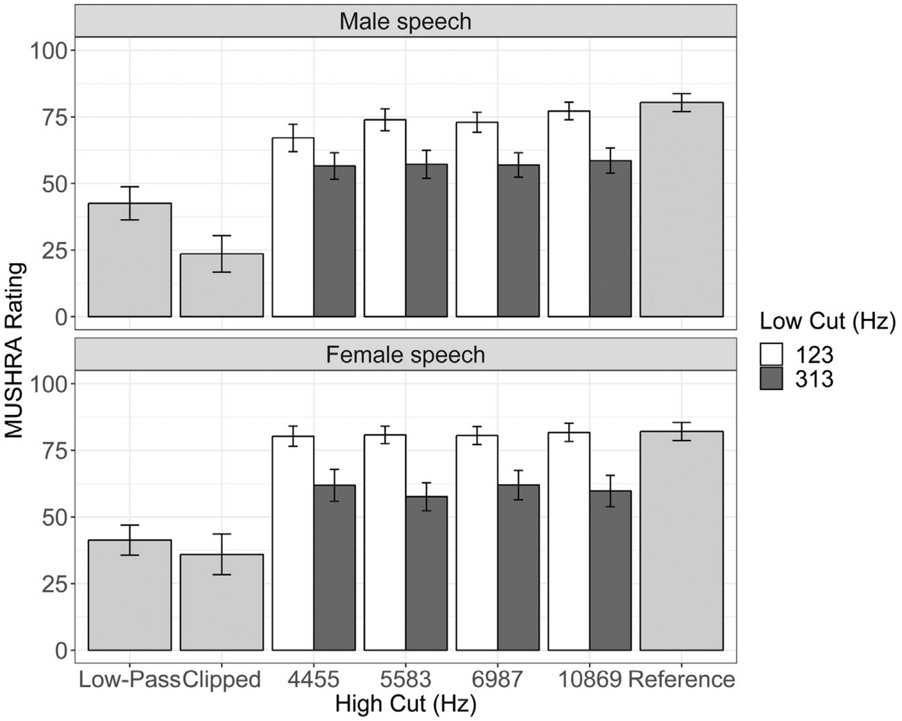

FIG. 2. Sound quality ratings for male speech stimuli (*top*) and female speech stimuli (*bottom*). Error bars represent one standard error of the mean.

and 10,869 high-frequency sound quality ratings were statistically comparable. These results suggest that the functional bandwidth of the study device is similar to the 123 to 10,869 Hz condition, and that low-frequency energy is most beneficial for device sound quality versus stimulus and high-cut frequency manipulations, with a

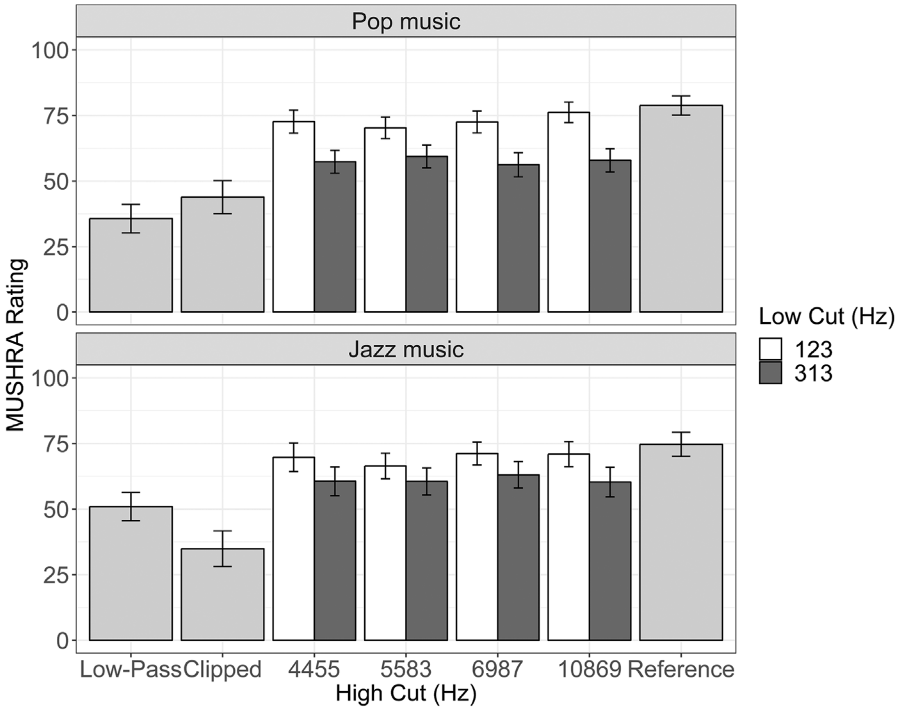

FIG. 3. Sound quality ratings for pop music stimuli (*top*) and jazz music stimuli (*bottom*). Error bars represent one standard error of the mean.

smaller but significant benefit for additional high-frequency energy.

DISCUSSION

This present study evaluated whether users perceived sound quality associated with bandwidth, and whether listeners preferred wider bandwidth in both low- and high-frequency ranges of speech and music stimuli while listening to aided sound via direct drive devices. Results suggest that the participants perceived higher sound quality when low frequency energy was present (to 123 Hz compared with 313 Hz) while wearing the direct drive hearing aids. The results also suggest that participants perceived higher sound quality when high frequency energy was present, although this effect was smaller than the effect for the low frequencies. These findings suggest that direct drive users with mild-sloping-to-severe sensorineural hearing loss experience improved sound quality when extended bandwidth acoustic content, spanning both the low and high frequency ranges, is available, and that this was attained in the as-clinically-fitted listening condition.

Impact of High-Frequency Audibility

A sound quality benefit of additional high-frequency content was observed in this study to some degree. Preference for the reference stimulus over other conditions that had low-frequency content filtered out may be attributed to the additional low-frequency content in the reference stimulus. However, listeners preferred the reference stimulus relative to conditions which removed high-frequency energy at cutoffs of 6987 Hz or lower. The 123 Hz low-cut conditions produced smaller high-frequency sound quality improvements relative to the 313 Hz test conditions, suggesting that high-frequency benefit is somewhat dependent on the low-frequency audibility, akin to the low frequency audibility acting as a ‘‘pedestal’’ for the high frequency audibility. Further, sound quality preferences for the 123 to 10,869 Hz bandwidth were comparable to that of the unfiltered reference condition, suggesting that the direct drive system is capable of delivering wideband suprathreshold functional amplification that is consistent with that of the unfiltered reference condition.

Impact of Low-Frequency Audibility

Sound quality benefit from an extended low-frequency cut-off was observed across all stimuli in this study. That is, listeners preferred listening to all speech and music stimuli when the low-frequency cut-off was 123 Hz rather than 313 Hz. These findings are consistent with those of past literature, in which additional low-frequency content contributes to enhanced sound quality for both speech (37–40) and music stimuli (17,41). Some authors have even recommended an extended low-frequency response in hearing aid music programs (42) and an extended-low frequency response has been observed in commercial hearing aid music programs relative to their corresponding speech programs (18).

While sound quality preferences due to extended low-frequency bandwidth occurred across all stimuli, magnitude of improvement in preference from the 313 to 123 Hz low-cut frequencies varied between stimuli. For instance, the magnitude of effect was larger for the pop music stimulus compared with the jazz music stimulus. The differences observed here may have also been attributed to acoustic differences between stimuli. For instance, the impact of hearing aid processing has had different impacts on sound quality ratings between different stimuli varying in acoustic content (32,33). In the current investigation, the jazz stimulus consisted of an acoustic double bass, piano, drum kit, and saxophone and the pop stimulus consisted of an electric bass guitar, electric guitar, drum kit, and vocalists. It is possible that the pop music stimulus consisted of more low-frequency content, which would have made it more sensitive to changes in low-frequency bandwidth. Additional low-frequency gain is associated with higher ratings of the sound quality descriptor ‘‘fullness’’ (11), which for music stimuli, has been demonstrated to be the most highly correlated sound quality descriptor with ratings of overall impression (32). Therefore, a difference in perceived magnitude of fullness may have been associated with the difference in effect sizes between the low-frequency cut-offs for the pop and jazz stimuli. This explanation is purely speculative and warrants an investigation of the interaction between different acoustic content and sound quality.

Comparison to Previous Studies of Bandwidth and Sound Quality

The findings from this group of listeners with hearing loss are consistent with previously-reported findings from listeners with normal hearing, in which highest naturalness ratings were associated with a bandwidth spanning 123 to 10,869 Hz or greater (14). More specifically, improvement in naturalness ratings with extended high-frequency audibility were apparent when low-frequency energy was also present in the stimulus. These results are similar to those observed in the current study, although we used a somewhat different rating scale (overall quality rather than naturalness). This suggests that overall sound quality may be impacted by bandwidth of fitting, but that best results are expected if bandwidth is extended in both the low and high frequencies, rather than only in one direction. A side-by-side comparison of overall sound quality ratings from the current study and perceived naturalness ratings from Moore and Tan’s study is illustrated in Figure 4. Overall, the current investigation’s results extend Moore and Tan’s findings to listeners with hearing loss, at least for the bandwidth conditions included in this study.

Previous investigations evaluated sound quality preferences using acoustic transducers for listeners with hearing loss (15,16) and found that shallower a audiometric slopes were correlated with greater high-frequency sound quality preferences. This study may be limited in that it did not systematically probe impacts of

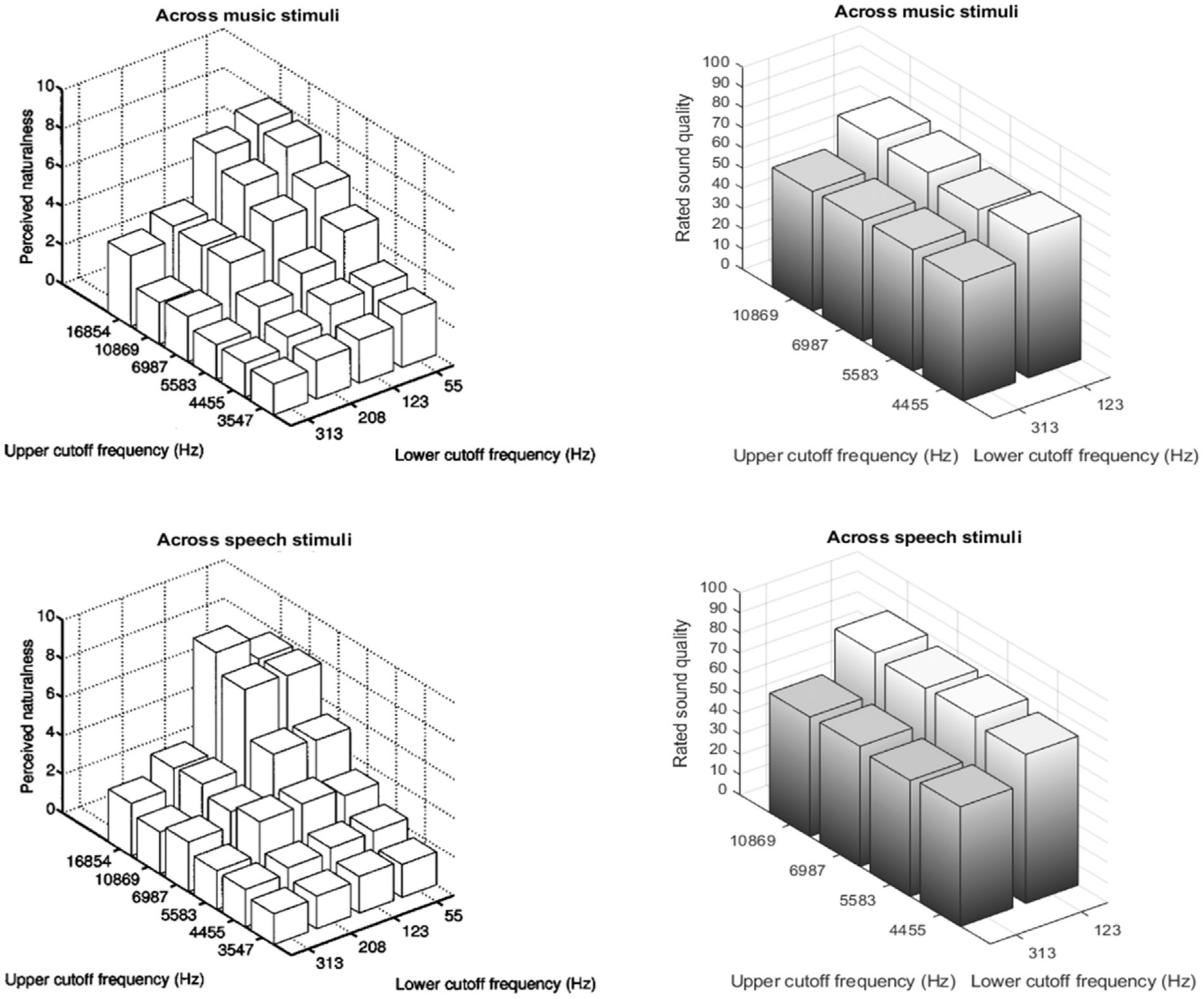

FIG. 4. Mean sound quality ratings from listeners with hearing loss in the current study (*right*) and mean perceived naturalness ratings from normal hearing listeners (*left*; reproduced from Moore BCJ, Tan C-T. Perceived naturalness of spectrally distorted speech and music. J Acoust Soc Am. 2003;114(1):408-419., with the permission of the Acoustical Society of America). Across music stimuli (*top*) and across speech stimuli (*bottom*). Mean ratings are illustrated on the *z* axis, upper cutoff frequencies are illustrated on the *y* axis, and lower cutoff frequencies are illustrated on the *x* axis.

bandwidth due to different hearing loss configurations. As such, we did not observe such a correlation in this study, which may be attributable to the range of audiograms differing somewhat across these studies. Another study limitation could be the device itself. Despite the novelty of extended bandwidth attributable to a direct drive hearing aid compared with traditional hearing aids, direct drive hearing aid bandwidth may still be narrower than those of headphones used to explore extended bandwidth sound quality for speech and music (14). There may be even greater sound quality benefits to be had if the functional bandwidth of the direct drive hearing aid can be further expanded. Another consideration explaining study differences may be that provision of extended bandwidth via a wearable device, with a trial period, may produce somewhat different outcomes than those which are seen in laboratory studies under headphones.

In summary, the results of this study demonstrate that the direct drive hearing device provided extended audible bandwidth amplification that enhanced the sound quality of speech and music passages in this sample of adult listeners with mild-sloping-to-severe hearing loss. Further research would be needed to determine if the findings presented here extend to listeners with both lesser and greater degrees of hearing loss. Finally, further research would be needed to determine whether these laboratory ratings of sound quality generalize to real world sound quality perceptions in real-world conditions.

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