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Effects of Amplification and Hearing-Aid Experience on the Contribution of Specific Frequency Bands to Loudness

Katie M. Thrailkill^{1,2}, Marc A. Brennan², and Walt Jesteadt¹

¹Boys Town National Research Hospital, Omaha, NE

²Department of Special Education and Communication Disorders, University of Nebraska-Lincoln, Lincoln, NE

Abstract

Objectives—The primary aim of this study is to describe the effect of hearing-aid amplification on the contribution of specific frequency bands to overall loudness in adult listeners with sensorineural hearing loss (SNHL). Results for listeners with SNHL were compared to results for listeners with normal hearing (NH) to evaluate whether amplification restores the normal perception of loudness for broadband sound. A secondary aim of this study is to determine if the loudness perception of new hearing-aid users becomes closer to normal over the first few months of hearing-aid use. It was hypothesized that amplification would cause the high-frequency bands to contribute most to the perception of loudness, and that this effect might decrease as new hearing-aid users adapt to amplification.

Design—In Experiment 1, 8 adult listeners with SNHL completed a 2-interval-forced-choice (2IFC) loudness task in unaided and aided conditions. A control group of 7 listeners with NH completed the task in the unaided condition only. Stimuli were composed of 7 summed noise bands whose levels were independently adjusted between presentations. During a trial, 2 stimuli were presented and listeners determined the louder one. The correlation between the difference in levels for a given noise band on every trial and the listener's response was calculated. The resulting measure is termed the perceptual weight because it provides an estimate of the relative contribution of a given frequency region to overall loudness. In Experiment 2, a separate group of 6 new hearing-aid users repeated identical procedures on 2 sessions separated by 12 weeks.

Results—Results for listeners with SNHL were similar in Experiments 1 and 2. In the unaided condition, perceptual weights were greatest for the low-frequency bands. In the aided condition, perceptual weights were greatest for the high-frequency bands. On average, the aided perceptual weights for listeners with SNHL for high-frequency bands were greater than the unaided weights for listeners with NH. In Experiment 2, hearing-aid experience did not have a significant effect on perceptual weights.

Address correspondence to Katie Thrailkill, Boys Town National Research Hospital, 555 N. 30th St., Omaha, NE 68131, USA. kthrailkill@huskers.unl.edu.

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These experiments were presented at 2 consecutive meetings of the American Auditory Society in Scottsdale, AZ; Experiment 1 was presented in 2016 and Experiment 2 was presented in 2017.

Conclusions—The high-frequencies appear to dominate loudness perception in listeners with SNHL using hearing aids as they do in listeners with NH. However, the results suggest that amplification causes high-frequencies to have a larger contribution to overall loudness compared to listeners with NH. The contribution of the high-frequencies to loudness did not change following an acclimatization period for the first-time hearing-aid users.

INTRODUCTION

Hearing aid amplification involves an inevitable tradeoff between maximizing audibility and avoiding loudness discomfort. Non-linear signal processing, which is based on compression, allows inputs spanning a broad dynamic range to be comfortably represented within the reduced dynamic range of individuals with sensorineural hearing loss (SNHL). A major goal of non-linear amplification strategies is to normalize loudness such that individuals with SNHL interpret any given sound with the same loudness as the average individual with normal hearing (NH). This concept of loudness normalization is fundamental to current validated non-linear hearing-aid fitting formulas such as NAL-NL2 (Keidser et al. 2012) and Desired Sensation Level (DSL) version 5.0 (Scollie et al. 2005).

Despite advances in controlling the loudness associated with amplification, loudness complaints remain common among hearing-aid users (Jenstad et al. 2003, Kochkin 2000, 2012). Clinicians typically manage these complaints through counseling, reduced gain, or a combination of the 2 methods. Loudness measures, such as uncomfortable loudness levels (ULLs) or categorical loudness scaling (CLS) can also be used in hearing aid fittings to reduce the likelihood of loudness-related issues. However, these specific measures of loudness are rarely performed in clinical settings (Mueller 2003). These measures are also limited because they are based on pure-tones or narrow bands of noise rather than broadband stimuli. Thus, they fail to account for spectral loudness summation (Zwicker et al, 1957; Otting et al, 2016) and are not representative of everyday sounds.

The experiments presented in this paper use an alternative loudness measure, perceptual weights, to explore the effect of amplification on loudness. The perceptual weights methodology uses a 2-interval forced choice (2-IFC) loudness judgment task to derive the importance of individual frequency regions to loudness decisions (Oberfeld et al. 2012; Jestadt et al. 2014, 2017). A parallel can be drawn between perceptual weights for loudness and band importance functions for speech perception, such as the Articulation Index. Band importance functions quantify the relative value of frequency regions to speech intelligibility, whereas perceptual weights quantify the relative contribution of frequency regions to overall loudness.

Adults fit with hearing aids for the first time are particularly prone to loudness-related issues. It is commonly thought that new hearing-aid users are more sensitive to loudness than experienced hearing-aid users. Dillon (2012) refers to a process called “adaptation to gain” that new hearing-aid users experience as they adjust, or acclimatize, to amplification and come to prefer slightly higher gains. This concept is pervasive in both the scientific literature and the professional community. For example, one modification of the NAL-NL2 fitting formula compared to the older version, NAL-NL1, is that it accounts for differences

in preferred gain between new and experienced hearing-aid users. In the clinic, Audiologists often set initial gain below prescription levels and gradually adjust it upwards as the person adapts to amplification and develops an improved tolerance for loudness. Most hearing-aid software now contains an acclimatization option that the clinician may enable according to the experience level and subjective preference of the patient. For a new hearing-aid user, gain will initially be set below targets, and the hearing aid will gradually increase gain to target levels over a specified time course.

Unfortunately, these practices do not have a strong evidence base because the literature has described mixed results. A few studies have revealed small differences (2-3 dB) between the preferred gain of new and experienced hearing-aids users (Cox & Alexander, 1994; Marriage et al. 2004; Keidser et al. 2008). For example, the preferred gain of 4 monaural hearing-aid users fit in an experiment by Gatehouse (1992) increased by an average of 4 dB over the 12-month course of that experiment. In contrast, many experiments have failed to reveal significant differences in preferred gain between new and experienced hearing-aid users (Cox & Alexander, 1992; Horwitz & Turner, 1997; Humes et al. 2002). Convery et al. (2005) reviewed 14 published studies on the topic and reanalyzed data from Cox and Alexander (1992), Horwitz and Turner (1997), and Humes et al. (2002). In no case was a significant effect of hearing-aid experience on preferred gain found.

There is modest evidence in support of loudness acclimatization from experiments that measured ULLs or estimated loudness growth functions using CLS, a procedure in which listeners assign loudness labels ranging from 'very soft' to 'very loud' to individually presented tones. Significantly greater ULLs (approximately 8 dB) have been reported in ears with hearing-aid experience compared to ears with no hearing-aid experience (Munro & Trotter, 2006; Munro et al. 2007). When comparing CLS functions obtained from 2 kHz tones, the mean intensity that non-hearing-aid users associated with some loudness categories has been reported to be less than experienced hearing-aid users by 4.5 dB (Olsen et al. 1999) to 8 dB (Philibert et al. 2002). Finally, Philibert et al. (2005) observed that the mean intensity of 2 kHz tones associated with the louder categories increased significantly over the first 6 months of hearing-aid use.

Perceptual weights showing the contribution of different frequency bands to the overall loudness of broadband sounds have previously been investigated using unaided stimuli in listeners with both NH and SNHL. Data from listeners with NH indicate an increased contribution of the lowest and highest frequency components to loudness decisions relative to the mid-frequency components (Leibold et al. 2007; Oberfeld et al. 2012; Jesteadt et al. 2014). The first report of perceptual weights for listeners with SNHL suggested that listeners with SNHL place greater weight than listeners with NH on the highest spectral components when judging the intensity of tone complexes (Doherty & Lufti, 1996). This finding was later attributed to that fact that Doherty and Lufti tested listeners with SNHL at a higher overall level and perceptual weights for high-frequency components increase with level (Leibold et al. 2009; Jesteadt et al. 2014). A recent perceptual weights experiment using noise-band complexes revealed a relatively lower weight for high-frequency components in listeners with SNHL, a result that was independent of presentation level (Jesteadt et al.

2017). Thus, findings indicate that the contribution of different frequency regions to loudness differs between listeners with NH and SNHL.

The primary objective of this study was to examine the effect of amplification on perceptual weights for loudness. In Experiment 1, participants with SNHL were tested in unaided and aided conditions using broadband noise stimuli. The aided condition involved a simulation of the gain-frequency response of a hearing aid set to DSL Adult targets. A group of adult participants with NH also completed the unaided condition to allow for comparison of the perceptual weights for listeners with SNHL to those for listeners with NH.

We posed the following research questions: 1) What are the effects of amplification on the relative contribution (perceptual weighting) of multiple frequency regions to overall loudness? and 2) How will aided perceptual weights for listeners with SNHL compare to unaided perceptual weights for listeners with NH? In other words, does amplification achieve its goal of loudness normalization when loudness is assessed in this way? These questions have important implications for hearing-aid fitting strategies and for addressing complaints regarding the loudness of hearing aids. It was hypothesized that hearing-aid amplification would cause an increase in the contribution of high-frequency bands to loudness. In the unaided condition, the low-frequency bands were expected to contribute most to loudness because the high-frequencies are inaudible for listeners with high-frequency SNHL.

EXPERIMENT 1

Materials and Methods

Participants—Eight adult listeners (4 males, 4 females; ages 21 to 63 years; mean age 47 years) with SNHL and seven listeners (3 males, 4 females, ages 22 to 52 years, mean age 35 years) with NH were recruited to participate in Experiment 1. All listeners had participated in similar studies and had experience with the task. All except 1 of the listeners with SNHL were experienced hearing-aid users. Pure-tone hearing thresholds were obtained using a conventional method (ASHA, 2005) at octave frequencies from 250 to 8,000 Hz, plus the inter-octave frequency of 6,000 Hz. Normal hearing was defined as pure-tone air-conduction thresholds ≤ 25 dB Hearing Level (HL) for all test frequencies. Sensorineural hearing loss was defined as pure-tone thresholds >25 dB HL at 3 or more octave frequencies, air-bone gaps < 15 dB, middle ear static admittance >0.20 mmho as indicated by tympanometry, and/or stable air-conduction thresholds in the case of previously documented SNHL. Participants received compensation of \$15 per hour for their participation. Experimental procedures were approved by the institutional review board.

One ear of each participant was selected for testing. The left ear was arbitrarily tested on all listeners with NH. For listeners with SNHL, the left ear was tested when hearing thresholds were symmetrical between ears, and the ear with poorer thresholds was tested when hearing thresholds between ears differed by ≥ 15 dB at one or more frequencies. In total, 6 left ears and 2 right ears were tested among the listeners with SNHL. Pure-tone air-conduction thresholds in dB HL for the test ear of each participant are shown in Table 1.

Stimuli

Unaided stimuli: Stimuli were 500 milliseconds (ms) in duration and consisted of 7 noise bands of equal level that were created separately by adding sinusoids with 1 hertz (Hz) spacing in random phase. The center frequencies of the noise bands were selected to align with the center-frequencies of the channels defined in the hearing-aid simulation software. Characteristics of each band including lower and upper cut-off frequencies, and bandwidths in hertz, octaves, and Equivalent Rectangular Bandwidth (ERB) are listed in Table 2.

The levels of individual noise bands were independently roved ± 2 , 4, or 6 dB from their base level to generate 500 unique stimulus files. The stimuli were calibrated using KEMAR with an IEC 711 coupler (G.R.A.S. Sound & Vibrations, Holte, Denmark). The mean levels of the 7 noise bands were adjusted in all stimuli so that the sound pressure level (SPL) of each band was approximately equal at the level of KEMAR's microphone (i.e. tympanic membrane).

Aided stimuli: Aided stimuli were created on an individual-subject basis by processing the 500 stimulus files through a MATLAB hearing-aid simulation software (McCreery et al. 2013, 2014; Brennan et al. 2014) designed to amplify signals according to DSL v5.0 Adult prescription targets (Scollie et al. 2005). Processing was completed at a sampling rate of 22.05 kHz. Stages included an input limiter, filterbank, wide dynamic range compression (WDRC), and an output limiter.

The input limiter had a threshold of 105 dB SPL with a compression ratio of 10:1 and a 1-ms attack time and 50-ms release time. The filterbank was composed of 8 overlapping channels. The cutoff frequencies of the 7 lowest channels corresponded to the end points of the noise bands described in Table 2 (for details see McCreery et al. 2013). WDRC occurred with a 100-ms attack time and a 300-ms release time. Finally, the output limiter considered the summed broadband signal following amplification, and compressed any outputs above 105 dB SPL using a 10:1 compression ratio and a 1-ms attack and 50-ms release time.

Levels were computed for individual aided stimuli using third-octave band filters (ANSI 2004) at the center frequency of each noise band. The resulting levels were used to calculate perceptual weights. The mean output level of each noise band and the pure-tone thresholds of each participant were converted from dB HL to dB SPL using correction values based on a KEMAR-to-headphone transform, measured in the laboratory, to approximate levels at the tympanic membrane. Figure 1 illustrates the mean output levels of noise bands in unaided and aided conditions relative to hearing thresholds (i.e. audibility) for individual listeners with SNHL. Each panel is analogous to the “speechmap” or “SPLogram” used clinically for hearing-aid verification. For the unaided stimuli, only the lower-frequency noise bands were audible for all listeners. All noise bands were audible for the aided stimuli.

Procedure—Participants were seated in front of a computer monitor in a double walled sound-attenuating booth. Stimuli were generated at 44,100 samples per second using 24-bit digital-to-analog converters (Digital Audio Labs, Chanhassen, MN), amplified, (HP4, PreSonus, Baton Rouge, LA) and presented monaurally to the test ear through Sennheiser HD-25 headphones (Wedemark, Germany). During the 2IFC task, participants listened to 2

randomly selected waveforms and were instructed to choose the louder one. All 500 stimulus files were available for presentation in either interval. Participants were provided a visual cue on a computer monitor at the beginning of each trial and during each interval as the stimuli were presented. The warning and inter-stimulus intervals were 500 ms. After the second interval, participants were prompted to indicate their response by using a mouse to click on the “interval 1” or “interval 2” response area on the monitor. A new trial began 500 ms after the listener selected their response.

One dB was added at random to the stimulus in 1 of the 2 intervals upon presentation. The purpose of the 1 dB increment was to create a small difference in loudness, on average, between the 2 intervals. The interval containing the additional decibel was defined as the “correct” response, even though this stimulus was not necessarily the louder one. Correctness was used as an indirect measure of the listeners’ attentiveness to the task by indicating whether performance was maintained above chance. Feedback regarding correctness was not provided. Rather, listeners were instructed that the louder interval may often not be obvious, in which case to take their best guess and not worry about their performance.

In the unaided condition, pairs of stimuli were presented to the listeners with SNHL at mean overall levels of 63 and 64 dB SPL. Mean presentation levels were increased to 73 and 74 dB SPL for 1 listener with SNHL (S-01) due to reported inaudibility at the lower level. In the aided condition, stimuli were scaled to an overall level of 63 dB SPL before input to the hearing-aid simulator. Output levels of the hearing-aid simulator varied across subjects depending on their hearing thresholds (see Fig. 1). Initially, the listeners with NH were tested in the unaided condition at a mean presentation level of 51 and 52 dB SPL. However, new data were later collected at 63 and 64 dB to allow for a more appropriate comparison to data from the listeners with SNHL. Only the latter data set is reported here.

Listeners completed blocks of 100 trials at a time, and were encouraged to take breaks between blocks. During a single session lasting 2 to 2.5 hours, the listeners with SNHL completed 500 unaided trials followed by 500 aided trials. The listeners with NH completed 500 trials in the unaided condition only. To rule out an effect of condition order, 6 of the 8 listeners with SNHL returned for a second session that was identical to the first except the aided condition was tested first. No effect of test order was observed, and the 2 sets of data were averaged in the analysis.

Analysis—For each listener and condition, trials were first sorted according to the correct answer interval. A multiple linear regression analysis then determined the relation between the level difference across intervals in each of the 7 noise bands (independent variable) and the listener’s response regarding the louder interval (dependent variable). The regression coefficients for each listener were normalized by dividing individual coefficients by the sum of the absolute values of the coefficients for all 7 bands (Kortekaas et al. 2003; Oberfeld et al. 2012). These normalized coefficients are termed “normalized perceptual weights” or “perceptual weights.” Finally, the separate normalized perceptual weights obtained for trials with the correct answer in the first or second interval were averaged after determining that there was no difference associated with the interval containing the correct answer.

A series of repeated-measures analyses of variance (ANOVAs) were completed to determine the differences in loudness weights by frequency band, hearing status, and amplification condition. Mauchly's Test of Sphericity was used. In cases where the assumption of sphericity was violated, the degrees of freedom were adjusted for using the Greenhouse-Geisser correction.

Results

Listeners with NH—Figure 2 displays individual normalized perceptual weights, in separate panels, for the 7 listeners with NH in the unaided condition. The lower-right panel shows the mean perceptual weights and standard errors across the 7 listeners with NH. Overall, the listeners with NH placed greatest weight on the lowest- and highest- frequency bands for loudness judgements. All 7 listeners placed increased weight on the highest-frequency band (band 7), and 6 out of 7 listeners placed an increased weight on the lowest-frequency band (band 1) compared to the adjacent band (band 2). The exception was listener N-03, whose perceptual weight for the lowest frequency band was negative. This is a mysterious result because a negative perceptual weight suggests that a decrease in energy results in an increase in loudness. A repeated measures ANOVA comparing the weights assigned to each of the frequency bands showed a significant effect of frequency band [$F(2.0,12.0)=5.8$; $p=.017$; $\eta^2=.77$].

Listeners with SNHL

Unaided vs. Aided: Figure 3 displays the normalized perceptual weights, in separate panels, for the 8 listeners with SNHL in unaided and aided conditions. In the unaided condition, the low-frequency bands generally received the greatest weight and the high-frequency bands received almost no weight, which is not a surprising finding considering that the high-frequency bands were largely inaudible. In the aided condition, results were consistent with the hypothesis that perceptual weights would be greatest in the high-frequency bands due to the restoration of high-frequency audibility provided by the hearing-aid simulator. Listener S-02 is the exception to the pattern described above because in the unaided condition he placed negative weight on the 2 lowest frequency bands. Negative perceptual weights were also observed in the aided condition for some listeners in the low-frequency bands (listener S-05) or in the mid-frequency bands (listeners S-02 and S-08).

A repeated-measures ANOVA comparing the weights assigned to each of the frequency bands in unaided vs. aided conditions showed a nonsignificant effect of amplification [$F(1,7)=.946$; $p=.363$; $\eta^2=.12$] and frequency band [$F(1.7,12)=3.58$; $p=.066$; $\eta^2=.34$] but a significant interaction of amplification with frequency band [$F(1.8,12)=7.3$; $p=.009$; $\eta^2=.51$].

Unaided SNHL vs. NH: Figure 4 compares the mean perceptual weights and standard errors for both listeners with SNHL and with NH. The unaided data for the listeners with SNHL show a similar pattern in the low frequencies to the control group with NH. That is, the lowest-frequency bands had a relatively greater contribution to loudness decisions. However, the listeners with SNHL gave less weight to the highest-frequency bands compared to the listeners with NH.

A repeated-measures ANOVA was completed with a within-subject factor of frequency band and a between-subject factor of hearing status to compare the unaided weights for the listeners with SNHL to the unaided weights for the listeners with NH. The loudness weights differed significantly across frequency band [$F(1.4,18.7) = 4.2$; $p = .042$; $\eta^2 = .24$] but not by hearing status [$F(1,13) = 1.3$; $p = .276$; $\eta^2 = .09$]. There was not a significant interaction of frequency band with hearing status [$F(1.4,18.6) = 2.7$; $p = .106$; $\eta^2 = .173$].

Aided SNHL vs. NH: In the aided condition, perceptual weights for the 2 highest-frequency bands were slightly greater than the weights for listeners with NH (Fig. 4). Conversely, perceptual weights for the low-frequency bands were less than the weights for listeners with NH. The aided weights for the listeners with SNHL were compared to the weights for the listeners with NH using a repeated-measures ANOVA with a within-subject factor of frequency band and a between-subject factor of hearing status. The loudness weights differed significantly across frequency band [$F(3.5,45.8) = 14.5$; $p < .001$; $\eta^2 = .53$], hearing status [$F(1,13) = 5.3$; $p = .039$; $\eta^2 = .29$], and by frequency band and hearing status [$F(6,78) = 4.4$; $p = .006$; $\eta^2 = .25$].

Discussion

The current data from listeners with NH agree with previous perceptual-weight data for broadband stimuli showing increased contribution of the lowest and highest frequency bands relative to mid-frequency bands to overall loudness (Leibold et al. 2007; Oberfeld et al. 2012; Jesteadt et al. 2014, 2017). As hypothesized, amplification caused an increase in the contribution of high-frequency bands to loudness as the hearing-aid simulator restored audibility to the listeners with SNHL. However, the aided weights for the listeners with SNHL showed significant differences from the unaided weights for listeners with NH. Specifically, the listeners with SNHL placed more weight on the high-frequency bands and less weight on the low-frequency bands than the listeners with NH. Surprisingly, the unaided results for the listeners with SNHL showed better statistical agreement with the control group than the aided results. The results do not provide good support for the DSL Adult amplification strategy because they suggest that the method fails to restore normal loudness perception, at least as measured by the perceptual weights methodology.

As stated previously, all except 1 of the participants in Experiment 1 had previous experience with hearing aids. Because loudness complaints are believed to be most prevalent among adults who obtain hearing aids for the first time and an ensuing acclimatization period may assist in remedying the problems associated with loudness, we speculated that the contribution of different frequency bands to loudness might change over the first few months of hearing-aid use.

We conducted Experiment 2 with the objective of investigating the effect of hearing-aid experience on perceptual weights. The unaided and aided perceptual weights for a group of first-time hearing-aid users were compared across a 12-week time span. We speculated that at the time of the initial provision of amplification, the aided perceptual weights might deviate even farther from the weights of the listeners with NH than observed in Experiment 1. However, following a few months of hearing-aid experience, the aided perceptual weights

—especially those for high-frequency bands—may be in closer alignment with the perceptual weights of the listeners with NH. The alternative (null) hypothesis was that the high-frequency contribution of loudness would remain the same over time, suggesting that hearing-aid experience does not contribute to loudness acclimatization.

EXPERIMENT 2

Materials and Methods

Participants—Six first-time adult hearing-aid users (3 males, 3 females; ages 60 to 79 years; mean age 70 years) with SNHL were recruited from the audiology clinic at Boys Town National Research Hospital in Omaha, Nebraska. All participants were screened with the Mini-Mental State Exam (MMSE) prior to their participation (Folstein et al. 1975) and their scores fell within the normal range (>24), suggesting the absence of cognitive impairments. All participants had bilateral, although not always symmetrical, SNHL. Test ears were selected according to a threshold criterion of 40-60 dB HL at 2,000 Hz. This criterion was chosen due to its similarity with the hearing levels of the participants in Experiment 1. For 2 participants, the ear with the better word recognition score was selected for testing. In total, 3 left ears and 3 right ears were tested. The air-conduction pure-tone thresholds for the test ear of each participant are shown in Table 3.

Hearing Aids—With the exception of a brief, in-office hearing-aid demonstration, no participant had worn hearing aids in the past. Hearing aids were fit on all subjects during the course of the study. The hearing aids were privately purchased and were recommended by a clinical audiologist during routine consultation. One participant chose a monaural hearing-aid fitting on her test ear, and the remaining 5 participants were fit binaurally. Hearing aids were from several different manufacturers, but were all the receiver-in-canal (RIC) style.

At the time of consent, all participants signed a release granting authorization for review of their audiology clinical records and hearing-aid programming profiles. Information was collated for each participant and is provided in Table 4. Hearing-aid manufacturers are listed to provide a sense of the variety and method of signal processing. The method of coupling to the ear (i.e. dome or custom earmold) is listed due to its acoustic effect. The speech intelligibility index (SII) as obtained for soft (55 dB SPL), average (65 dB SPL) and loud (75 dB SPL) speech inputs to an Audioscan Verifit (Dorchester, Ontario) system is listed as an estimate of aided audibility. Frequency-lowering information (active or disabled, and the start frequency if active) as well as the maximum audible frequency are provided because they are important considerations for the audibility of high-frequency sounds. The maximum audible frequency was approximated at the point where the 65 dB SPL speech input intersected hearing thresholds during real-ear verification with frequency lowering turned on (if applicable). Finally, datalogging values for average daily use and volume control use are listed because this information could be important for ascertaining any effect of amplification on loudness acclimatization.

Stimuli—The same unaided stimuli from Experiment 1 were used for Experiment 2. However, the procedure for generating the aided stimuli was modified in 3 ways from Experiment 1. The first modification was that the hearing-aid simulator did not scale all

stimuli to 63 dB SPL prior to amplification. In Experiment 1, the scaling had unintended effects on the range of levels within individual noise bands, as measured across all stimuli. Consequently, the ranges were as great as 15 dB for some listeners, which was larger than the 12 dB range of levels across the unaided stimuli. For Experiment 2, the overall level of the 500 stimulus files was 63 dB SPL on average but was varied at the input of the hearing-aid simulator. This method maintained the same overall aided presentation levels as in Experiment 1 while preserving the intended 12 dB range of levels within individual noise bands. The second modification was that a linear amplification scheme was used instead of WDRC to simplify processing and analysis.

After collecting data on the first listener (S-09) it was discovered that the hearing-aid simulator applied negative gain to band 1 (see Fig. 5) according to the DSL strategy for cases where hearing thresholds are in the normal range. The third modification of the hearing-aid simulator prevented the reoccurrence of negative gain for subsequent participants.

Levels were computed for individual aided stimuli using third-octave band filters (ANSI 2004) at the center frequency of each noise band. Correction factors based on the KEMAR-to-headphone transform function were applied to estimate the levels in dB SPL at the tympanic membrane. Figure 5 illustrates the mean output levels of the noise bands in the unaided and aided conditions relative to hearing thresholds (i.e. audibility) for individual listeners in Experiment 2.

Procedure—Each listener completed two, 2-3 hour sessions, each consisting of 500 trials in the unaided condition followed by 500 trials in the aided condition. As in Experiment 1, random pairs of stimuli were presented at an overall mean level of 63 and 64 dB SPL during the unaided trials, and at the level equal to the output of the hearing-aid simulator but with 1 dB added to one of the intervals during the aided trials. For one listener (S-13), the unaided presentation level was increased to a mean level of 73 and 74 dB SPL due to reported inaudibility at the lower level. The first session was completed before fitting of hearing aids, and the second session was completed 12-13 weeks after the fitting and verification of hearing aids to DSL Adult or NAL-NL2 prescriptive targets. Test conditions for the second session were identical to those for the first session. Data analysis for both sessions was identical to Experiment 1.

Results

Figure 6 shows the individual normalized perceptual weights in unaided (2 left columns) and aided (2 right columns) conditions across the 2 test sessions for the first-time hearing-aid users. Hearing-aid experience is shown as the parameter with the filled symbols representing the first session occurring before any hearing-aid experience (0 weeks) and the open symbols representing the second test session occurring 12-13 weeks following individual hearing-aid fittings. Figure 7 shows the mean and standard errors for the normalized perceptual weights across the same 6 listeners. Also shown in Figure 7 alongside the data from the aided condition are the mean normalized perceptual weights for listeners with NH from Experiment 1. It is apparent from Figures 6 and 7 that the pattern of perceptual weights

was highly replicable across time. Only slight differences are noted. For instance, in the unaided condition, a greater mean perceptual weight was observed during the second test session than during the first test session for the lowest-frequency band (Fig. 7). This effect was largely driven by data from 2 individual listeners (S-10 and S-12).

Effect of Hearing-Aid Experience—A repeated-measures ANOVA was completed with the within-subject factors of frequency band, time, and amplification condition (aided, unaided) for the loudness weights for the listeners with SNHL. Results confirm that there was not a significant effect of time [$F(1,5) = .02$; $p = .889$; $\eta^2 < .01$], frequency band [$F(6,30) = .96$; $p = .471$; $\eta^2 = .16$], or amplification condition [$F(1,5) = .72$; $p = .435$; $\eta^2 = .13$]. None of the interactions with time were significant. Specifically, frequency band did not interact significantly with time [$F(6,30) = .82$; $p = .566$; $\eta^2 = .14$], time did not interact significantly with the amplification condition [$F(1,5) = .01$; $p = .927$; $\eta^2 < .01$], and the interaction of frequency band, time, and amplification were not statistically significant [$F(6,30) = 1.2$; $p = .355$; $\eta^2 = .19$]. As in Experiment 1, amplification condition interacted significantly with frequency band [$F(6,30) = 11.3$; $p < .011$; $\eta^2 = .69$].

SNHL Unaided: Experiment 1 vs. Experiment 2—For the listeners with SNHL, a difference was noted in the unaided perceptual weights between Experiment 1 and 2. The listeners in Experiment 2 appeared to assign more weight to the mid-frequency bands in the unaided condition than the listeners with SNHL in Experiment 1 (compare Fig. 6 to Fig. 3). Specifically, the peak perceptual weight in the unaided condition occurred at a mid-frequency band for 4 of the 6 listeners. In contrast, this pattern is only observed for 1 listener (S-03) in Experiment 1.

To determine the significance of this difference, a repeated-measures ANOVA was completed with a within-subject factor of frequency band and a between-subject factor of experimental group to compare the unaided loudness weights between the listeners with SNHL in Experiments 1 and 2. The ANOVA was completed after averaging the perceptual weights for the 2 tests sessions in Experiment 2. The effect of frequency band was significant [$F(1.7,20.9) = 4.8$; $p = .023$; $\eta^2 = .29$]. However, there was not a significant effect of the experimental group [$F(1,12) = .82$; $p = .38$; $\eta^2 = .06$] and the interaction of frequency band with experimental group was not significant [$F(1.7,20.8) = .62$; $p = .526$; $\eta^2 = .05$].

SNHL Aided: Experiment 1 vs. Experiment 2—Differences in aided perceptual weights between Experiments 1 and 2 were also noted. Mean data indicate that the listeners in Experiment 2 placed more weight on the low- and mid- frequency bands in the aided condition compared to the listeners in Experiment 1. The aided weights for bands 2 through 5 better matched the weights for listeners with NH than the aided weights in Experiment 1 (compare Fig. 7 to Figure 4).

To assess these differences, a repeated-measures ANOVA was also completed with a within-subject factor of frequency band and a between-subject factor of experimental group to compare the aided loudness weights between the listeners with SNHL in Experiments 1 and 2. The ANOVA was completed after averaging the perceptual weights for the 2 tests sessions

in Experiment 2. The effect of frequency band was significant [$F(3.3,40.2) = 17.7$; $p < .001$; $\eta^2 = .60$]. However, there was not a significant effect of experimental group [$F(1,12) = 4.2$; $p = .063$; $\eta^2 = .26$] and the interaction of frequency band with experimental group was not significant [$F(3.3,40.2) = 0.49$; $p = .709$; $\eta^2 = .04$].

Unaided: SNHL vs NH—The average loudness weights for the 2 test sessions were calculated for the listeners with SNHL and used in a repeated-measures ANOVA with a within-subject factor of frequency band and a between-subject factor of hearing status to compare the unaided loudness weights between listeners with SNHL and NH. The main effect of frequency band [$F(2.8,30.7) = 3.5$; $p = .031$; $\eta^2 = .24$] and the interaction of frequency band and hearing status were statistically significant [$F(2.8,30.7) = 4.5$; $p = .012$; $\eta^2 = .29$]. The main effect of hearing status [$F(1,11) = 1.8$; $p = .209$; $\eta^2 = .14$] was not statistically significant.

In a subsequent analysis, we sought to determine the relationship between individuals' mean unaided normalized perceptual weights and their hearing threshold at each frequency band. It was presumed that perceptual weights would be negatively correlated with hearing sensitivity: as hearing thresholds increase (become poorer), perceptual weights might be expected to decrease due to less audibility of stimuli. A logarithmic interpolation was completed on the audiograms of each listener with SNHL in Experiments 1 and 2 to estimate their hearing thresholds at the center frequencies of the 7 noise bands used in the stimuli. Negative correlations were found across subjects for the perceptual weights for band 3 (centered at 636 Hz, $r = -0.26$, $p = 0.37$), band 4 (centered at 990 Hz, $r = -0.71$, $p = 0.004$), band 5 (centered at 1569 Hz, $r = -0.91$, $p < 0.00001$), and band 6 (centered at 2512 Hz, $r = -0.27$, $p = 0.35$) and the interpolated hearing thresholds at those center frequencies. The correlations observed for several frequency bands indicate that much of the variability in the unaided weights is explained by variability in hearing thresholds (audibility). Where audibility was uniformly high (bands 1 and 2) or low (band 7), correlations were not observed.

Aided SNHL vs. NH—Lastly, a repeated-measures ANOVA was completed with a within-subject factor of frequency band and between-subject factor of hearing status to compare the aided loudness weights, averaged between the 2 sessions, for the listeners with SNHL to the unaided loudness weights for the listeners with NH. The loudness weights differed significantly across frequency band [$F(2.9,31.4) = 10.1$; $p < .001$; $\eta^2 = .20$], but not by hearing status [$F(1,11) = .27$; $p = .613$; $\eta^2 = .02$] or by frequency band and hearing status [$F(2.8,31.4) = 2.7$; $p = .06$; $\eta^2 = .20$].

Discussion

The unaided and aided perceptual weights obtained from the listeners with SNHL were statistically consistent across the 2 experiments. Contrary to hypothesis, the contribution of different frequency bands to overall loudness was not affected by 12 weeks of hearing-aid experience. Furthermore, the aided perceptual weights for the high-frequency bands were not any greater for the group of new hearing-aid users in Experiment 2 than for the participants in Experiment 1. These 2 findings suggest that the perceptual weight measure is

not sensitive to an effect of hearing-aid acclimatization. Surprisingly, however, the aided weights for the low- and mid- frequency bands showed a much closer approximation to the weights of the control group in Experiment 2 than in Experiment 1.

The results of Experiment 2 provide more support for the DSL Adult's ability to achieve loudness normalization than Experiment 1 because Experiment 2 did not show a statistically significant effect of hearing status when comparing the aided weights to the weights for the NH controls. As in Experiment 1, the listeners with SNHL placed more weight on the 2 highest-frequency bands in the aided condition compared to listeners with NH, suggesting that the high-frequencies contribute to overall loudness to a greater-than-normal degree in adult listeners with SNHL using the DSL amplification strategy.

GENERAL DISCUSSION

Because our experiment amplified stimuli according to the DSL Adult formula, it is not clear how perceptual weights would be affected by amplification according to other fitting strategies and therefore our findings may not be generalized to all hearing-aid fittings. For example, the commonly used NAL-NL2 formula is based more on maximizing intelligibility than normalizing loudness and prescribes less high-frequency gain for sloping SNHL than the DSL Adult formula (Dillon 2012). Therefore, it is possible that the aided perceptual weights using NAL-NL2 would not be as great and would show a better match to NH data than was found in the current experiments. Alternatively, it may also be possible that perceptual weights are not sensitive to slight differences in hearing-aid prescriptions. Further work is needed to determine the sensitivity of the perceptual weights paradigm to different amplification strategies.

An inherent disadvantage of the perceptual weight paradigm is that it is unclear whether listeners respond to differences in loudness or whether they respond to some other perceptual attribute of the stimuli. For example, one participant in Experiment 2 remarked that he could distinguish the stimuli in the intervals according to differences in the "volume of rushing air" and also the "fullness of tone." We believe that an example of listeners making judgments on perceptual attributes other than loudness is contained in the results from Experiment 1. Specifically, recall that a few of the listeners with SNHL placed negative perceptual weights on some low- and mid-frequency bands in the aided condition. Negative weights are counterintuitive to our interpretation of data because they suggest that an increase in level causes reduced loudness. An explanation may be that for listeners with high-frequency hearing loss, decreasing the level of low-frequency components effectively increases the high-frequency emphasis of the stimulus. This spectral change may be perceived as more annoying or aversive, rather than an increase in loudness per se.

An important limitation to the current experiment is that it is difficult to separate the effects of frequency-specific amplification from the effects of increasing overall presentation level. Presentation level has been shown to have a large influence on perceptual weights, especially for high-frequency components. In one of the earliest studies comparing perceptual weights between listeners with SNHL and those with NH, Doherty and Lufti (1996) presented stimuli at a mean level of 65 dB SPL for listeners with NH and a mean

level of 80 dB SPL for listeners with SNHL. Initially, the results were interpreted to suggest that listeners with SNHL place more weight on highest-frequency components than listeners with NH. Several subsequent experiments have cast doubt on this conclusion, however, by showing that listeners with NH give more weight to high-frequency components as presentation levels increase (Leibold et al. 2009, Jesteadt et al. 2014, Calandruccio et al. 2016).

In the present experiments, although presentation level (in terms of SPL) was controlled between listener groups in the unaided condition, it was not controlled between groups in the aided condition. The results showing that the DSL Adult amplification method caused the high-frequency bands to contribute more weight to loudness compared to listeners with NH may have been due to the specific frequency-gain response of the hearing-aid simulator, or it may have been due—at least in part—to a basic effect of increased presentation level. Future work might address this issue by using spectral shaping to explore the effect of different gain-frequency responses on the perceptual weights of listeners with NH. However, such a comparison within the confines of the current experiment would have been difficult because our listeners with NH would have, in theory, needed to be tested using all the different sets of aided stimuli created for each individual listener with SNHL.

Ultimately, when evaluating the effects of amplification on the loudness perception of persons with SNHL, it is the normal, unaided perception that is the appropriate reference for comparison. Because the stimuli used for the unaided condition in listeners with NH were also used as input to the hearing-aid simulator, the comparison of aided perceptual weights for listeners with SNHL to the unaided perceptual weights for listeners with NH is appropriate to address the issue of whether amplification has restored normal perception of loudness.

Another variable potentially confounding the results of our experiments is that the 7 noise bands composing the stimuli were not equal in ERB bandwidth. The ERB bandwidth became larger as a function of frequency, such that the lowest frequency band was 2.8 ERB wide and the highest frequency band was 3.9 ERB wide (see Table 2). These bandwidths were chosen to align with the channels of the hearing-aid simulation software to allow for independent amplification of the noise bands. Stimuli with a larger perceptual bandwidth can be expected to contribute more to loudness than stimuli with a narrower perceptual bandwidth, and this effect may have contributed to the increased perceptual weights of the high-frequency bands once they were amplified to audible level for the listeners with SNHL. For the listeners with NH, an increased perceptual weight for high-frequency components has been shown even for stimuli consisting of noise bands of equal level and ERB (Jesteadt et al 2017), suggesting that any effect of bandwidth on the perceptual weights is secondary to larger effects of relative frequency. Additionally, because the same stimuli were used to test both the listeners with NH and SNHL, the unequal bandwidths of the noise bands should not impact the comparison of weights between listener groups. Therefore, the unequal bandwidths would not seem to limit our conclusions regarding the ability of the DSL Adult formula to normalize loudness.

Consider also that listeners with SNHL are thought to have poorer frequency selectivity and broadened auditory filters compared to listeners with NH (Glasberg & Moore, 1986). This functional difference may impact comparisons of loudness to the extent that it also relates to spread of excitation. The increased perceptual weights for the high-frequency bands in listeners with NH is believed to be, in part, an edge effect reflecting a spread of excitation to frequency regions beyond those contained in the stimuli (see Jesteadt et al., 2017 for a more detailed discussion). For listeners with SNHL, poorer frequency selectivity would theoretically correspond to greater upward spread of excitation than in normal ears, but this effect would be counteracted by a reduced hearing sensitivity at those higher-frequencies. Therefore, the influence of spread of excitation on the increased perceptual weights of high-frequency bands for listeners with SNHL remains unclear.

The use of a hearing aid-simulator rather than participants' own hearing aids may have impacted the findings observed. The rationale for using a hearing-aid simulator was that it would provide more precise experimental control. Hearing-aid properties can vary widely between manufacturers and between individuals, which can make it difficult to monitor and control the methods of signal processing. Furthermore, hearing aids are designed to amplify speech rather than noise, and modern hearing aids contain digital noise reduction features that reduce gain in response to noise-like inputs. Thus, real hearing-aids were not preferred for testing the selected stimuli. We did collect information about our participants' actual hearing aids in Experiment 2 to assess how that might influence results (Table 4), but there was not enough variance in the perceptual weights, nor enough participants, to reveal any association of hearing-aid settings to the perceptual weights.

Results from Experiment 2 suggest the contribution of different frequency regions to loudness does not change after the first few months of hearing-aid listening experience. This finding was contrary to our hypothesis that an acclimatization effect might be apparent in perceptual weights for the high-frequency bands in the aided condition. The current results are more consistent with findings from previous literature describing the preferred gain of hearing-aid users, which generally do not support the concept of loudness acclimatization (Convery et al. 2005).

One explanation for the lack of an observed acclimatization effect is that the perceptual weight methodology is insensitive to slight changes in the specific loudness at certain frequencies. Perceptual weights indicate the *relative* contribution of several frequency regions to loudness rather than absolute loudness. ULLs and CLS appear to be the most sensitive measures to loudness acclimatization, and should be included in addition to measures of perceptual weight in future studies. Previous work has demonstrated increased ULLs (Munro & Trotter, 2006; Munro et al. 2007) and significant decreases in the intensity of pure-tones associated with loudness categories for CLS (Olsen et al. 1999; Philibert et al. 2002, 2005) in listeners with SNHL with hearing-aid experience as compared to those without hearing-aid experience.

Another explanation is that the listeners in our experiment did not have a severe enough hearing loss for an acclimatization effect to be observed. Keidser et al. (2008) reported that the difference in preferred gain between new and experienced hearing-aid users increased as

a function of the severity of hearing loss. The average hearing thresholds at 2 and 4 kHz for the listeners in Experiment 2 were 48 and 54 dB HL, respectively. Results may have been different if listeners with greater degrees of hearing loss had been tested.

A third reason might be attributed to Experiment 2's small sample size of 6 participants. Individuals with SNHL are highly variable and have differing needs with respect to hearing-aid management. For instance, one participant in our study (S-12) reported that his hearing aids were never too loud. Bentler and Cooley (2001) found that the ULLs of individuals with the same degree of hearing loss vary by as much as 40 to 50 dB for any given frequency. Due to the heterogeneity of persons with SNHL, it is difficult to generalize the results of any experiment to any given individual with hearing loss. Future experiments should aim for testing more participants due to the large heterogeneity of listeners with SNHL.

Finally, it may be argued that the 12-week time period was not sufficient time for an acclimatization effect to be observed. However, there is indirect evidence from our experiments showing that a longer time period likely would not have revealed a change in the perceptual weights. Our reasoning is that 7 out of the 8 listeners in Experiment 1 reported at least part-time current or past hearing aid use. Because there was not a significant difference in the perceptual weights obtained from those listeners and the perceptual weights from listeners in Experiment 2 with no prior hearing aid use, it seems unlikely that a difference in perceptual weights would have been observed had we continued to test the new-hearing aid users over a period of several additional months or years.

The results of the 2 experiments are clinically valuable because they suggest that high-frequency components of broadband stimuli contribute to loudness complaints of hearing-aid users, and that the effect persists with increasing amplification experience. Consequently, a potential strategy for managing loudness complaints may be to reduce the high-frequency emphasis by decreasing gain for high-frequency inputs or increasing gain for low-frequency inputs. While more research would be required to determine the effectiveness of this strategy, it is nevertheless worthwhile for clinicians to rethink their views regarding the effect of frequency on loudness, and to reconsider their strategies for managing the loudness complaints of hearing-aid patients.

CONCLUSIONS

- A measure of the contribution of different frequency regions to the overall loudness of broadband sounds suggests that the higher-frequency components dominate loudness perception in individuals with SNHL listening through hearing aids.
- Listeners with NH also give increased perceptual weight to high-frequency components of broadband sounds, but not as much as listeners with SNHL amplified according to the DSL Adult prescription formula.
- The first few months of hearing-aid use do not affect the relative contribution of different frequency bands to loudness perception.

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Figure 1.

Unaided and aided output levels for individual listeners with SNHL in Experiment 1. Mean unaided (squares) and aided (circles) levels across the 500 stimulus files, calculated in third-octave bands at the center frequency of each noise band, are shown with the pure-tone audiometric thresholds (asterisks) of each listener.

Figure 2.

Normalized perceptual weights in the unaided condition for 7 listeners with normal hearing.

The panels labeled “N-01” to “N-07” display individual results for each respective listener.

The eighth panel labeled “Mean” displays the average results across the listeners.

Figure 3.
Individual normalized perceptual weights for the 8 listeners with SNHL in unaided and aided conditions.

Figure 4. Means and standard errors for normalized perceptual weights for 7 listeners with NH and 8 listeners with SNHL.

Figure 5.

Unaided and aided output levels for individual listeners in Experiment 2. Mean unaided (squares) and aided (circles) levels across the 500 stimulus files, calculated in third-octave bands around the center frequency of each noise band, are shown with the pure-tone audiometric thresholds (asterisks) of each listener.

Figure 6.

Normalized perceptual weights for individual first-time hearing aid users with SNHL in unaided and aided conditions across 2 test sessions. The panels labeled “S-09” to “S-14” show individual results for each respective listener. Hearing-aid experience is the parameter with the filled symbols representing the first test session at 0 weeks of HA experience and the open symbols representing the second test session at 12 weeks of HA experience. The unaided condition is displayed in the left 2 columns and the aided condition is shown in the right 2 columns.

Figure 7. Means and standard errors for normalized perceptual weights for 6 first-time hearing-aid users with SNHL in unaided and aided conditions across 12 weeks of hearing-aid experience. Mean Normalized Perceptual Weights from the listeners in Experiment 1 with NH are displayed alongside the data from the aided condition.

Table 1

Test-ear Hearing Thresholds (dB HL) of Listeners in Experiment 1.

A. Listeners with Sensorineural Hearing Loss							
Subject	Ear	250	500	1000	2000	4000	8000
S-01	R	55	50	40	50	65	85
S-02	L	25	40	55	65	60	80
S-03	L	25	35	25	35	50	65
S-04	L	15	40	55	55	55	75
S-05	R	5	35	45	65	50	25
S-06	L	40	40	50	50	60	55
S-07	L	20	40	45	40	50	55
S-08	L	25	60	60	55	50	35
<i>Mean (SD)</i>		<i>26.3 (14.3)</i>	<i>42.5 (7.9)</i>	<i>46.9 (10.3)</i>	<i>51.9 (10.0)</i>	<i>55.0 (5.6)</i>	<i>55.6 (24.0)</i>
B. Listeners with Normal Hearing							
Subject	Ear	250	500	1000	2000	4000	8000
N-01	L	10	0	0	10	10	5
N-02	L	0	-5	0	0	10	15
N-03	L	5	5	0	5	10	20
N-04	L	10	10	5	0	0	0
N-05	L	15	5	-5	5	10	20
N-06	L	15	0	0	10	15	25
N-07	L	15	5	5	5	0	15
<i>Mean (SD)</i>		<i>10.0 (5.3)</i>	<i>2.9 (4.5)</i>	<i>0.7 (3.2)</i>	<i>5.0 (3.8)</i>	<i>7.9 (5.2)</i>	<i>13.6 (8.3)</i>

Table 2

Characteristics of 7 Noise-Band Stimuli

Noise-Band	Center Frequency (Hz)	Low Frequency (Hz)	High Frequency (Hz)	Bandwidth (Hz)	Bandwidth (octaves)	Bandwidth (ERB)
1	232	172	314	142	0.87	2.81
2	400	315	509	194	0.69	2.83
3	636	510	794	284	0.64	3.02
4	990	795	1234	439	0.64	3.31
5	1569	1235	1994	759	0.69	3.88
6	2512	1995	3164	1169	0.67	3.92
7	3958	3165	4950	1785	0.64	3.92

ERB - Equivalent Rectangular Bandwidth

Table 3

Test-ear Hearing Thresholds (dB HL) of Listeners in Experiment 2.

Subject	Ear	Frequency (Hz)						
		250	500	1000	2000	4000	6000	8000
S-09	R	15	10	20	40	45	60	80
S-10	L	30	30	45	55	70	80	NR
S-11	R	35	40	35	50	65	65	70
S-12	L	20	20	20	40	50	65	65
S-13	R	35	40	60	55	35	50	40
S-14	L	15	35	40	50	60	60	60
Mean (SD)		25.0 (8.7)	29.2 (11.0)	36.7 (15.1)	48.3 (5.8)	54.2 (12.0)	63.3 (9.0)	63.0 (13.9)

Table 4

Hearing-aid Characteristics of Listeners in Experiment 2.

Subject	Manufacturer	Coupling to Ear	Fitting Formula	Datalogging (hours/day)	Speech Intelligibility Index (SII)	Frequency Lowering (Start Freq.)	Maximum Audible Frequency	Volume Control Use
S-09	Phonak	Custom mold	DSL 5.0 a	12-12.7	71, 81, 85	On (4.5 kHz)	4.5 kHz	0
S-10	Signia	Closed dome	NAL-NL2	13-15	40, 50, 65	Off	3.7 kHz	1-3 steps/day
S-11	Phonak	Custom ear mold	DSL 5.0 a	6.2	41, 66, 80	Off	4.0 kHz	-2 steps/day
S-12	ReSound	Open dome	DSL 5.0 a	12-2	65, 78, 81	On (4.0 kHz)	4.5 kHz	-3 dB (1 time)
S-13	Phonak	Power dome	DSL 5.0 a	N/A	26, 54, 80	Off	6.0 kHz	N/A
S-14	Phonak	Closed dome	DSL 5.0 a	12.1-12.8	42, 55, 78	On (4.4 kHz)	3.0 kHz	0