Influence of Hearing Loss on the Perceptual Strategies of Children and Adults

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To accommodate growing vocabularies, young children are thought to modify their perceptual weights as they gain experience with speech and language. The purpose of the present study was to determine whether the perceptual weights of children and adults with hearing loss differ from those of their normal-hearing counterparts. Adults and children with normal hearing and with hearing loss served as participants. Fricative and vowel segments within consonant-vowel-consonant stimuli were presented at randomly selected levels under two conditions: unaltered and with the formant transition removed. Overall performance for each group was calculated as a function of segment level. Perceptual weights were also calculated for each group using point-biserial correlation coefficients that relate the level of each segment to performance. Results revealed child-adult differences in overall performance and also revealed an effect of hearing loss. Despite these performance differences, the pattern of perceptual weights was similar across all four groups for most conditions.

KEY WORDS: children, adults, speech perception, perceptual strategies

Although considerable work has been conducted on the speech perception strategies of children with normal hearing, little is known about the perceptual strategies of children who must learn speech and language skills in the presence of hearing loss. We know from studies of children with normal hearing that perceptual strategies are refined as children gain experience with speech and language. For example, Nittrouer and Studdert-Kennedy (1987) found that younger children (3-, 4-, and 5-year-olds) pay particular attention to the acoustic properties of speech that specify vocal tract movement (e.g., formant transitions), whereas older children and adults attend more to the details of the acoustic signal (e.g., fricative noise). These findings, along with additional data, led to the Developmental Weighting Shift model of speech perception, which suggests that the early perceptual strategies of young children are effective as long as their vocabularies are not too large (Nittrouer, 1992, 1996; Nittrouer & Crowther, 1998; Nittrouer & Studdert-Kennedy, 1987). As more words are learned, children must shift their attention to details of the acoustic signal so that items can be represented more precisely.

Several questions regarding perceptual strategies become apparent when one considers listeners with hearing loss. For example, what happens to the well-established perceptual strategies of adults when hearing loss is acquired later in life? Do these adults shift their attention

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away from increasingly inaudible acoustic details to more audible but less informative ones (e.g., from a fricative noise to a formant transition), or do they attend to speech as they did when their hearing was normal? More importantly, how does hearing loss influence the development of perceptual strategies in children, and are those strategies optimal for perception? Finally, can perceptual strategies be altered as needed to accommodate changes in amplification systems, progressive hearing loss, and/or difficult listening situations (e.g., noise)?

Although little direct evidence is available, two studies by Doherty and Lutfi (1996, 1999) suggest that the perceptual strategies of adults with hearing loss differ from those of adults with normal hearing. In the later study, the perceptual strategies of adults with and without hearing loss were examined for three target tones (0.25, 1, and 4 kHz) presented in a six-tone complex. The level of each of the three target tones was randomly varied across trials at intensities sufficiently audible to accommodate the sloping high-frequency hearing losses of the listeners with hearing loss. The listeners were asked to indicate which of two complexes in a two-alternative forced choice task contained the more intense target tone. A correlational analysis was used to determine the relative weight given to each of the three tones. The performance of the adults with normal hearing was found to correlate best with the level of the 0.25-kHz tone, whereas the performance of the listeners with hearing loss correlated best with the level of the 4-kHz tone. In other words, the adults with normal hearing assigned more weight (or attended more) to the 0.25-kHz tone and the adults with hearing loss assigned more weight to the 4-kHz tone. The results of this and an earlier study by the same authors (Doherty & Lutfi, 1996) suggest that the listeners with hearing loss attended more to frequencies associated with cochlear damage even when more tonal information was available in frequency regions of normal or near normal hearing.

Zeng and Turner (1990) studied fricative perception in 4 listeners with normal hearing and 3 listeners with hearing loss. Stimuli were four consonant-vowel syllables composed of voiceless fricatives (/s/, /ʃ/, /f/, and /θ/) in an /i/ context. To determine the relative contribution of the fricative noise to each syllable, the stimuli were first presented in their entirety and then presented without the vowel segment. All stimuli were presented at a number of levels, taking into consideration the thresholds of each listener. Performance for each group was calculated as a function of audibility. Results revealed that the adults with hearing loss performed almost as well as the listeners with normal hearing when identifying the fricative noise, suggesting that both groups recognized the aperiodic noise segment as meaningful to perception. When the audibility of the lower-frequency formant transition within each syllable was calculated, the results revealed substantially poorer performance for the adults with hearing loss, even though the formant transitions were more audible than the fricative segments. The authors concluded that adults with hearing loss might be unable to discriminate the rapid, dynamic spectral information provided in formant transitions.

Unfortunately, little is known about the perceptual strategies of young children with hearing loss. Pittman and Stelmachowicz (2000) studied the strategies of older children (8–12 years old) and adults with normal hearing and with hearing loss. They used four vowel-consonant stimuli composed of the voiceless fricatives /s/, /ʃ/, /f/, and /θ/ in an /u/ vowel context. Each syllable was presented in its entirety, but the vowel, transition, and fricative segments were presented at randomly chosen levels. Identification of the fricative was correlated with the level of each segment using a correlational method similar to that of Doherty and Lutfi (1996). Although all four groups attended most to the fricative segments of /s/ and /ʃ/, the strategies of the listeners with hearing loss with regard to both segments of /uf/ and /uθ/ were poorly defined. In addition, the children with hearing loss showed poorer overall performance, suggesting that many of these children could not use their strategies as efficiently as their hearing- and age-matched counterparts.

Although it would be ideal to address all of the questions noted earlier, they would exceed the scope of what can be answered in a single study. For that reason, the purpose of this study was to compare the perceptual strategies of children and adults with hearing loss with those of children and adults with normal hearing.

Methods

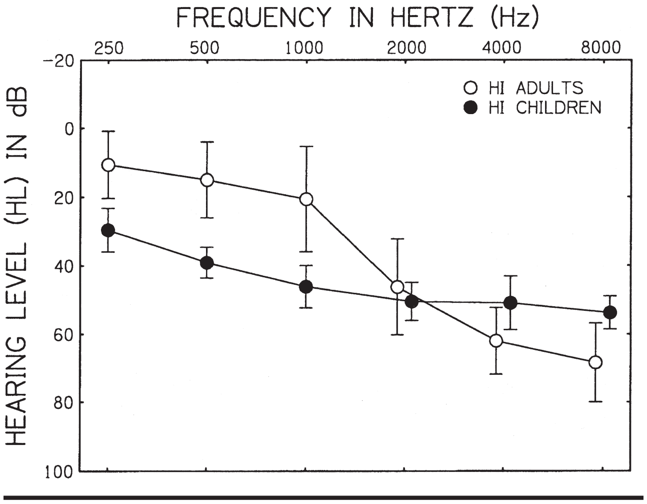
Listeners

A total of 40 listeners participated in this study. Two groups of listeners with normal hearing consisted of 10 adults (20–44 years old, M = 28 years) and 10 children (5–8 years old, M = 6 years, 9 months). These listeners had hearing thresholds of 15 dB or less at octave frequencies from 0.25 through 8 kHz. Two groups of listeners with hearing loss consisted of 10 adults (49–66 years old, M = 59 years) and 10 children (5–10 years old, M = 8 years, 3 months). These listeners displayed high-frequency sloping sensorineural hearing losses. It was necessary to recruit somewhat older adults with hearing loss to obtain individuals with acquired hearing loss. It was also necessary to include several children with hearing loss older than 8 years to obtain an adequate number of children with homogeneous hearing losses that were congenital in nature. All of the children with hearing loss communicated orally and were performing at grade level in school. Figure 1 shows the mean pure-tone air-condition thresholds (±1 *SD*) for the children and adults with hearing loss.

Stimuli

Four consonant-vowel-consonant words were used as stimuli (*sack*, *sock*, *shack*, and *shock*). These words contained formant transitions unique to the combination of the fricatives and vowels. For example, the peak energy for a fricative /s/ produced by a male talker falls roughly at 5 kHz, whereas the peak energy of /ʃ/ falls around 3.5 kHz. When these fricatives are followed by the vowels /ɑ/ and /æ/, with second formant frequencies occurring typically at 1.7 and 0.85 kHz, respectively, formant transitions unique to each fricative are produced. The intentional combination of these fricative and vowel segments allowed us to determine the weight given to the fricative and vowel segments through a series of decisions made by each listener. It was expected that the listeners would first dichotomize their responses according to one of the segments perceived (fricative or vowel) and then use their perceptual strategies to choose their final response. For example, if the vowel /æ/ was perceived, the listener would ignore the words *sock* and *shock* and choose between the words *sack* and *shack* based on their ability to use the fricative and/or the formant transition information. A listener having difficulty using formant transition information may dichotomize correctly but fail to choose the correct word. In general, this paradigm allowed us to present a number of response alternatives for meaningful words that differed slightly in acoustic properties. These stimuli were also useful for children in that the fricative-vowel segments became meaningful words to children by simply adding the final plosive /k/ to each syllable. Because the levels of the segments were varied on each trial (described below), this paradigm also allowed us to determine the weight given to each segment along a parameter that is important to listeners with hearing loss, namely audibility (also described below).

Figure 1. Mean pure-tone thresholds (±1 *SD*) in dB HL for the hearing-impaired (HI) adults (open circles) and children (filled circles).



Each word was recorded by an adult male in a sound-treated room using a microphone with a flat frequency response to 10 kHz (AKG Acoustics, C535 EB). The speech samples were amplified (Shure, M267), filtered at 10 kHz (TDT, PF1), and digitized at a sampling rate of 22.5 kHz. The initial fricative (/s/ or /ʃ/), medial vowel (/ɑ/ or /æ/), and final voiceless plosive (/k/) in each word were identified using a digital editing program (Cool Edit 96). The plosive /k/ and its preceding silent gap were replaced in each word with a single version of the phoneme produced by the same talker. These words were then used to create stimuli for two conditions: with formant transitions and without formant transitions. In the first condition, no changes were made to the fricative and vowel segments. In the second condition, the formant transitions were removed by replacing the /ɑ/ and /æ/ vowel segments with the same vowels spoken in isolation by the same talker. Spectrograms of the stimuli in both conditions are shown in Figure 2. For the original stimuli (left panels), varying degrees of formant transitions are apparent. For example, a larger formant transition occurred for words beginning with /ʃ/ than for /s/. For the stimuli without transitions (right panels), nearly flat formant frequencies are apparent for each stimulus. By removing the formant transition in the second condition, the listeners were forced to use the small spectral differences in the fricative segments for perception. This allowed us to determine the ability of each group to use different aspects of the stimuli when important acoustic information was removed.

Procedure

Listeners were seated in a sound-treated room and asked to identify each word presented monaurally through the same earphone used to obtain hearing thresholds (Sennheiser, HD-25). Listeners indicated the word they heard by touching the appropriate response box on a touch-screen monitor or by selecting it with a mouse. The response boxes were labeled with pictures of each word. Before testing, the children were asked to identify each picture to determine if the words were familiar to them. For children unfamiliar with a word, additional familiarization tasks were performed until each child was able to identify the words with ease.

A computer program (MATLAB, Mathworks) was used to present the stimuli, provide reinforcement for correct responses, and store trial-by-trial data. For each trial, the program randomly selected the stimulus, as well as separate amplitude levels for the fricative and vowel segments. That is, each word was presented in its entirety, but the separate amplitudes of the fricative and vowel segments within each word were varied from trial to trial. The amplitude of the final plosive /k/ did not vary. For the listeners with normal hearing, five levels were presented in 12-dB steps for a total range of 48 dB. For the listeners with hearing loss, the stimuli were frequency shaped to compensate for each listener's hearing thresholds. Due to the reduced dynamic range of these listeners, presentation level, step size, and amplitude range were calculated individually to ensure signal audibility. These stimuli were presented in 5- to 12-dB step sizes, corresponding to a total amplitude range of 20 to 48 dB. Fifteen repetitions of the stimuli were presented at each level for a total of 600 trials (4 words × 5 segment levels × 15 repetitions × 2 listening conditions). Figure 3 illustrates the range of amplitude levels for the fricative and vowel segments (light and dark shaded areas, respectively) relative to the hearing thresholds of a listener with hearing loss (filled circles). In this example, the spectra represent the 1% peaks of speech analyzed in 1/3-octave bands. On any given trial, one level of each segment (one dotted and one dashed line) was selected from

Figure 2. Spectrograms of the consonant-vowel-consonant stimuli in their original form (left panels) and without formant transitions (right panels).

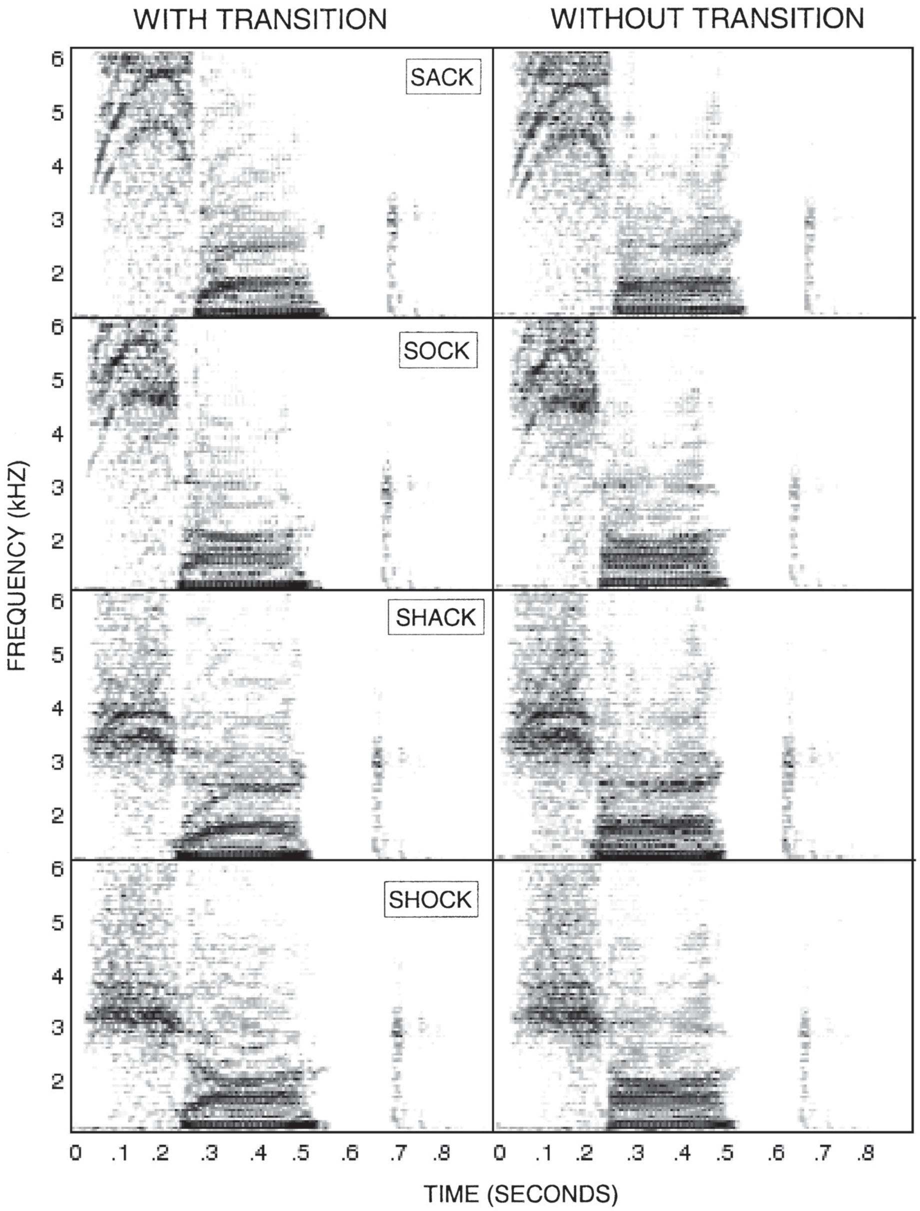
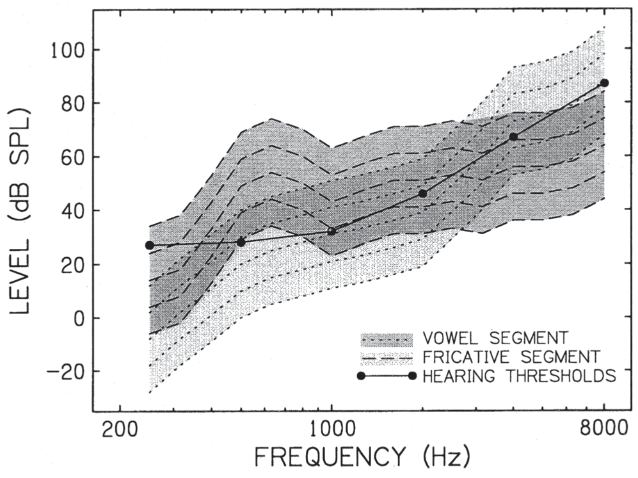


Figure 3. Example of amplitude variation for the fricative (dotted lines) and vowel (dashed lines) segments calculated for a hypothetical hearing loss (solid line).



each shaded area and presented. To reduce spectral splatter at the segment boundaries due to potential discontinuities in amplitude, a moving-average filter was applied to the temporal amplification profile to obtain smooth changes in level between segments. The filter had low-pass characteristics with the –3 dB point of its transfer function at 100 Hz.

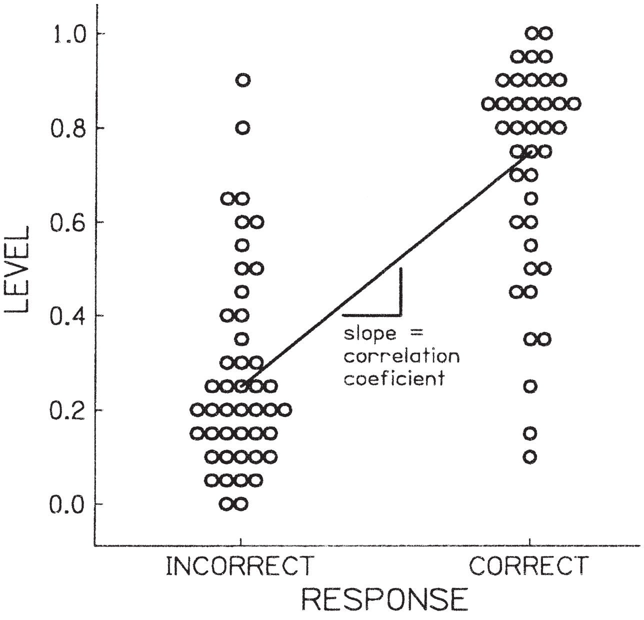
Calculating Perceptual Weight

Because attention to specific segments of speech was of interest in the present study, perceptual weight was defined as a change in performance as a function of changing presentation level. Perceptual weight was quantified using a method similar to that of Pittman and Stelmachowicz (2000). Specifically, point-biserial correlation coefficients were calculated using the correct and incorrect responses of each listener relative to the level of each stimulus segment (fricative or vowel). This method is illustrated in Figure 4, where the presentation level of the trial-by-trial data is plotted as a function of the response (incorrect or correct). The slope of a line intersecting the mean presentation level in each column is the correlation coefficient. A positive correlation indicates that performance improved as the level of the segment increased, and a correlation near 0 indicates that performance remained unchanged regardless of the level of the segment. Although negative correlations did not occur, they would indicate a decrease in performance with increasing stimulus level.

Short-Term Audibility

To accurately compute the level of the stimulus segment relative to the hearing thresholds of each listener, a measure of short-term audibility (STA) was used. Measures of sensation level are typical for these applications; however, the calculation of STA includes values of importance for each of 17 frequency bands between 0.25 and 8 kHz. In this way, both the listeners with hearing loss and with normal hearing could be compared using a metric intended for use with speech perception. Because the audibility of speech is typically calculated for continuous discourse, it was necessary to modify the procedure to calculate audibility for the short duration fricative and vowel segments. Each segment was first recorded in a 2-cm^3 coupler at 100 dB SPL. The 1% peak amplitudes of each recorded segment were then measured in seventeen 1/3-octave bands (TOB) using a 20-ms Hanning window (50% overlap). Finally, STA was calculated using a modification of the Articulation Index (American National Standards Institute, 1969) for each of the 8 segments (4 words × 2 segments) and five amplitude levels. The modified formula was:

Figure 4. Graphical representation of a point-biserial correlation coefficient calculation. The short-term audibility (STA) of trial-by-trial data are plotted as a function of the response. Data are jittered to illustrate the density of responses at each STA.



$$STA = \frac{1}{20}\sum_{i=1}^{17}[TOB_i - \theta_i]\,W_i$$

where i is the number of the 1/3-octave band, TOB_i is the 1% peak level for the ith 1/3-octave band in the stimulus segment (re: 2-cm^3 coupler), and θ_i is the hearing threshold in dB SPL referenced to the same coupler.[1]

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[1] Hearing thresholds were measured at octave frequencies and interpolated across the seventeen 1/3-octave bands.

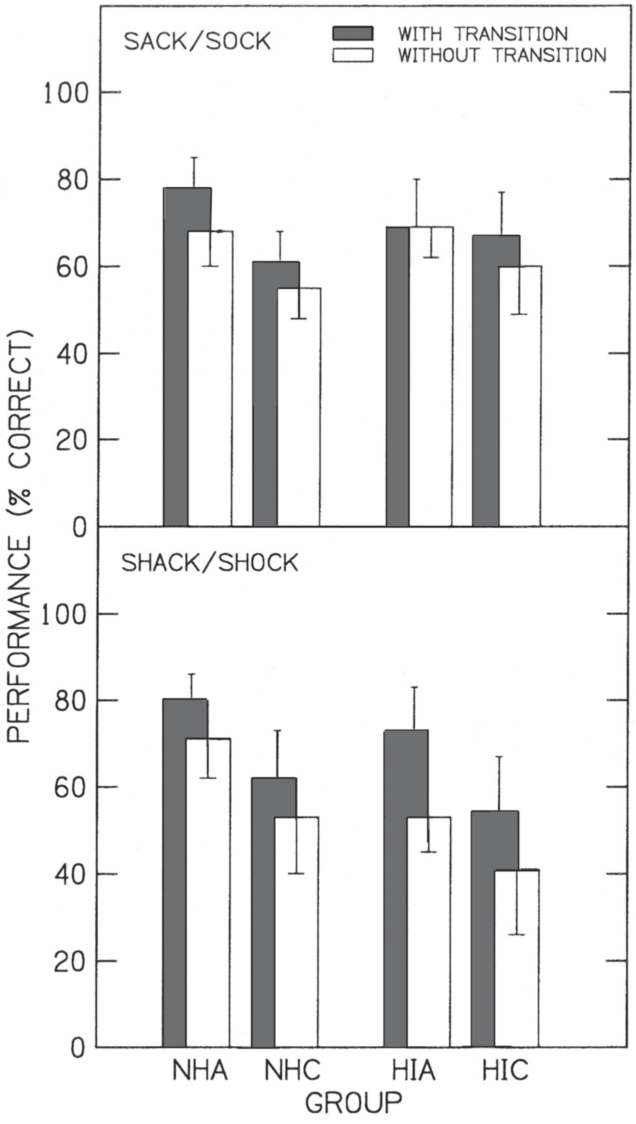
These values are multiplied by the importance value assigned to each band (W_i) and summed. The signal-to-noise ratio in each band ($TOB_i - \theta_i$) as restricted to a range of 0 to 20 dB so that when multiplied by 1/20, the resulting index ranged from 0.0 to 1.0. Importance functions for nonsense syllables were used in this calculation (American National Standards Institute, 1969).

Results

Recall that the purpose of the present study was to compare the perceptual strategies of children and adults with hearing loss with those of children and adults with normal hearing. Initial data analyses revealed similar results for both /s/ stimuli (*sack* and *sock*) and for both /ʃ/ stimuli (*shack* and *shock*); thus, the data were grouped by fricative. Figure 5 shows overall performance (±1 *SD*) as a function of group for the /s/ and /ʃ/ stimuli (upper and lower panels, respectively). The solid bars represent the stimuli with formant transitions, and the open bars represent the stimuli without formant transitions. In general, better performance was achieved by all groups for the stimuli with formant transitions than for the stimuli without formant transitions except for the adults with hearing loss listening to the /s/ stimuli. Also, child-adult differences were apparent for the listeners with normal hearing for both stimuli and listening conditions. Similar results were apparent for the children and adults with hearing loss.

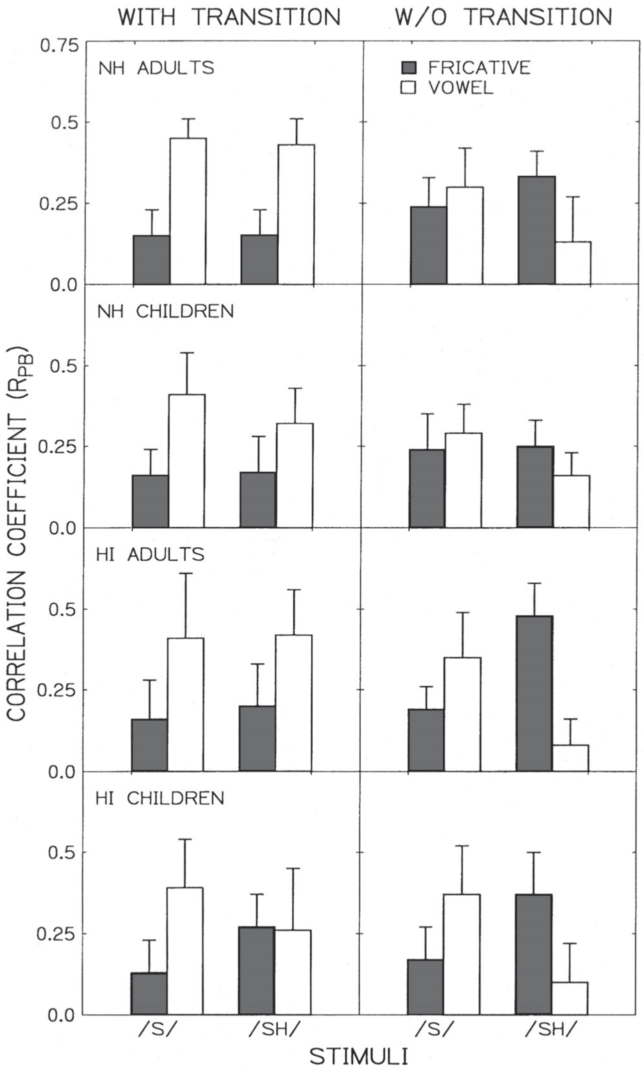
An Analysis of Variance was conducted on percent-correct performance to examine differences between groups, stimuli, and listening conditions. The between-subjects factor was group (adults with normal hearing, children with normal hearing, adults with hearing loss, and children with hearing loss), and the within-subjects factors were listening condition (with and without formant transition) and fricative (/s/ and /ʃ/). Results revealed significant main effects for listening condition [$F(1, 36) = 95.165$, $p < .001$] and fricative [$F(1, 36) = 14.944$, $p = .001$] as well as a listening condition × fricative interaction [$F(1, 36) = 25.596$, $p < .001$]. Significant group effects also were found [$F(3, 36) = 11.902$, $p = .001$]. Post hoc testing using Scheffé's multiple comparisons revealed significantly poorer performance for the /s/ and /ʃ/ stimuli by the children with normal hearing relative to that of the adults with normal hearing in both listening conditions. For the /ʃ/ stimuli, the performance of the children with hearing loss was poorer than that of the adults with hearing loss for the stimuli with formant transitions; the adults with hearing loss performed more poorly than the adults with normal hearing for the stimuli without formant transitions. In general, these results revealed significant effects of fricative and listening condition as well as the effects of hearing loss and development.

Figure 5. Mean performance for stimuli with formant transitions (filled bars) and without formant transitions (open bars) for the normal-hearing adults (NHA), normal-hearing children (NHC), hearing-impaired adults (HIA), and hearing-impaired children (HIC). Error bars represent ±1 standard deviation.



The perceptual weights that correspond to the performance shown in Figure 5 are illustrated in Figure 6. In this figure, the average correlation coefficients are shown (±1 *SD*) as a function of stimulus for each group. The results for the stimuli with and without formant transitions are given in the left and right panels, respectively. The filled and open bars represent the correlation coefficients for the fricative and vowel segments, respectively. Each solid and open bar in Figure 5 corresponds to the combined weight of the fricative and vowel segments displayed in Figure 6. Recall that a perceptual weight is calculated by correlating the

Figure 6. Point-biserial correlation coefficients for the /s/ and /ʃ/ stimuli plotted as a function of segment for the children and adults with normal hearing and with hearing loss.



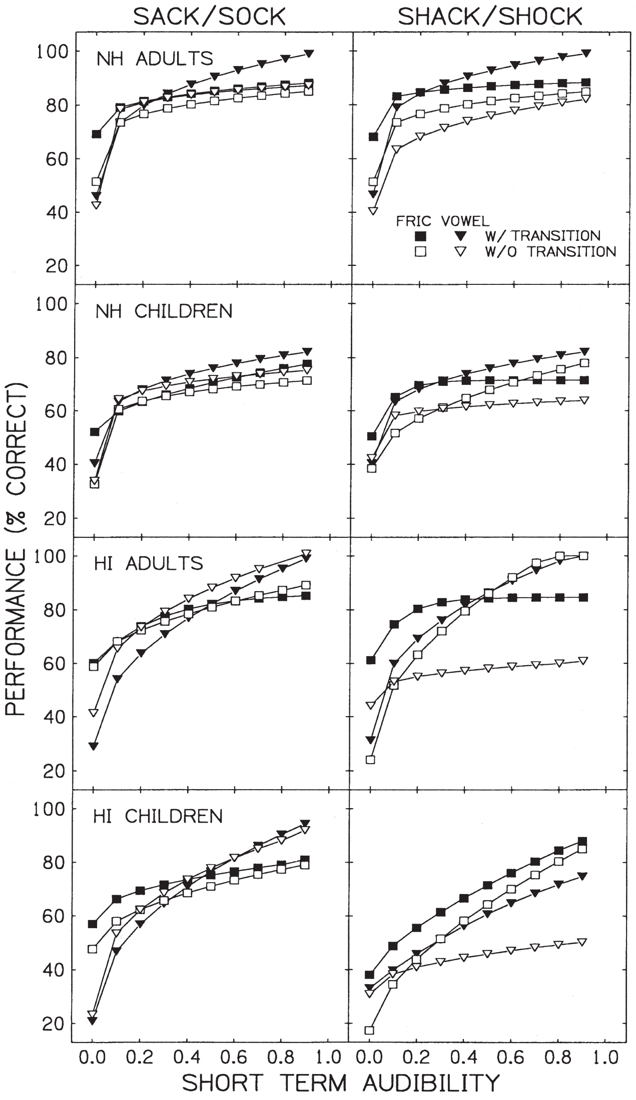
trial-by-trial STA levels with the response (correct or incorrect). Using this method, these weights indicate the relation between performance for the /s/ and /ʃ/ words and the audibility of each segment. Specifically, the more performance improved as audibility of a segment increased, the higher the weight. For example, a correlation coefficient of .20 or less corresponded to less than a 30% change in performance across all levels of audibility. Correlation coefficients greater than .20 occurred for those segments where performance improved substantially more than 30% across the range of audibility levels.

In terms of perceptual weights for the unaltered stimuli (left panels), each group appeared to rely heavily on the audibility of the vowel segment for perception, except for the children with hearing loss when the fricative /ʃ/ was used. Surprisingly, children with hearing loss relied as heavily on the audibility of the fricative segment of the /ʃ/ stimuli as on the vowel segment, suggesting that they were unable to use the dynamic formant transition of /ʃ/ as efficiently as their age- and hearing-matched counterparts. When the formant transitions were removed (right panels), all groups appeared to rely heavily on the audibility of the vowel for the /s/ stimuli. In contrast, all groups shifted their attention to the fricative for the /ʃ/ stimuli when the primary source of information was no longer available. Interestingly, the listeners with hearing loss appeared to rely more heavily on the audibility of the fricative segment than did the listeners with normal hearing. The markedly different perceptual weights for the /s/ and /ʃ/ stimuli may be related to the magnitude of the formant transitions associated with the fricatives /s/ and /ʃ/. Because the formant transitions for the /ʃ/ stimuli were more extensive than for the /s/ stimuli, the absence of the formant information was more detrimental to perception. In general, these results suggest that the formant transitions in each word were important to perception and that the magnitude of the formant transitions influenced performance.

It is tempting to try to relate the perceptual weights shown in Figure 6 to the overall performance shown in Figure 5. However, it is important to remember that point-biserial correlation coefficients do not represent overall performance but rather the *relation* between performance and audibility. This complex relation is illustrated in the performance-STA functions shown in Figure 7. In this figure, each function represents a best fit to the individual data for each group with respect to listening condition and segment. The squares and triangles represent the fricative and vowel segments, respectively. The open symbols indicate conditions where the transition was removed. Point-biserial correlation coefficients are related to the slopes of each function in that performance changed as a function of the audibility of each segment. However, overall performance cannot be predicted from the correlation coefficients. See, for example, the solid boxes and the open triangles representing the adults with hearing loss's data for the /ʃ/ stimuli. In this example, the weights associated with these functions (0.20 and 0.08, respectively) are both relatively low, yet substantial differences in performance were observed.

Although the performance-STA functions in Figure 7 provide an estimate of perceptual weights, the goodness-of-fit of each function must be considered. For these functions, goodness-of-fit varied widely, making it difficult to compare them across groups or conditions. Point-biserial correlations, however, can be considered more reliable estimates of perceptual weight because goodness-of-fit measures are not applicable to this calculation.

Figure 7. Performance-STA functions for the /s/ (left panels) and /ʃ/ (right panels) stimuli plotted for each segment and listening condition. The filled and open symbols represent the stimuli with and without formant transitions, respectively. The squares and triangles represent the fricative and vowel segments, respectively.



Discussion

The purpose of the present study was to compare the perceptual strategies of children and adults with hearing loss with those of children and adults with normal hearing. It is important to remember that the term “weight” used in the present study does not imply a conscious decision on the part of the listener. Although many models of speech perception describe a series of decisions or stages, the use of this term is unrelated to those theories. It is also important to note that the perceptual weights reported in this study cannot be generalized to everyday communication. Instead, the strategies observed were sufficient for differentiating between the four stimuli presented in this study. More or fewer choices may have resulted in very different strategies. Even so, the perceptual weights demonstrated by each of the four groups may indicate which groups are able to accommodate less than perfect acoustic information.

In general, the overall performance of the children with normal hearing was lower than that of the adults. This is consistent with a number of studies showing adult-child differences in performance (Hnath-Chisolm, Laipply, & Boothroyd, 1998; Neuman & Hockberg, 1983; Nozza, Rossman, & Bond, 1991; Stelmachowicz, Hoover, Lewis, Kortekaas, & Pittman, 2000). Although similar adult-child differences were observed for the listeners with hearing loss, these findings may have been influenced by the fact that the adults acquired their losses later in adulthood and the children had prelingual and early onset of hearing loss. The effect of hearing status on overall performance also was apparent in that the performance of the listeners with hearing loss was often poorer than that of their counterparts with normal hearing.

Despite the differences in overall performance, similar perceptual weights were observed across all four groups for most stimuli. When the formant transitions were available, all four groups relied heavily on the audibility of the vowel. When the formant transitions were removed, each group continued to rely on the audibility of the vowel in the /s/ stimuli but shifted their attention to the fricative for the /ʃ/ stimuli. The differences in overall performance across groups suggest additional effects of hearing loss independent of perceptual weights. The varying magnitude of the perceptual weights suggests that the audibility of certain segments relates more closely to performance than that of other segments. This was particularly true for the listeners with hearing loss for /ʃ/, where removal of the formant transitions resulted in an increase in weight for the fricative.

Although the results of previous studies suggest that adults with hearing loss may not be able to discriminate the rapid, dynamic spectral information in a formant transition (Zeng & Turner, 1990), the adults with hearing loss in the present study appeared to rely heavily on that information. In fact, when the formant information was removed, the performance of the adults with hearing loss decreased more than any other group, suggesting an even greater reliance on that information than previously reported. This discrepancy may be due to differences between the magnitude of the formant transitions for the two vowels used in the present study and that of the /i/ vowel used by Zeng and Turner. Although the magnitudes of the transitions were not reported in the Zeng and Turner study, the high-frequency formants of /i/ may have produced relatively weak formant transitions when preceded by the predominantly high-frequency fricatives.

These results are also interesting in light of the weighting strategies reported by Doherty and Lutfi (1996). In their study, the adults with hearing loss assigned more weight to stimuli with respect to frequency regions of greatest hearing loss. That would suggest that the adults with hearing loss in the present study would favor the high-frequency fricative information over the lower-frequency vowel information in both listening conditions. However, the results suggest that the adults with hearing loss were equally capable of using information in all frequency regions as long as the information was sufficiently audible. Again, differences in stimuli might account for these discrepancies. Doherty and Lutfi (1996) presented nonmeaningful tonal complexes, whereas meaningful consonant-vowel-consonant stimuli were used in the present study.

Although the stimulus manipulations in this study were artificial, theoretically the perceptual weights used by each group may indicate whether or not they can accommodate less than perfect communication environments. For example, a listener who can easily change his or her attention to alternate acoustic information may be better able to communicate in adverse listening environments where noise, reverberation, or distance may make important acoustic information difficult to perceive. The methodology in the current study did not allow us to explore the relation between perceptual weights and performance directly. Future studies are necessary to determine how perceptual weights relate to performance, if perceptual weights change with experience, and if perceptual weights can be systematically altered through training to improve performance.

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