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Research Article

The Impact of Increasing Hearing Aid High-Frequency Bandwidth

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Abstract

Rationale

The purpose of this study was to investigate the influence of high-frequency cut-off on speech perception in quiet and noise; specifically to determine if a significant benefit is observed on speech recognition testing in quiet and noise as high-frequency information is amplified with receiver-in-the canal (RIC) devices using a commonly used fitting rationale.

Methods

Eighteen adults with high-frequency hearing loss (HFHL) were fitted with bilateral RIC hearing aids programmed to NAL-NL1 targets in three high-frequency cut-off conditions: 4000, 5500, and 7500 Hz. Speech perception was assessed using Pascoe's High Frequency Word List and the Hearing in Noise Test (HINT).

Results

The results indicated that the participants in this study benefited from amplification through 4000 Hz. There was a tendency for performance to increase on Pascoe's High Frequency Word List as cut-off condition increased, but there was no effect of cut-off condition on performance on the HINT. Statistical analyses of the data indicated that increasing cut-off frequency past 4000 Hz had minimal impact on the scores for both test measures when using an NAL-NL1 target.

Introduction

High-frequency hearing loss (HFHL) is the most common configuration of hearing loss for adults, especially first-time hearing aid users (Hannulu, Bloigu, Majamaa, Sorri, & Maki-Torkko, 2011; Van Tasell, 1993). Individuals with this type of hearing loss have normal hearing to a mild hearing loss for low- to mid-frequency sounds sloping to poorer hearing (of varying severity) for high-frequencies such as 2000 or 4000 through 8000 Hz (Mueller, Bryant, Brown & Budinger, 1991; Tye-Murray, 2004). This type of loss is common among individuals with a history of presbycusis (Schuknect, 1955), ototoxicity (Ballantyne, 1973), and exposure to noise (Sataloff, Vassallo, & Menduke, 1967).

Adults with HFHL often are fitted with receiver-in-canal (RIC) hearing aids. The RIC devices offer the advantage of an open ear to minimize perceived occlusion (Kiessling, Brenner, Jesperson, Groth, & Jensen, 2005; Kiessling, Margolf-Hackl, Geller, & Olsen, 2003; Kuk & Keenan, 2006; Kuk, Keenan, & Lau, 2005; Vasil & Cienkowski, 2006) and, due to new receiver technology, potentially include extended bandwidth receivers (Kuk & Baekgaard, 2008). The popularity of these devices is growing rapidly. In 2009, it was reported that "mini-BTE" hearing aids were worn by 25.3% of individuals that participated in the MarketTrak survey (Kochkin, 2011). Recently, Kirkwood (2012) suggested that approximately 63% of BTE hearing aid sales for the first quarter in 2012 were RIC. This was compared to 2009 when 58% of BTEs purchased were conventional BTE devices (Kirkwood, 2012).

Although the benefits of RIC fittings have been argued; clinically, bandwidth effects have not been investigated specifically for RIC fittings or for traditional fitting algorithms. In early work, Fletcher (1953) noted that individuals with a loss between 2000 and 8000 Hz were at the most risk of missing auditory cues for consonant perception. Consonant understanding is highly dependent upon the perception of second and third formant frequencies of adjacent vowels (Boothroyd, 1978), and differentiate place of articulation

Delattre, Liberman, & Cooper, 1955; Liberman, Cooper, Shankweiler, & Studdert-Kennedy, 1967). The high-frequency speech energy beyond 4000 Hz has been shown to be important (Heinz & Stevens, 1961; Hughes & Halle, 1956; Sher & Owens, 1974), for perceiving final consonants such as /s/, especially when produced by female and child speakers (Stelmachowicz, Pittman, Hoover, & Lewis, 2001; 2002; Stelmachowicz, Pittman, Hoover, Lewis, & Moeller, 2004). In addition, auditory access to resonances between 3500-8000 Hz helped to differentiate voiced from voiceless fricatives (Heinz & Stevens, 1961; Hughes & Halle, 1956; Minifie, 1973). This suggests that audibility of high-frequency speech information is crucial to consonant perception.

Investigations of whether adults with HFHL can benefit from extended high-frequency amplification have produced conflicting results. Numerous studies have demonstrated improved speech recognition with increased high-frequency audibility (Beamer, Grant, & Walden 2000; Hornsby & Ricketts, 2003, 2006; Horwitz, Ahlstrom, & Dubno, 2008; Pascoe, 1975; Plyler & Fleck, 2006; Skinner, 1980; Sullivan, Allsman, Nielsen, & Mobley, 1992; Turner & Henry, 2002). In contrast, a number of investigators reported that speech recognition remains constant or deteriorates as amplification is provided at higher frequencies (Amos & Humes, 2007; Baer, Moore, & Kluk, 2002; Ching, Dillon, & Byrne, 1998; Hogan & Turner, 1998; Horwitz et al., 2008; Murray & Byrne, 1986; Rankovic, 1991; Skinner, 1980; Sullivan et al., 1992; Turner & Cummings, 1999; Vickers, Moore, & Baer, 2001). However, these results are not easily compared to clinically fitted RIC devices. Much of the bandwidth research has utilized digitized and spectrally-shaped speech signals presented through headphones or inserts (Sullivan et al., 1992; Turner & Henry, 2002; Vickers et al., 2001) or in monaural conditions (Hogan & Turner, 1998; Hornsby & Ricketts, 2003; 2006; Horwitz et al., 2008; Preminger & Wiley, 1985; Souza & Bishop, 2002). In all of these cases, the devices and headphones blocked the ear canal from being "open." During an "open" fitting, frequencies below 1500 Hz are attenuated (Lybarger, 1985). As a result, RIC hearing aids provide a unique acoustic situation in that there is minimal balance between the low- and high-frequency acoustic information. This is unlike conventional hearing aids with vents or when listening with headphones.

A second challenge for the application of these results to clinical fittings is a lack of a standardized fitting protocols among the research studies. Presently there are two prescriptive fitting methods that have been widely used across hearing aid manufacturers: National Acoustics Laboratory Nonlinear 1 (NAL-NL1; Byrne, Dillon, Ching, Katsch, & Keidser, 2001) and Desired Sensation Level (DSLv5.0; Scollie et al., 2005) (Ricketts & Mueller, 2009). For adult hearing aid users, the most common prescriptive fitting algorithm utilized is NAL-NL1 due to the substantial amount of evidence that supports patient preference and success with this type of fitting (Byrne et al., 2001; Keidser & Grant, 2001; Mueller, 2005; Ricketts & Muller, 2009). The rationale behind NAL-NL1 is to maximize speech intelligibility for specific loudness levels (Byrne et al., 2001). The result may be prescribed gain for high-frequencies that is less than optimal for audibility for individuals with sloping losses (Byrne et al., 2001). The question then remains as to whether the increased high-frequency cut-off is worthwhile and meaningful for individuals with sloping HFHL fitted with RIC hearing aids to a standard and commonly used prescriptive fitting algorithm.

The purpose of this study was to further investigate the influence of high-frequency cut-off on speech perception in quiet and noise. Specifically, we aimed to determine if a significant benefit is observed on speech recognition testing in quiet and noise as high-frequency information is amplified with RIC devices using a commonly used fitting rationale. If not, were there negative consequences that would lead to reduced performance with an RIC device?

Methods

Participants

An a priori power analyses indicated that for an repeated measures model, a sample size of 17 would result in power of .80. Four females and 14 males were recruited from the areas surrounding the University of Connecticut. The mean age of the participants was 62.94 years with a standard deviation (*SD*) of 5.22 years. Eleven participants were non-hearing aid users and 7 individuals were binaural hearing aid users, with the average years of use at 3.25 years (*SD* = 3.91 years). The mean hearing thresholds for the 18 participants are displayed in Figure 1. On average, the participants had normal hearing from 250 through 1000 Hz sloping to a moderate to moderately-severe sensorineural hearing loss in both ears. This research was approved by the University of Connecticut Institutional Review Board and informed consent was obtained from all participants. All participants were provided financial compensation following completion of the protocol.

Inclusion criteria were set such that participants with central deficits or dead regions were not included. This was determined by performance on the Dichotic Digits Test (Musiek, Gollegly, Kibbe, & Verkest-Lenz (1991) and Threshold in Equalizing Noise (HL) test (Moore, Glasberg, &

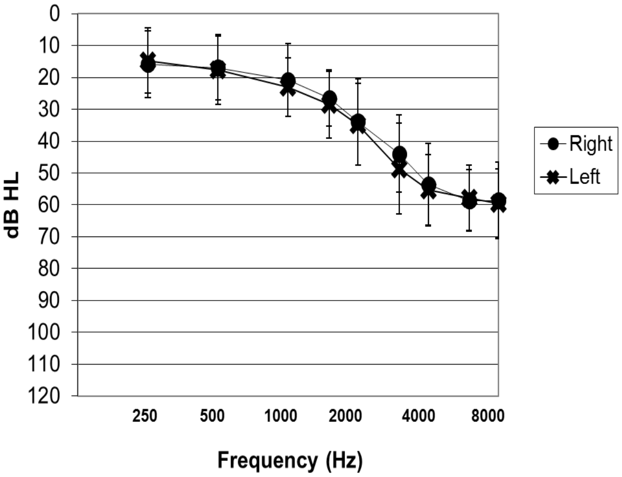

Figure 1. Mean audiometric thresholds for all participants. Error bars represent one standard deviation.

Stone, 2004) respectively. The Dichotic Digits Test was administered at 50 dB SL re: the threshold at 1000 Hz. Participants were instructed to repeat all four numbers they heard. Musiek and colleagues (1991) determined that use of standard criterion for individuals with HFHL yielded a high false positive rate. Based on their data of 30 individuals with hearing loss, they adjusted the criterion from 90% in each ear to 77% in the left ear and 85% in the right ear (Musiek et al., 1991). This adjusted criterion was used as the screening criterion for all participants. For the TEN (HL) test, participants were asked to detect pure tones in the presence of broadband noise presented at 10 dB SL re: the threshold at each frequency. The researchers calculated the difference between the intensity level of the detected pure tones and the intensity level of broadband noise. If a difference was greater than 14 dB, this indicated the presence of a dead region. The use of 14 dB is a conservative cut-off for screening for cochlear dead regions (Hornsby & Ricketts, 2006; Summers et al., 2003).

Hearing Aids

Commercially available RIC hearing aids with a bandwidth upper limit over 8000 Hz as defined by coupler measures according to ANSI S3.22 (1996) were utilized for this study. The hearing aid receivers were fitted according to manufacturer specifications for each participant as receiver length and receiver tip size varied based on individual pinnae sizes and canal circumferences. The hearing aids were fitted binaurally using individualized gain responses set to the NAL-NL1 target for comfort and audibility (Byrne et al., 2001). An individualized gain response was chosen because each individual's hearing loss is unique and should not be fitted with the same response. In addition, the use of individualized fitting responses has been shown to provide more significant, clinically relevant information, especially for speech intelligibility in noise studies (Horwitz et al., 2008).

Prior to programming for the high-frequency cut-off conditions, the low- and mid-frequency-band channels were fitted with gain according to the manufacturer NAL-NL1 targets and were not adjusted for the duration of the study. Noise reduction and directional microphone settings were disabled. All programs utilized the recommended general compression settings in the manufacturer software.

An initial starting point for bandwidth conditions was established using coupler measures. Following ANSI S3.22 (1996) standards for coupler measures, the input composite signal level was set to 60 dB SPL with the hearing aid at user settings. From this response curve, the high-frequency average (HFA; average intensity at 1000, 1600, and 2500 Hz) was calculated by the Fonix 7000 hearing aid analyzer. A line was drawn at the intensity level obtained by taking the HFA and subtracting 20. The intersection with the high-frequency portion of the response curve was considered the cut-off frequency for the upper limit of the hearing aid. Gain was reduced within channels in the manufacturer software to create the three upper frequency cut-offs programs with boundaries at 4000 Hz, 5500 Hz and 7500 Hz, as confirmed in the coupler. These bandwidth conditions were chosen based on the limitations of the hearing aid, use of similar bandwidth and cut-off conditions in the literature, and the limitations of the frequency responses of the verification equipment.

Audiometric information for each participant was entered into the Fonix 7000 real ear module and individualized NAL-NL1 target values were created for a 50 dB SPL signal. The real ear data was used to verify that the cut-off frequencies were correct, that the high-frequency roll-off was similar in all three programs, and that the output met NAL-NL1 targets. Real-ear aided responses (REARs) were obtained with a 50 dB SPL composite signal. The settings on the hearing aids were adjusted as needed through the manufacturer software to be within 5 dB SPL of the NAL-NL1 target as calculated using the Fonix Real Ear NOAH Module (Version 2.12). It should be noted that gain for channels from 2000 through 8000 Hz always was increased to meet NAL-NL1 target values on the Fonix 7000. For all participants, three programs were created: Program 1 was a full-bandwidth (7500 Hz) condition, Program 2 was a mid-bandwidth condition (5500 Hz), and Program 3 was a low-bandwidth condition

(4000 Hz). Figure 2 displays the average REARs for all three conditions in comparison to audiometric information and average target values.

The REARs were compared with each participant's loudness discomfort levels (LDLs) to ensure that hearing aid output did not exceed discomfort levels. Unaided LDLs were obtained using the Contour Test of Loudness Perception (Cox, Alexander, Taylor, & Gray, 1997). This test was chosen because it was designed specifically for hearing aid fittings.

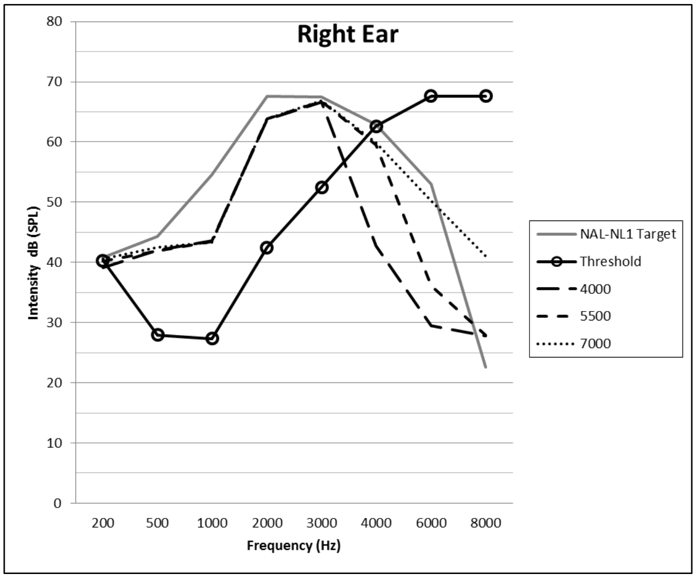

Figure 2. Mean REARs for all three bandwidth cut-off conditions for the right ear (top) and left ear (bottom). Mean NAL-NL1 target values and mean participant audiometric thresholds are also plotted.

Stimuli

Word Recognition in Quiet

Assessment of speech perception for individuals with hearing loss is most often completed through word recognition testing. It has been shown that individuals with HFHL can achieve scores of 90-100% on traditional word recognition tests in an unaided condition (Maroonroge & Diefendorf, 1984; Roup & Noe, 2009; Schwartz & Walden, 1983; Sher & Owens, 1974). Individuals with HFHL performed well on word tests that are not high-frequency weighted because they had access to the low-frequency vowel and mid-frequency consonant information. In addition, many of these tests use familiar words that are easy to decipher if a person does not hear all the information (Maroonroge & Diefendorf, 1984). Therefore commonly used word recognition materials may not be sensitive enough for individuals with sloping hearing losses. For this study, an intelligibility test with primarily high-frequency information was chosen in order to accurately assess speech perception ability and prevent ceiling effects.

To evaluate the effect of bandwidth on speech intelligibility in quiet, the Pascoe High-Frequency Word List (Pascoe, 1975) was used. Pascoe's High Frequency Word List contains 50 monosyllabic words with primarily high-frequency consonant information. The list contains consonants, over 60% of which are voiceless fricatives and plosives, combined with three vocalic nuclei /ɪ/, /ɑɪ/, and /oʊ/. These consonant sounds contain high-frequency energy that would be difficult for individuals with HFHL without amplification to perceive at normal conversational levels. The remaining consonants contain primarily low-frequency energy as nasals, laterals, and voiced plosives (Pascoe, 1975; Skinner & Miller, 1983). This high-frequency word list is unique because every word was chosen so that there were at least six other words that were similar in the list (Pascoe, 1975). The list contains groups of easily-confused words which allowed for easy and various randomizations of list presentation and prevented against learning effects. It has been used previously in bandwidth literature (Pascoe, 1975; Skinner, 1980; Skinner & Miller, 1983) and allowed for direct comparison with previous reported results.

A standardized commercially recorded version of Pascoe's word list has not been produced; therefore, recordings were developed for this study. The words were produced by a female speaker in her 20s, as female and child voices are more likely to produce high-frequency response errors (Gardner, 1984; Stelmachowicz et al., 2001; 2004). This speaker was chosen out of a pool of female speakers because she was a native English speaker that had a high fundamental frequency (above 200 Hz), clear speech without roughness (as subjectively rated by two listeners), and fricative and plosive energy above 6000 Hz. The speech stimuli were recorded in a sound-treated room and the female speaker monitored the level of her voice using a sound level meter. A Shure BG 1.1 microphone was connected to a Dell Latitude D620 laptop computer and the words were recorded using Cool Edit Pro 2.0 digital audio software. Each word was presented in the middle of a carrier phrase, "Write________, please" followed by a pause. The words were recorded at a sampling rate of 44,100 Hz in stereo with 16-bit resolution. Anti-aliasing was not necessary because the sampling rate was greater than twice the widest bandwidth condition. Steady-state background noise, a product of the recording microphone, and background noise, a product of the recording microphone, and pops were removed from recordings using the noise reduction and pop elimination tools within Cool Edit Pro 2.0.

An acoustical analysis of the Pascoe stimuli was performed to ensure adequate high-frequency information and consistency in the frequency components of the consonant sounds. The acoustic analysis was conducted using Adobe Audition 3. Frequency information was analyzed using Fast Fourier Transform (FFT) with a Hanning Window set to 1024 Hz. The FFT produced a spectrum for the specific sound that was being analyzed. The FFT analysis was conducted for each initial and final consonant sound as well as all vowel sounds. The window at which the FFT was performed was chosen by the researcher by looking at the spectrogram for each word. For each sound, a 10 ms time window was analyzed. For fricatives, a window at which frication noise was present on the spectrogram was chosen for the analysis. For stops, the burst segment was chosen for analysis and for the nasals, the point at which murmur was present was chosen for FFT analysis. The FFT analysis provided peak frequency values for each window. The peak frequency information was recorded and compared to normative values previously reported in the literature (Minifie, 1973).

DirectRT software for psychology experiments was used to randomize and present all words in each condition. The software was loaded on a Dell Otiplex GX620 computer. The computer audio output was directed to the audio inputs of a GSI 10 audiometer. The stimuli were presented at 55 dB SPL, a level encountered in everyday life for soft conversational speech. This level was also chosen from a preliminary study which suggested that the presentation level of Pascoe's High Frequency Word List needed to be at least 55 dB SPL in order for normal hearing individuals to score over 90%. The level was calibrated in the sound field using the substitution method. Participants were seated at 0 degrees azimuth at a distance of 3 feet from a GSI sound-field speaker within a sound-treated booth (ANSI S3.1-1999).

Following the procedures used in three similar studies, participants were instructed to listen to each stimulus and write their response (Pascoe, 1975; Skinner, 1980; Skinner & Miller, 1983). The participants were provided sufficient time to write their response following each presentation because the pause time was controlled by the researchers. Written responses were chosen to prevent auditor bias. Words were scored phonetically such that the words did not need to be spelled correctly in order to be considered correct.

Sentence Recognition in Noise

One of the most common complaints of individuals with a HFHL is that they have difficulty hearing in noisy environments (Roup & Noe, 2009). Studies have demonstrated that more significant differences in speech perception ability are observed in the presence of background noise (Horwitz et al., 2008; Pascoe, 1975; Schwartz, Surr, Montgomery, Prosek, & Walden, 1979). Since individuals with HFHL rely on their low-frequency hearing for speech perception, the addition of low-frequency background noise, if loud enough, may mask low-frequency information that would usually be available to individuals with sloping hearing losses (Horwitz et al., 2008).

A standardized recorded version of the Hearing in Noise Test (HINT: Nilsson, Soli, & Sullivan, 1994) was used as the sentence test in noise. Use of the recorded HINT allowed for computerized scoring procedures and randomization of lists. The HINT was chosen because it is an adaptive procedure that yields a signal-to-noise ratio (SNR) that reflects 50% correct identification. As a result, the HINT was not subject to floor or ceiling effects when utilizing this test.

The HINT was presented through one sound-field speaker at 0 degrees azimuth in order to simulate the most difficult listening environment where speech and noise are coming from the same direction. The broadband noise was presented at a fixed level of 50 dB SPL. This level was chosen to be consistent with the presentation of Pascoe's High Frequency Word List at a low-level and to prevent output from reaching levels of discomfort for the participants. Twenty sentences were presented in each bandwidth condition and participants were asked to repeat the sentence they heard. If they repeated the entire sentence correctly, the researcher would press "yes" and if they repeated the sentence incorrectly, the researcher would press "no". The level of the sentence was adjusted after each response. If the participant's response was correct, the level of sentence was decreased; if the participant's response was incorrect, the level of sentence was increased. Following the presentation of all sentences, a SNR threshold was calculated for each bandwidth condition that reflected 50% correct identification.

Procedures

All testing was completed within 1 to 2 sessions lasting approximately 2 to 3 hours total. All screening and unaided testing was performed first and the hearing aid fitting and testing was conducted in the later part of the session or in the subsequent session. Cut-off frequency conditions were randomized such that the effect of condition order could be analyzed as a between-subjects variable. During testing, programs were changed by the researcher using the program button on the hearing aid. Participants were blinded to each condition. In addition, order of HINT vs. Pascoe list tests were randomized among all subjects.

Results

Word Recognition in Quiet

A repeated measures analysis of variance (R-ANOVA) was completed to investigate if changes to hearing aid high-frequency cut-off resulted in statistically significant differences in scores on Pascoe's High Frequency Word List. According to the results from the Huynh-Feldt test of within-subject effects, there was a significant main effect of condition, $F(3, 45) = 52.292$, $p < .001$, $\eta^2_p = .777$ indicating that the results on Pascoe's High Frequency Word List were condition dependent. Results for the interaction between condition and randomization indicated that there was no effect, $F(6, 45) = .712$, $p = .617$, $\eta^2_p = .087$. Group means and standard deviations per condition are displayed in Figure 3. Review of mean data suggested that there was a difference between the unaided condition and the three aided cut-off conditions and a tendency for scores to improve as cut-off frequency was increased. However, the differences between the three aided conditions were slight. The difference between the 4000 Hz and 7500 Hz conditions was approximately 6%. The standard deviations overlap considerably when data were collapsed, supporting minimal differences between the three conditions. To further analyze the main effect of condition found in the R-ANOVA, paired *t*-test comparisons were performed for the Pascoe's High Frequency Word List scores in all conditions. The results are displayed in Table 1. The paired *t* -tests demonstrated scores for the unaided condition were significantly lower in comparison to all aided conditions, $p < .001$. Among the aided conditions, the 4000 Hz and 7500 Hz conditions were significantly different after Bonferonni correction ($p < .02$), however, the 5500 Hz condition was not significantly different from either the low or high cut-off frequency conditions.

Table 1. Paired *t*-test results comparing the results on Pascoe's High Frequency Word List between conditions.

Conditions	t	*df*	*p*-value
Unaided vs. 4000 Hz	-6.93	17	.00*
Unaided vs. 5500 Hz	-9.24	17	.00*
Unaided vs. 7500 Hz	-9.23	17	.00*
4000 Hz vs. 5500 Hz	-2.29	17	.04
4000 Hz vs. 7500 Hz	-3.16	17	.01*
5500 Hz vs. 7500 Hz	-0.82	17	.42

*Significant at the Bonferroni specified level $p < .02$.

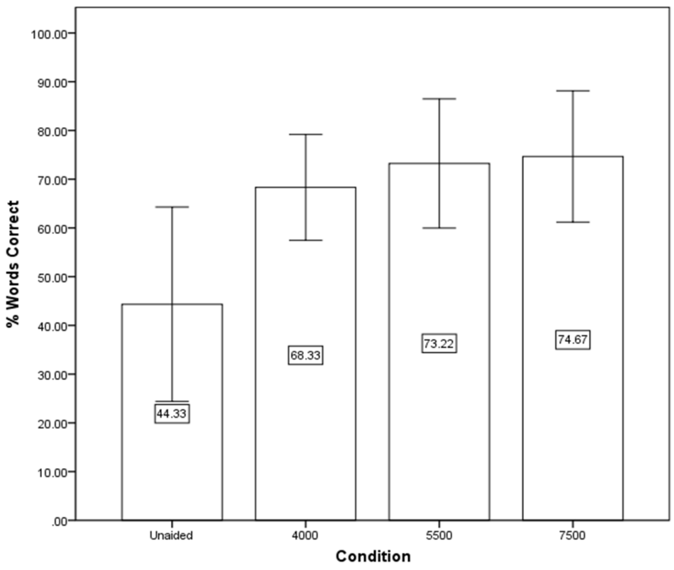

Figure 3. Mean percent correct score for Pascoe's High Frequency Word List in the four conditions. Error bars indicate one standard deviation.

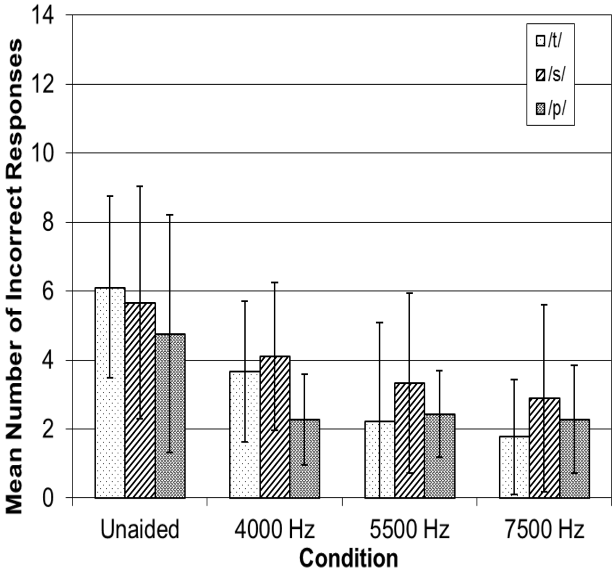

Figure 4. Mean number of phoneme errors for /t/, /s/, and /p/ on Pascoe's High Frequency Word List in the four conditions. Error bars indicate one standard deviation.

Results from Pascoe's High Frequency Word List also were analyzed according to number of phoneme errors for three of the most commonly occurring sounds: /t/, /p/, and /s/. The results are displayed in Figure 4. Overall, there was a trend for the number of errors to decrease as cut-off frequency increased. An R-ANOVA was conducted to determine if there was an interaction between bandwidth condition and phonemic errors. The Huynh-Feldt test of within-subject effects revealed a significant interaction between these two factors $F(6, 96) = 2.766$, $p = .028$. In reviewing the mean data, it was apparent that number of errors for each phoneme differed with increasing high-frequency bandwidth. Paired *t*-tests were conducted for each consonant. The results revealed that errors for /t/ and /s/ were significantly different among the three conditions such that errors were reduced as cut-off frequency increased $p < .02$. Number of errors for /p/ did not change between the three cut-off conditions.

Pearson correlation coefficients were obtained for Pascoe's High Frequency Word List, average thresholds from 1500 to 8000 Hz and average loudness discomfort levels. As displayed in Table 2, the scores in all three aided conditions were significantly negatively correlated with hearing thresholds. The results suggested that as the thresholds increased, scores decreased. Interestingly, the strongest correlation for the 4000 Hz condition was with the 3000 Hz threshold and the strongest correlation for the largest bandwidth condition was with the 2000 Hz threshold. Loudness discomfort levels were not significantly correlated to the scores on Pascoe's High Frequency Word List.

Table 2. Correlations between scores on Pascoe's High Frequency Word List and hearing thresholds. Thresholds were averaged for right and left ears.

Condition	Threshold Test Frequency (Hz)				
	2000	3000	4000	6000	8000
4000 Hz	-.55	-.74**	-.67**	-.51	-.36
5500 Hz	-.78**	-.54**	-.50	-.51	-.41
7500 Hz	-.73**	-.59**	-.53	-.57*	-.54

Note. *$p < .01$, **$p < .00$

Sentence Recognition in Noise

Mean reception thresholds for sentences (RTSs) in comparison to reported norms are displayed in Figure 5. It should be noted that the lower the RTS, the better the ability to hear in noise. A review of mean data suggested there was a change from the unaided to the aided conditions. Participants performed better in the aided conditions overall. The 50th percentile scores for normal hearing American-English speakers has been shown to be -2.6 dB SNR with a standard deviation of 1.0 dB (Soli & Wong, 2008; Vermiglio, 2008). In comparison to the normative data, the participants performed more poorly such that they needed the SNR to be 1 to 1.5 dB higher to achieve a 50% score.

An R-ANOVA was completed to determine if changes to hearing aid cut-off frequency resulted in statistically significant differences in the scores on the HINT. The results of the Huynh-Feldt test of within-subject effects indicated that there was a significant effect of condition, $F(3, 45) = 14.147$, $p < .001$, $\eta^2_p = .485$. This implied that the HINT scores changed as a result of increasing and decreasing access to high-frequency information. There was no interaction between condition and randomization, $F(6, 45) = .736$, $p = .624$, $\eta^2_p = .089$.

A review of Figure 5 suggested a tendency for improvement as cut-off frequency was increased. Interestingly, as bandwidth condition was increased, variability in scores decreased. However, the most noticeable difference was between the unaided condition and the three frequency cut-off conditions. Paired *t*-tests were conducted

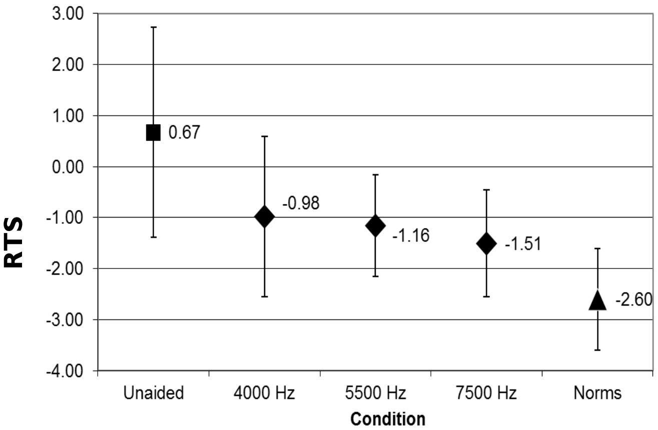

Figure 5. Mean HINT SRTN for each cut-off frequency condition and norms (Soli & Wong, 2008; Vermiglio, 2008) with error bars indicating one standard deviation.

for RTS in each of the three conditions. The results were not significant for any of the three conditions suggesting that cut-off frequency did not influence RTS results for the participants. The significant difference observed in the R-ANOVA likely was the result of the difference in RTS from the unaided condition and the three aided conditions or under-powering of the test. The R-ANOVA was repeated for the three aided conditions alone. The results supported that aiding individuals with HFHL improves the ability to hear in steady-state background noise, but that increasing the cut-off frequency from 4000 Hz does not significantly improve performance for this test.

Pearson correlations were conducted for the HINT scores in each aided condition, average thresholds from 250 through 8000 Hz and loudness discomfort levels. Scores on the HINT were not significantly correlated with thresholds or discomfort levels.

Discussion

Word Recognition in Quiet

The results of this investigation indicated that performance increased in quiet from the unaided to aided conditions. The statistical analyses suggested a main effect of condition, primarily the result of the large difference between the unaided and three aided conditions. The results supported a small but statistically significant difference between the lowest cut-off frequency (4000 Hz) and highest cut-off frequency (7500 Hz) conditions, supporting best performance at the most extended bandwidth. The mid cut-off condition (5500 Hz) was not significantly different from either of the other two aided conditions.

In the literature, performance on Pascoe's High Frequency Word List has been shown to be optimal when amplification was provided through 6300 Hz in comparison to other hearing aid frequency responses, including an extension out to 8000 Hz (Pascoe, 1975; Skinner & Miller, 1983). Additional research focusing on the effects of bandwidth on speech perception in quiet found no change in performance with increasing bandwidth beyond 4500 Hz (Hogan & Turner, 1998; Horwitz et al., 2008; Schwartz et al., 1979; Sullivan et al., 1992). The results from this study also demonstrated that providing amplification through 4000 Hz using an NAL-NL1 target resulted in a significant difference in performance on a high-frequency word recognition list and that extension beyond 4000 Hz provided slight improvement with no adverse impact on performance.

The use of Pascoe's High Frequency Word List in the current study and those by Skinner and colleagues (1980; 1983) and Pascoe (1975) suggested that this list of stimuli may be useful in assessing benefit with high-frequency amplification for individuals with HFHL. When consonants with high-frequency emphasis, such as /s/ and /t/, were analyzed separately, differences in conditions were clearly observed. Individuals, on average, had the least amount of errors for /s/ and /t/ when they had access to the highest cut-off condition. This is understandable because the peak energy for /t/ was located at 5300 Hz and the peak energy for /s/ was above 6000 Hz. Because peak energy for /p/ was between 1500-3000 Hz, individuals reached maximum performance once they had access to the lowest cut-off condition.

In reviewing the results of the phonetic analysis for the sounds /s/, /t/ and /p/, it was apparent that no participant missed all of the high-frequency phonemes in the unaided condition. This may be the result of access to cues from the formant transitions. Consonants are not perceived in isolation; they appear next to and are part of adjacent vowels. Research has demonstrated that the second formant vocalic transitions differentiate stop consonants (Cooper, Delattre, Liberman, Borst & Gerstman, 1952; Delattre et al., 1955). It is possible that participants were able to use the frequencies from formant transitions to determine the correct phoneme. For example, if the rise or fall of the transition was audible to the participant, he/she may have been able to deduce the correct phoneme from the second formant transition alone. As a result, the acoustic analysis of vowels in addition to consonants needs to be taken into account when considering audibility of speech information and performance scores since there may have been coarticulation effects which impacted scores.

In the current study, audiometric thresholds were highly correlated with scores for the three cut-off conditions. This is consistent with the results from Skinner (1980) in which she demonstrated audibility as a significant factor in the increased scores on Pascoe's High Frequency Word List. It has been reported in the literature that hearing loss can account for 65-90% of the variance in speech perception scores for older adults (Festen & Plomp, 1983; Humes, 1991; 1996; 2002; Humes & Christopherson, 1991; Humes & Roberts, 1990). In analyzing individual thresholds, 2000 and 3000 Hz had the strongest significant relationship with speech perception score. It is understandable that there would be a strong correlation between 2000 Hz and the scores because Pascoe's High Frequency Word List included consonants and vowels with energy at 2000 Hz.

Sentence Recognition in Noise

The HINT was used to determine if speech perception in noise was influenced by increases in cut-off frequency. A significant effect was found for amplification through 4000 Hz.

Once again, this supported that there were significant differences between the unaided and aided conditions. However, the ANOVA and paired comparison results did not support a difference among cut-off conditions for RTSs. As a result, increasing the cut-off frequency did not result in increased performance in background noise for all of the participants.

Although other studies have indicated differences in performance in noise, the results have not been remarkable. Hornsby and Ricketts (2006) tested individuals with HFHL using the Connected Speech Test (CST; Cox, Alexander & Gilmore, 1987) presented at a +6 dB SNR. They compared 12 filter conditions with the two highest cut-off frequency low-pass conditions at 3150 and 7069 Hz. Although they had indicated that there was a difference in increasing the cut-off frequency, this difference was 6% on average between these two conditions. This can be considered a slight difference and similar to the current results of the HINT. Plyler and Fleck (2006) also reported significant differences on the CST in noise between two bandwidth conditions, the maximum (6000 Hz) and minimum (3000 Hz) audibility conditions. These differences were small, but significant. They also used the HINT and observed significant differences between the two conditions. The minimum audibility condition (3000 Hz) yielded average scores around 1 dB SNR for the individuals with moderate HFHL and 2.5 dB SNR for individuals with moderately-severe to severe HFHL. These scores were similar to the unaided scores that were obtained by all participants in the current study. The maximum audibility (6000 Hz) condition yielded average RTS thresholds around -1 dB for the moderate HFHL group and around 0 dB for the more severe HFHL group. Again, these results are similar to the results of the current study in that aided HINT RTSs were between -0.5 dB and -1.5 dB. The statistically significant results of that study also may have been the result of a difference in procedures used by Plyler and Fleck (2006). The researchers kept the speech signal constant at 65 dB SPL and adjusted the level of background noise. In the current study, the HINT background noise was set to 50 dB SPL and the sentence levels were adjusted to obtain RTS.

Sullivan and colleagues (1992) demonstrated that cut-off frequency influenced scores on a nonsense syllable test when presented in background noise. However, the cut-off frequencies were over four octaves apart. The middle response was at 1700 Hz and the high-frequency cut-off was 6000 Hz. As a result, the effects that were observed could have been the result of amplifying 2000 or 4000 Hz, instead of extending from 4000 to 6000 Hz. Turner and Henry (2002) found that when nonsense syllables were severely limited by background noise, providing amplification to make speech audible showed positive benefit in all cases, even with additional high-frequency information. However, differences between conditions and performance scores were not provided and it is unclear how much benefit was received from adding additional high-frequency information. They argued that there was no detriment to providing high-frequency audibility, even if benefit was not significant (Turner & Henry, 2002). Similarly, the results from the current study showed that increasing the high-frequency cut-off for individuals with HFHL did not influence speech perception in noise as assessed by the HINT. Therefore, like Turner and Henry (2002), providing amplification improved performance and additional high-frequency information did not degrade performance.

NAL-NL1

Overall, the results from this study did not demonstrate consistent measureable improvement in individuals with HFHL as a function of more access to high-frequency information. Horwitz and colleagues (2008) suggested that a lack of significant differences in their study may be the result of narrow high-frequency ranges being added and low audibility for high-frequency speech information due to elevated thresholds and the NAL-NL1 target (Horwitz et al., 2008). The minimal improvement from the 4000 to 7500 Hz condition is likely the result of a lack of audibility in the high frequencies considering many of the speech cues in the high-frequency region are of low intensity. An NAL-NL1 fitting algorithm does not attempt to produce high levels of amplification for frequencies with the greatest losses in a sloping hearing loss. In fact, the NAL-NL1 fitting algorithm recommends gain in the high frequencies should be equal to or less than the gain at 2500 Hz (Byrne et al., 2001). As displayed in Figure 2, the NAL-NL1 target values were below thresholds at 6000 and 8000 Hz and audibility at these frequencies was not reached for individuals with thresholds over 55 to 60 dB HL. It has been suggested that NAL-NL1 is most appropriate for a mild and moderate, flat and gently sloping symmetrical loss (Schum, 2009). An NAL-NL1 target may be a fine starting point for fitting sloping losses, however, the fitting may need to be modified to achieve maximum benefit or audibility from extended bandwidth. Therefore, although RIC hearing aids are marketed as having extended bandwidth receivers, clinicians should be aware that fitting to an NAL-NL1 target will result in minimal audibility above 6000 Hz.

There have been two concerns noted with regard to amplifying the high frequencies. One concern for individuals with HFHL was that full high-frequency audibility can lead to comfort and sound quality issues (Schum, 2009; Skinner, 1980).

In addition, depending on the extent of damage to the cochlea, audibility does not necessarily guarantee usable hearing, especially when amplifying high-frequency information (Schum, 2009). A second concern was a lack of balance between low-/ mid- and high-frequency information. Skinner and Miller (1983) compared the results of bandwidth on word identification. They found that high-frequency amplification needed to be in appropriate balance with low-frequency energy around 500 Hz in order for sound quality to be acceptable and speech intelligibility to be maximized. Amplification was not adjusted below 2000 Hz and the low-frequency cut-off was not adjusted in the current protocol. Skinner (1980) indicated that spectral configuration of the speech energy was an important factor in the scores on Pascoe's High Frequency Word List. She recommended that hearing aids should be set so that the lower band differs approximately 15 dB from the higher band (above 2000 Hz). This balance was not maintained for this research study and may have been a factor in the results. It has been suggested that to optimize fittings for individuals with sloping losses, gain should be reduced in the high frequencies and audibility should be targeted to the mid-frequency transition region (Schum, 2009). As supported in this study, amplifying up to 4000 Hz provides significant benefit for high-frequency consonants and for listening in background noise. However, the benefits of "extended bandwidth" would not be available if audibility was not prescribed in these frequencies.

Finally, it should be noted that minimal differences may have also been seen due to the small effect size and low statistical power. While estimated power was high for the four conditions, the comparison of the three aided conditions yielded an effect size and power estimate that were low. In order to increase the statistical power, the sample size would need to be doubled.

Conclusion

Theoretically, providing additional high-frequency audibility should be beneficial to individuals with HFHL. The purpose of this study was to determine whether extended high-frequency cut-offs in RIC hearing aids programmed using NAL-NL1 targets benefit patients with HFHL on measures of speech recognition in quiet and noise. The results of this study indicated that individuals with HFHL benefit from amplification through 4000 Hz as there were significant differences between unaided and aided conditions for both test measures. While the results were similar to those previously reported, it should be noted that the linguistic and acoustic composition of the stimuli used in this study may have also had an impact on the results. There was a tendency for performance to increase on Pascoe's High Frequency Word List presented in quiet as cut-off frequency increased. However, the difference in performance between the lowest cut-off and highest cut-off was minimal. This is likely due to reduced audibility in the high frequencies, the result of using NAL-NL1 targets. On the HINT, there was no influence of cut-off frequency on performance between the three aided conditions. Therefore, extending high-frequency cut-offs past 4000 Hz may not have a positive or negative impact on RTSs for individuals with sloping HFHL when hearing aids are programmed to an NAL-NL1 target.

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