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Effects of low-pass filtering on the perception of word-final plurality markers in children and adults with normal hearing

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Abstract

Purpose—The purpose of this study was to evaluate the effect of low-pass filtering on the detection of word-final /s/ and /z/ for children and adults with normal hearing.

Method—Stimuli were nouns from the UWO Plurals Test (Glista & Scollie, 2012), low-pass filtered with five different cutoff frequencies: 8000, 5000, 4000, 3000, and 2000 Hz. Listeners were children (age range = 7 to 13 years) and adults with normal hearing. The task was a two-alternative forced-choice with a picture-pointing response.

Results—Performance was worse for lower than for higher low-pass filter cutoff frequencies, but the effect of low-pass filtering was similar for children and adults. Nearly all listeners achieved 100%-correct performance when stimuli were low-pass filtered with cutoff frequencies of 8000 or 5000 Hz. Performance remained well above chance even for the most severe filtering condition (2000 Hz). Restricting high-frequency audibility influenced performance for plural items to a greater extent than for singular items.

Conclusions—The results indicate that children and adults with normal hearing can use acoustic information below the spectral range of frication noise typically associated with /s/ and /z/ to discriminate between singular and plural forms of nouns in the context of the UWO Plurals Test.

INTRODUCTION

Children, both with normal hearing and with hearing loss, often require a wider acoustic bandwidth than adults to accurately perceive certain speech sounds (e.g., McCreery & Stelmachowicz, 2011; Mlot, Buss, & Hall 2010; Pittman, 2008; Stelmachowicz, Lewis, Choi, & Hoover, 2007; Stelmachowicz, Pittman, Hoover, & Lewis, 2001). For example, Stelmachowicz et al. (2001) examined fricative perception in children and adults with sensorineural hearing loss and children and adults with normal hearing. Stimuli were

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consonant-vowel or vowel-consonant syllables that contained the vowel /i/ and the consonants /s/, /f/, or /θ/. The syllables were low-pass filtered at cutoff frequencies ranging from 9000 to 2000 Hz. The task was three-alternative forced choice consonant identification, with a picture-pointing response. Both groups of children showed a greater decrement in performance than the corresponding groups of adults when bandwidth was reduced via low-pass filtering.

Specific to children with hearing loss, reduced audibility of high-frequency speech cues may contribute to delays in the production and perception of fricatives/affricates (e.g., Elfenbein, Hardin-Jones, & Davis, 1994; Moeller et al., 2007; Pittman, 2008; Stelmachowicz et al., 2001; Stelmachowicz, Pittman, Hoover, & Lewis, 2002). For example, Moeller et al. (2007) compared the vocalizations and early verbalizations of infants with hearing loss to those of infants with normal hearing using a longitudinal study design. Despite being fitted with hearing aids by at least their first birthday, children with hearing loss acquired fricatives/affricates later than their peers with normal hearing sensitivity. Moeller et al. (2007) suggested these delays in speech production reflect limited access to high-frequency speech cues despite the provision of appropriately fitted hearing aids.

Considerable evidence supports the idea that providing high-frequency acoustic information improves children's speech perception (e.g., McCreery & Stelmachowicz, 2011; Pittman & Stelmachowicz, 2000; Stelmachowicz et al., 2001). In combination with high-frequency gain limitations of conventional behind-the-ear hearing aids (e.g., Ricketts, Dittberner, & Johnson, 2008), this evidence has motivated efforts to incorporate frequency-lowering signal processing into pediatric hearing aid fittings (reviewed by McCreery, Venediktov, Coleman, & Leech, 2012). The widespread use of frequency-lowering technologies in recent years (Jones & Launer, 2010; Teie, 2012) has created a critical need for valid and reliable assessment tools to measure aided speech perception outcomes associated with the provision of high-frequency cues. One such outcome measure is the University of Western Ontario (UWO) Plurals test (Glista & Scollie, 2012), now freely available on compact disk (CD) through the hearing aid manufacturer Phonak. The goal of this test is to measure detection of the fricatives /s/ and /z/ in the word-final position. Stimuli consist of the singular and plural forms of 15 English nouns that vary in syllable length (e.g., ant/ants, flower/flowers, butterfly/butterflies). The words were produced by an adult female talker. Glista and Scollie (2012) selected these test items based on stimuli used in previous studies showing detrimental effects of low-pass filtering on the perception of the phonemes /s/ and /z/ for children with hearing loss (Stelmachowicz et al., 2002). The bandwidth of frication noise for the plural items included in the UWO Plurals test falls within the range of 4000 – 10000 Hz (average peak = 5000 Hz). The commercially available recordings include 10 randomized lists of the 30 words that have been mixed with continuous speech-shaped noise at a +20 dB signal-to-noise (SNR) ratio. The rationale for testing in noise was to mask a potential offset cue associated with the noise floor of the recordings, thus removing a cue to recording duration that could indicate the presence of /s/ or /z/ in the absence of frication noise. Glista and Scollie (2012) reported that, after noise was added, listeners with normal hearing were unable to reliably detect the word-final plurality markers when the test stimuli were low-pass filtered with a cutoff frequency of 3000 Hz. The test is typically administered as a two-alternative, forced choice (2AFC) requiring a picture-pointing response. Two pictures corresponding to the singular and plural form of the target word are presented on each trial. The pictures can be shown on a computer monitor or using picture cards. After the target word is presented, participants select the picture from the closed set of two responses that best describes what they heard. The recommended age range for this test is between 6 and 81 years (Glista & Scollie, 2012).

The UWO Plurals test appears to be sensitive to changes in high-frequency audibility under some conditions (e.g., Glista et al., 2009; Glista & Scollie, 2012; Wolfe et al., 2009; 2011). However, acoustic and linguistic features of speech are redundant. Cues other than frication noise may also provide important information regarding the identification of “high-frequency” phonemes such as /s/ (e.g., Dubno & Levitt, 1981; Owens & Schubert, 1977; Stelmachowicz et al., 2002; Whalen, 1981). Stelmachowicz et al. (2002), for example, recognized this possibility in a study that examined aided perception of /s/ and /z/ in children with hearing loss by stating that, “audibility of fricative noise is not the only cue to perception of plurals” (p. 323). If listeners are able to make use of these additional cues, some of which are relatively low frequency, this might compromise attempts to evaluate the influence of high-frequency audibility using the UWO Plurals Test (e.g., Glista & Scollie, 2012).

Published data indicate that adults can identify fricatives/affricates using relatively low-frequency speech cues (e.g., Mann & Repp, 1980; Whalen, 1981). Whalen (1981) observed that adults with normal hearing accurately labelled /s/ in the context of a 2AFC task based solely on the formant transition of either a leading or a following vowel. Interestingly, non-native speakers tested in that study showed the same pattern of results as native English speakers, suggesting that listeners relied on acoustic/phonetic cues to make their decisions, rather than relying on their linguistic experience with the target language. We are unaware of similar data reported in the literature for children with or with hearing loss in which access to high-frequency frication noise was restricted. However, findings from a series of studies by Nittrouer and colleagues (reviewed by Nittrouer, 2002) provide compelling evidence that children with normal hearing not only make effective use of cues lower in frequency than the typical bandwidth of frication noise to identify /s/, they tend to rely less heavily on frication noise and more heavily on formant transitions than adults. Results from subsequent studies involving children with hearing loss are compatible with the idea that children with hearing loss can likewise use cues lower in frequency than the typical bandwidth of frication noise to identify /s/ (Glista et al., 2009; Glista & Scollie, 2012; Glista, Scollie, & Sulkers, 2012; Hillock-Dunn, Buss, Duncan, Roush, & Leibold, 2014; Pittman, Stelmachowicz, Lewis, and Hoover, 2002; Wolfe et al.; 2009; 2011). For example, Pittman et al. (2002) evaluated the perceptual weights listeners assign to the fricative and vowel segments of consonant-vowel-consonant stimuli, comparing words with an unaltered formant transition and words in which the formant transition was removed. Listeners were children and adults with hearing loss, and children and adults with normal hearing. All four groups of listeners heavily weighted the vowel segment of the word to identify /s/. Note also that published studies using the UWO Plurals Test are consistent with the possibility that lower-frequency cues can support detection of word-final /s/ and /z/. Percent correct performance on the UWO Plurals Test is consistently 70% or better for children with hearing loss, regardless of whether or not the high-frequency frication noise was audible (Glista et al., 2009; Glista & Scollie, 2012; Glista et al., 2012; Wolfe et al.; 2009; 2011).

The purpose of the present study was to evaluate the effect of low-pass filtering on the detection of word-final /s/ and /z/. Performance for children and adults with normal hearing was assessed using the UWO Plurals Test (Glista & Scollie, 2012) for a series of low-pass filter conditions. Based on results from previous studies (e.g., McCreery & Stelmachowicz, 2011; Pittman, 2008; Stelmachowicz et al., 2002), poorer overall performance was expected for children and adults as the cutoff frequency for the low-pass filter was decreased. In addition, we expected that children would be more detrimentally affected by reductions in high-frequency bandwidth than adults. However, we predicted that both age groups would perform above chance when the low-pass filter removed the high-frequency frication noise. This result would indicate the availability and utilization of lower-frequency acoustic cues that aid in the detection of word-final pluralization, such as formant transitions.

METHODS

Listeners

Listeners were nine children and eight adults. The child group ranged in age from 7.1 to 13.2 years (*M* = 10.1; *SD* = 2.1), and the adult group ranged in age from 18.2 to 24.9 years (*M* = 21.3; *SD* = 2.6). All listeners were native speakers of American English with normal hearing sensitivity, defined as pure-tone thresholds of 20 dB HL or better at octave frequencies 250–8000 Hz (ANSI, 2010). Exclusion criteria included known developmental delays, a history of hearing problems, previous experience listening in psychophysical studies, and reported chronic middle ear disease.

Stimuli

Stimuli were the CD recordings of the UWO Plurals Test distributed by Phonak. This test is composed of 10 lists with 30 words per list. As described in the introduction section, each 30-word list includes the singular and plural forms of 15 nouns spoken by an adult female. The words on the commercially available CD are mixed with continuous speech-shaped noise at a +20 dB SNR.

Conditions and Instrumentation

Listeners were tested in low-pass filter conditions with five different cutoff frequencies: 8000, 5000, 4000, 3000, and 2000 Hz. To create these five conditions, the stimuli were routed from a CD player into a filter (Kemo VB8, 80 dB/oct). The output from the filter was routed to an audiometer (Grason-Stadler GSI 61) for amplification and then was presented in the sound field of a 7X7-foot, single-walled, sound-treated booth (IAC) via a loudspeaker (JBL Control 1 Pro). Following the procedures described in the UWO Plurals Test manual, stimulus presentation level was verified prior to each session using a Larson Davis (Model 824) sound level meter to ensure a presentation level of 55 dB(A).

Procedure

Listeners were tested while seated 3.3 feet directly in front of the loudspeaker inside the single-walled booth. The height the listener's chair was adjusted so that the stimuli would be presented at approximately 0° azimuth and 0° elevation. Following Glista and Scollie (2012), a 2AFC paradigm was used. Pictures corresponding to the singular and plural form of the target word were presented on a 7-inch handheld computer monitor. After each stimulus presentation, the listener pointed to the picture that best represented what they thought they heard. An experimenter located in the room behind the listener manually scored each response on the printed score sheet associated with the assigned word list.

A block of testing consisted of the completion of a 30-word list for each of the five low-pass filter conditions. All listeners completed two blocks of testing, resulting in four presentations of each of the 15 words (60 trials) per low-pass filter condition. The order of testing was randomized across all five conditions within blocks for each listener. Presentation order for the 10 word lists was randomly selected for each listener, with no list repeated during testing. Data were collected in a single session lasting approximately 45 minutes for adults and 60 minutes for children, including breaks.

RESULTS

Individual (open symbols) and group average (filled circles) percent correct scores are shown for adults (Figure 1) and children (Figure 2), plotted as a function of the cutoff frequency of the low-pass filter. Error bars represent ± one standard error of the mean (SEM) across listeners within each age group. Performance for the 8000- and 5000-Hz cutoff conditions was at ceiling for both age groups. The average percent correct score for adults was 99.8% for both the 8000- and 5000-Hz cutoff conditions. The average percent correct score for children was 99.1% for the 8000-Hz cutoff condition and 99.4% correct for the 5000-Hz cutoff condition. Poorer performance was observed for both age groups as the cutoff of the low-pass filter was reduced below 5000 Hz. For adults, the average decrement in performance was 2.7 percentage points between 5000 and 4000 Hz, 11.3 percentage points between 4000 and 3000 Hz, and 16.5 percentage points between 3000 and 2000 Hz. For children, the average decrease in performance was 6.3 percentage points between 5000 and 4000 Hz, 12.6 percentage points between 4000 and 3000 Hz, and 9.4 percentage points between 3000 and 2000 Hz. Despite the large age range of children tested (7–13 years), there was no indication that performance improved with increasing age within the child group. For example, there was no correlation between children's age and performance for the 2000-Hz cutoff condition ($r = -0.03$; $p = 0.93$).

An examination of the data for both age groups revealed a bias for listeners to report hearing singular forms of the test items for the two most severe filtering conditions (3000 and 2000 Hz). For example, children made a total of 172 errors for the 2000-Hz cutoff condition. Sixty-one of those errors (35%) resulted from singular items being incorrectly identified as plural, and 111 (65%) errors resulted from plural items being incorrectly identified as singular. Adults made a total of 146 errors for the 2000-Hz cutoff condition. Twenty-nine errors (20%) were the result of incorrect identification of singular items as plural and 117 errors (80%) were the opposite.

Figure 3 shows percent correct scores for singular (open symbols) and plural (filled symbols) items, plotted as a function of the cutoff frequency of the low-pass filter. Data for children and adults are shown by the black and gray triangles, respectively. Error bars represent ± one SEM. Consistent with the overall percent correct scores presented in Figures 1 and 2, scores for singular-only and plural-only items were at ceiling for the 8000- and 5000-Hz cutoff conditions, and performance systematically decreased as the cutoff of the low-pass filter decreased in frequency between 5000 and 2000 Hz. However, restricting high-frequency audibility appeared to influence performance for plural items to a greater extent than for singular items. For example, the average difference in performance between singular and plural items for the 2000-Hz cutoff condition was 36.7 percentage points for adults and 19.3 percentage points for children.

Percent correct scores were converted to rationalized arcsine units (RAUs) prior to statistical analyses to prevent bias due to non-uniformity of variance (Studebaker, 1985). Prior to application of the arcsine transform, percent correct scores were adjusted to account for effects related to guessing in a 2AFC paradigm. Adjusted scores were computed as: $y = [x - (100/n)] * (n/(n-1))$, where n = the number of alternatives (in this case 2), x is the raw percent correct score, and y is the adjusted value after the effect of random correct guesses has been removed.[1] Results of a repeated-measures analysis of variance (ANOVA) on the transformed data confirmed the trends observed in Figures 1, 2, and 3. This analysis had a between-subjects factor of Age (children, adults) and within-subjects factors of Filter Cutoff (8000, 5000, 4000, 3000, 2000 Hz) and Word Form (singular, plural). Mauchly's test of sphericity was significant for Filter Cutoff ($W_9 = 0.09$; $p < 0.001$) and Filter Cutoff X Word Form ($W9 = 0.01$; $p < 0.0001$), so Greenhouse-Geisser corrections were applied. The main effect of Age was not significant ($F1,15 = 2.65$; $p = 0.12$; $\eta^2_{partial} = 0.15$), indicating similar performance for adults and children. The main effect of Filter Cutoff was significant ($F2.6,38.5 = 127.3.3$; $p < 0.001$; $\eta^2_{partial} = 0.90$), indicating differences in performance across the five low-pass filter conditions. The main effect of Word Form was also significant ($F1,15 = 8.99$; $p < 0.01$; $\eta^2_{partial} = 0.38$), indicating differences in performance between singular and plural forms of the target words. Interactions between Age and Filter Cutoff ($F2.6,15 = 0.67$; $p = 0.62$; $\eta^2_{partial} = 0.04$), Age and Word Form ($F1,15 = 0.74$; $p = 0.74$; $\eta^2_{partial} = 0.008$), and between all three factors ($F1.5,15 = 0.51$; $p = 0.56$; $\eta^2_{partial} = 0.03$) were not significant. There was, however, a significant interaction of Filter Cutoff and Word Form ($F1.5,23.2 = 10.57$; $p < 0.01$; $\eta^2_{partial} = 0.41$), as performance for plural items decreased more rapidly with decreasing filter cutoff than performance for singular items.

The two-way interaction between Filter Cutoff and Word Form was evaluated using a simple main effects analysis (Kirk, 1968). The cutoff frequency of the low-pass filter influenced performance for both singular ($F4,12 = 11.36$; $p < 0.001$) and plural ($F4,12 = 34.86$; $p < 0.001$) word forms. The significant simple main effects of Filter Cutoff were further analyzed by pairwise comparisons using the Sidak adjustment for multiple comparisons. For singular word forms, performance was significantly poorer when the cutoff frequency of the low-pass filter was 2000 Hz compared to 4000, 5000, and 8000 Hz,

[1]Adjusted percent correct scores were negative for three children and three adults for plural word forms with a cutoff frequency of 2000 Hz. These values were set to zero before the RAU transform was applied.

but not compared to 3000 Hz. Performance was also significantly poorer when the cutoff frequency was 3000 Hz compared to the three less severe cutoff conditions (4000, 5000, and 8000 Hz). Performance was not significantly different between low-pass filter conditions with cutoff frequencies of 4000, 5000, and 8000 Hz. A different pattern of results was observed for plural word forms. Consistent with results for the singular word forms, performance was significantly poorer when the cutoff frequency of the low-pass filter was 2000 Hz compared to all other cutoff frequencies, and when the cutoff frequency was 3000 Hz compared to the three higher cutoff frequencies. However, performance was also significantly poorer when the cutoff frequency of the low-pass filter was 4000 Hz compared to the higher two cutoff conditions (5000 and 8000 Hz). No significant difference in performance was observed for plural word forms between low-pass filter conditions with cutoff frequencies of 5000 and 8000 Hz.

Listeners in both age groups performed well above chance for even for the most severe low-pass filtering condition, with one child (C8) and two adults (A7 and A8) achieving 80% correct or higher for the 2000-Hz cutoff condition. These observations motivated an examination of performance for each token pair. Specifically, it was of interest to examine whether some of the words included in the UWO Plurals Test were more resistant to the removal of high-frequency energy than others. Figure 4 shows the average percent correct discrimination for individual word pairs in the data of adults (filled squares) and children (open squares) for the 2000-Hz cutoff condition. Error bars represent ± one SEM across listeners within each group. Data at or above the solid horizontal line suggest better-than-chance performance. Visual inspection of the data suggests that the influence of low-pass filtering may have been greater for some token pairs than for others. For example, adults and children performed at chance for the discrimination of crayon/crayons. In contrast, performance was close to ceiling for both age groups for the discrimination of shoe/shoes. A similar pattern of performance across items was generally observed for children and adults. Exceptions include book/books, crab/crabs, and fly/flies. Despite the substantial differences in performance observed across token pairs and the limited differences observed across children and adults, performance for the majority of items appeared to be greater than chance. Exceptions include book/books (children only), crab/crabs (adults only), crayon/crayons (both groups), and sock/socks (children only).

DISCUSSION

Effect of Low-Pass Filtering on Plural Detection for Children and Adults with Normal Hearing

The present results are in agreement with previous data showing a detrimental influence of reducing bandwidth on speech perception (e.g., McCreery & Stelmachowicz, 2011; Pittman, 2008; Stelmachowicz et al., 2001). Average performance for adults was 30 percentage points higher for the widest (cutoff = 8000 Hz) compared to the narrowest (cutoff = 2000 Hz) low-pass filter condition. Similarly, children's average percent correct score was 28 percentage points higher for the 8000-compared to the 2000-Hz cutoff condition.

No evidence was found to support the a priori prediction that the effect of low-pass filtering would be greater for children than for adults. Equivalent performance and a similar pattern of results across the five low-pass filter conditions were observed for the two age groups. The lack of a significant interaction between age group and amount of low-pass filtering is somewhat surprising, given previous reports showing that children's speech perception is more negatively affected than adults' when the high-frequency bandwidth of speech is limited (e.g., Kortekaas & Stelmachowicz, 2000; Stelmachowicz et al. 2001). However, an examination of the literature related to the influence of high-frequency audibility on children's speech recognition suggests that child-adult differences are not uniformly observed when high-frequency bandwidth is restricted (e.g., McCreery & Stelmachowicz, 2011; Pittman, 2008). For example, McCreery and Stelmachowicz (2011) examined speech recognition in the presence of steady-state noise for a large sample of 116 children (5–13 years) and 19 adults with normal hearing. The stimuli were filtered consonant-vowel-consonant (CVC) non-words, including three low-pass filter conditions with upper cutoffs frequencies of 5657, 2829, and 1415 Hz. Although children performed more poorly on the 2AFC task than adults overall, there was no evidence that children's speech recognition was more detrimentally affected than adults' when high-frequency information was limited via low-pass filtering.

Consideration of Bottom-Up Factors

The present findings indicate that both children and adults used acoustic cues that were lower in frequency than the frication noise of /s/ or /z/ to detect word-final pluralization in the context of the UWO Plurals Test. While removing high-frequency frication noise resulted in decreased performance, percent correct scores remained well above chance for even the most aggressive low-pass filter condition. Average percent correct scores for children and adults in the 2000-Hz cutoff condition were 71.1% and 69.4%, respectively. An examination of word errors for each token pair provides additional evidence that children and adults successfully used relatively low-frequency information to support plural detection for the majority of token pairs in the absence of frication noise. Both age groups of listeners demonstrated near perfect performance for some token pairs while performing at chance for others.

One potential source of relatively low-frequency acoustic information is co-articulation with the vowel immediately preceding the word-final /s/ or /z/. Specifically, results from previous studies have shown that adults can identify high-frequency fricatives such as /s/ based solely on the formant transitions of the preceding or following vowel (e.g., Dubno & Levitt, 1981; Whalen, 1981). The inclusion of speech-shaped noise mixed in the recordings used here complicates efforts to evaluate the importance of formant-transition cues or other potential acoustic cues that could have impacted performance in the present study. That is, we were unable to adequately evaluate acoustic cues within the target stimuli since we were unable to remove the speech-shaped noise mixed with the target words on the tracks of the commercially distributed CD. Additional research is needed to determine the specific acoustic cues that remain audible to listeners after low-pass filtering has been applied, and to evaluate the conditions under which this information can be successfully used by children and adults. As discussed in the introduction to this paper, results from Nittrouer and colleagues (reviewed by Nittrouer, 2002) indicate that children with normal hearing tend to rely heavily formant transitions to identify /s/, at least when multiple speech cues are available.

Generalization to Children with Hearing Loss

Future research is needed to determine whether the present results generalize to children with hearing loss, who may require greater access to high-frequency speech cues to achieve similar speech recognition performance as their peers with normal hearing (e.g., Pittman & Stelmachowicz, 2000; Stelmachowicz et al., 2001; 2002). For example, Stelmachowicz et al. (2001) evaluated the influence of high-frequency audibility on fricative perception in the context of a nonsense syllable recognition task. Listeners were children and adults with normal hearing and with hearing loss. The speech tokens were low-pass filtered at five cutoff frequencies ranging from 9000 to 2000 Hz. Age and hearing loss influenced the perception of /s/ in that study. Both groups of children performed more poorly than the corresponding group of adults. Moreover, lower percent correct scores were observed for children and adults with hearing loss compared to their peers with normal hearing.

One possible reason that children with hearing loss may require greater audibility of high-frequency acoustic information than children with normal hearing is that they have less linguistic experience. It has been suggested that reduced linguistic experience limits the extent to which children with hearing loss are able to compensate for the reduced quality and quantity of speech cues inherent in limited-bandwidth conditions (e.g., Nittrouer & Boothroyd, 1990). Note, however, that children with hearing loss appear to use relatively low-frequency acoustic cues to detect word-final pluralization under some conditions. One line of evidence supporting this idea comes from the results of studies that investigated children's aided speech perception outcomes with NLFC processing using the UWO Plurals Test. Across studies that have included this measure, percent correct scores with NLFC turned off are consistently 70% correct or higher despite confirmation that the audible bandwidth for most children included in these studies did not extend above 4000 Hz with NLFC turned off (Glista et al., 2009; Glista & Scollie, 2012; Glista, Scollie, & Sulkers, 2012; Wolfe et al.; 2009; 2011). We recently observed similarly high performance (>80%) with NLFC deactivated for the identification of /s/ for children with hearing loss in the context of a 12-alternative consonant identification task (Hillock-Dunn et al., 2014). Additional research is needed to evaluate the conditions under which children with hearing loss can effectively use lower-frequency speech cues to perceive fricatives. It is likely that children's performance will be influenced by multiple factors, including age, degree of hearing loss, linguistic experience, and the context with which the stimuli are presented (e.g., Nittrouer & Boothroyd, 1990).

Implications for measuring potential benefits associated with frequency-lowering technologies

The functional benefits of incorporating frequency-lowering processing into pediatric hearing aid fittings remain controversial (reviewed by Alexander, 2013). Nonetheless, the use of frequency-lowering processing has become widespread in both pediatric and adult hearing aid fittings (Jones & Launer, 2010; Teie, 2012). Thus, it is important that valid, reliable, and clinically feasible assessment tools be made available to clinicians to measure potential benefits associated with changes in hearing aid signal processing. The present results indicate that additional research is warranted to ensure that the UWO Plurals Test accurately predicts the benefit of increased high-frequency audibility associated with frequency lowering. Despite limiting high-frequency audibility via low-pass filtering, performance for both normal-hearing children and adults in the present study remained around 70% correct for even the most severe low-pass filtering conditions. Above-chance performance does not necessarily indicate that this test is insensitive to changes in performance associated with the provision of frequency lowering. However, these results suggest that listeners can accurately discrimination between singular and plural word forms when they have access to spectral bandwidths that are typically provided by conventional hearing aids.

A potentially greater concern is the observation of ceiling effects for the majority of children and adults for low-pass filtering conditions with cutoff frequencies as low as 4000 Hz. The clinical scoring procedure for the UWO Plurals Test utilizes critical ranges derived from the binomial theorem (Thornton & Raffin, 1978). Six of nine children and six of eight adults included in the present study had scores greater than 92% correct for the 4000-Hz cutoff condition, precluding statistical analysis of critical difference scores. These findings raise the question of whether similar performance across different signal-processing conditions (i.e., NLFC activated versus NLFC deactivated) in hearing-aid users may be due to listeners' greater reliance on relatively low-frequency information under conditions in which high-frequency bandwidth is restricted. Additional research is needed to evaluate the conditions under which children with hearing loss can effectively use lower-frequency speech cues to perceive fricatives.

It may be possible to build upon the framework of the UWO Plurals Test, by generating stimuli that control for potential low- and mid-frequency acoustic cues and/or incorporate changes to the testing protocol to reduce the likelihood of ceiling effects. This approach would require a careful examination of the acoustic properties of all test items to determine whether or not listeners based their decisions solely on the presence/absence of high-frequency frication noise. In addition, it is clear that speech recognition depends not only on acoustic information, but also on the listener's prior knowledge and/or expectations (e.g., Remez, Rubin, Pisoni, & Carrell, 1981; Sohoglu, Peelle, Carlyon, and Davis, 2012). Thus, one question to consider is whether top-down factors contributed to the pattern of results observed across low-pass filter conditions. Further investigation of the effects of top-down factors such as linguistic context and the listener's expectations on speech recognition for high-frequency speech contrasts may help to identify stimuli and tasks that are sensitive to changes in high-frequency audibility.

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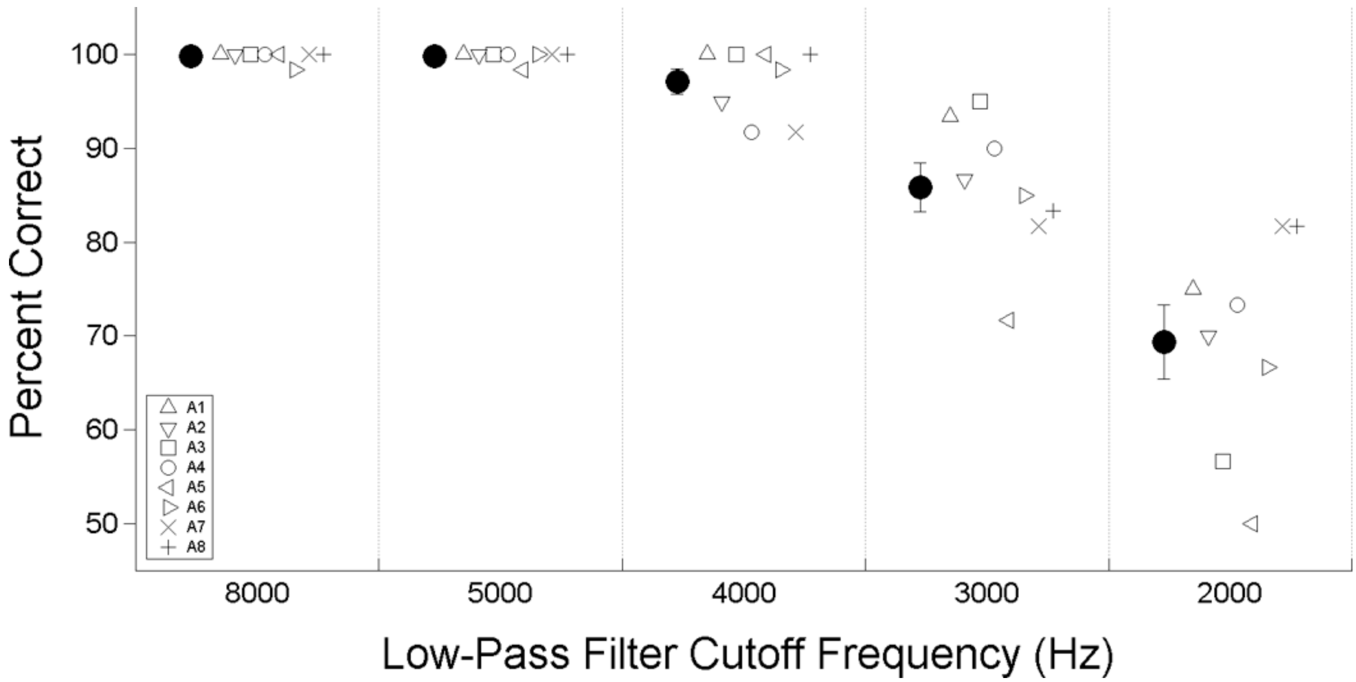

Figure 1.

Individual (open symbols) and group average (filled circles) percent correct scores for adults are plotted as a function of the cutoff frequency of the low-pass filter. Error bars represent ± one standard error of the mean percent correct scores.

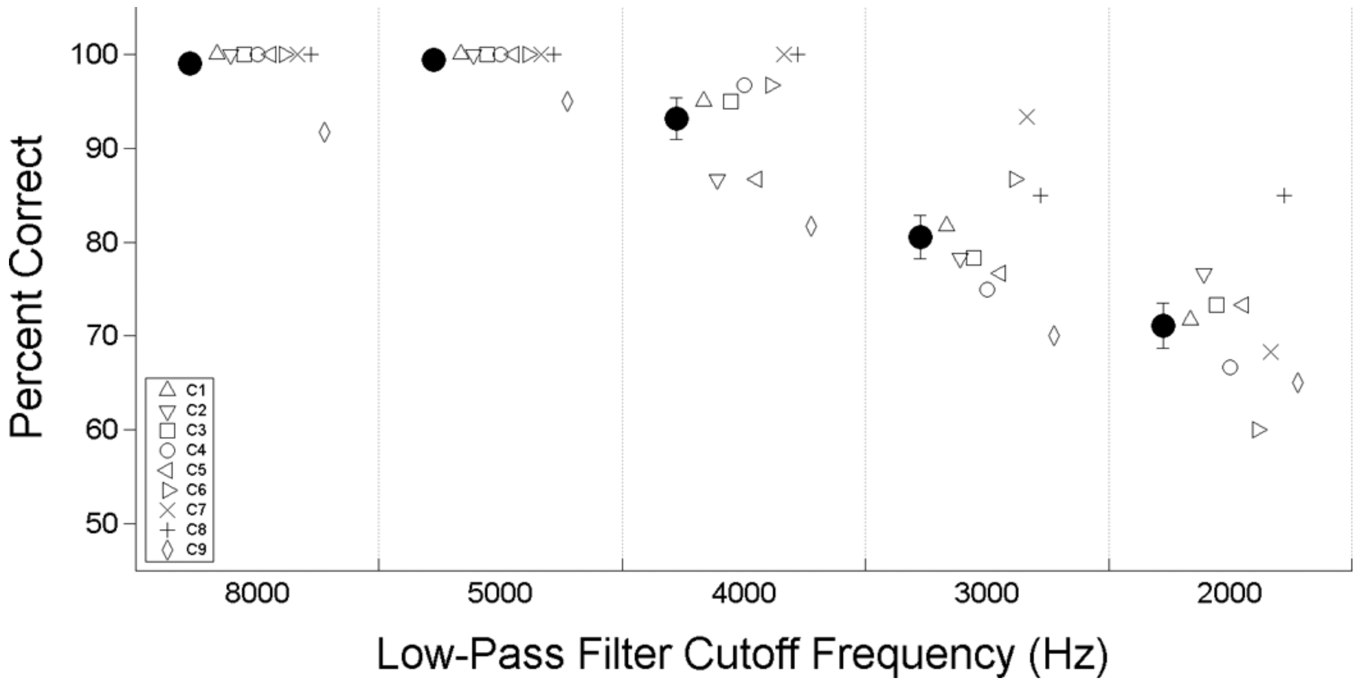

Figure 2.

Individual (open symbols) and group average (filled circles) percent correct scores for children are plotted as a function of the cutoff frequency of the low-pass filter. Error bars represent ± one standard error of the mean percent correct scores.

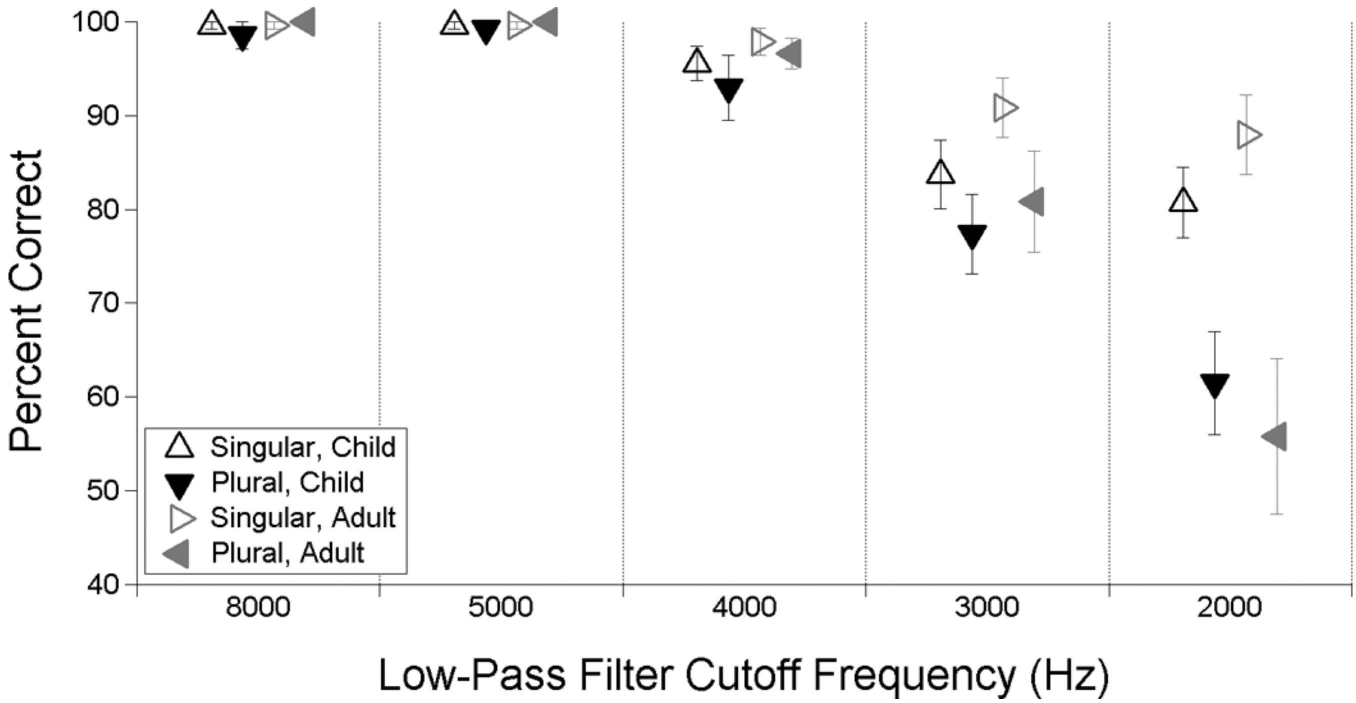

Figure 3.

Average percent correct scores for singular (open symbols) and plural (filled symbols) items are plotted as a function of the cutoff frequency of the low-pass filter. Data for children are shown by the black triangles, and data for adults are shown by the gray triangles. Error bars represent ± one standard estimate of the mean.

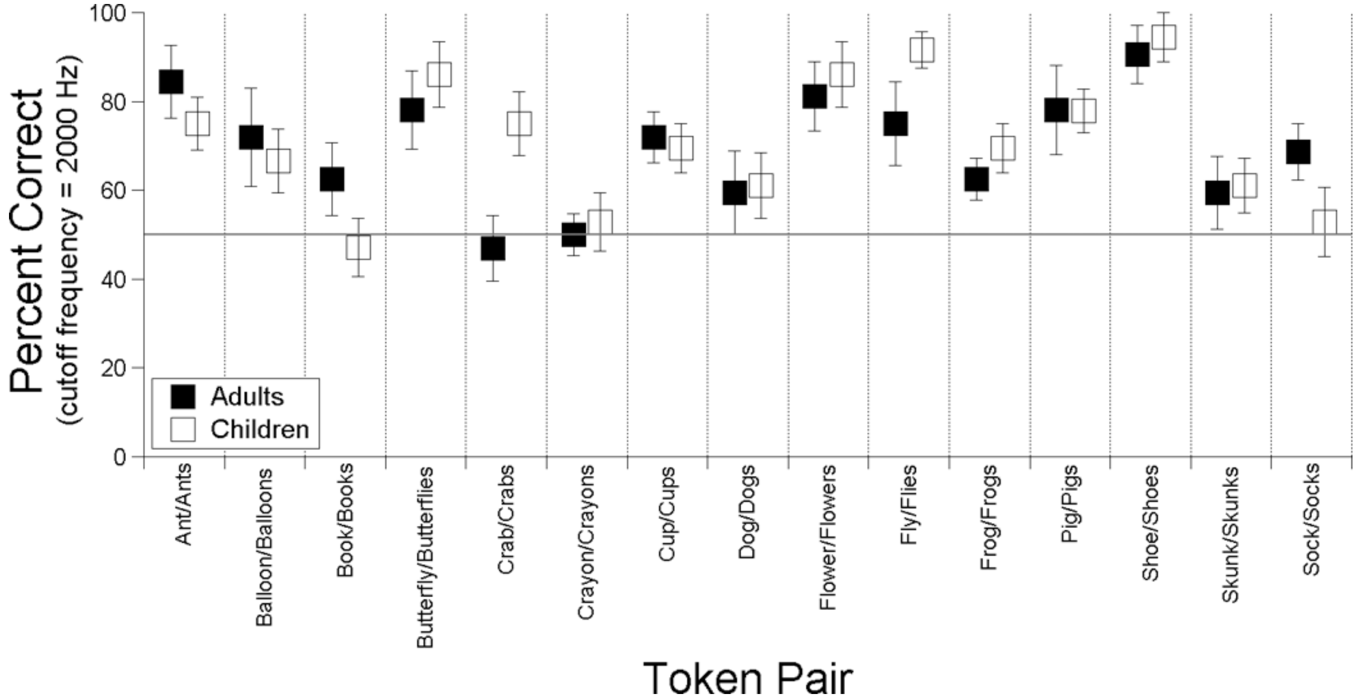

Figure 4.

The average percent correct discrimination for individual word pairs in the data of adults (filled squares) and children (open squares) is shown for each of the 15 token pairs. Error bars represent ± one standard estimate of the mean.