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Identification of Acoustically Similar and Dissimilar Vowels in Profoundly Deaf Adults Who Use Hearing Aids and/or Cochlear Implants: Some Preliminary Findings

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Abstract

Purpose—In this study, the authors examined the effects of aging and residual hearing on the identification of acoustically similar and dissimilar vowels in adults with postlingual deafness who use hearing aids (HAs) and/or cochlear implants (CIs).

Method—The authors used two groups of acoustically similar and dissimilar vowels to assess vowel identification. Also, the Consonant–Nucleus–Consonant Word Recognition Test (Peterson & Lehiste, 1962) and sentences from the Hearing in Noise Test (Nilsson, Soli, & Sullivan, 1994) were administered. Forty CI recipients with postlingual deafness (ages 31–81 years) participated in the study.

Results—Acoustically similar vowels were more difficult to identify than acoustically dissimilar vowels. With increasing age, performance deteriorated when identifying acoustically similar vowels. Vowel identification was also affected by the use of a contralateral HA and the degree of residual hearing prior to implantation. Moderate correlations were found between speech perception and vowel identification performance.

Conclusions—Identification performance was affected by the acoustic similarity of the vowels. Older adults experienced more difficulty identifying acoustically similar confusable vowels than did younger adults. The findings might lend support to the *ease of language understanding model* (Ronnberg, Rudner, Foo, & Lunner, 2008), which proposes that the quality and perceptual robustness of acoustic input affects speech perception.

Keywords

cochlear implants; speech perception; aging; hearing loss

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Previous research has revealed that similarity among groups of speech signals will affect the perception of those signals. Specifically, Turner and Henn (1989) found that adults with normal hearing and adults with hearing loss made more identification errors with vowel pairs having similar acoustic properties (i.e., /æ-ε/ and /ʌ-a/) than with vowel pairs having less acoustic similarity (e.g., /æ-ʌ/ or /ε-a/). In addition, it has been found that the lexical similarity among groups of words affects the identification of those words. Specifically, it has been revealed that individuals with normal hearing and individuals with hearing loss have much more difficulty identifying words with many similar lexical neighbors that occur infrequently in the language than words with fewer neighbors that occur more frequently (Kirk, Pisoni, & Osberger, 1995; Luce & Pisoni, 1998). It has also been reported that the acoustic similarity of vowels and words influences the recall of lists of those items (Cleary, 1996; Conrad & Hull, 1964; Wickelgren, 1965).

For individuals who have profound hearing loss, the identification of similar speech items can be improved through the use of cochlear implants (CIs). A large and growing body of evidence has demonstrated that CIs significantly improve speech perception for profoundly deaf listeners (Zeng, 2004). However, much more information is required to improve our understanding of how the CI speech processing affects performance under suboptimal listening conditions such as noise, acoustic similarity, increased cognitive load, or dual-task performance. There are still many basic questions about how the processing of speech cues conveyed by a CI affects performance in adults, particularly older implanted adults. The heavy reliance on temporal cues to process speech through a CI may adversely affect older adults' ability to make optimal use of the limited acoustic information conveyed by CIs when compared younger adults with CIs.

In the population of aging individuals who have not received CIs, it has been found that temporal discrimination skills deteriorate with age (Fitzgibbons & Gordon-Salant, 1996, 2004; Gordon-Salant & Fitzgibbons, 2001). The majority of speech processing strategies that are commonly used, however, rely on the extraction and representation of amplitude modulation cues to code speech signals. The fine spectral cues in the speech signal are not directly coded or transmitted by the current generation of CIs. Typically, signals are processed through a filter bank, half-wave rectified, and then low-pass filtered to extract the temporal envelope of speech in each frequency band (Wilson et al., 1991). The temporal envelope in each band is then used to modulate pulse trains of electrical stimulation that are used to directly stimulate auditory neurons. As a result, very limited spectral resolution is provided via the current speech processing strategies commonly used by CI recipients. Consequently, the recognition of speech is carried out with a greater reliance on temporal as opposed to spectral information in the speech signal. The emphasis and heavy reliance on temporal cues in speech may have several implications for older CI recipients and their ability to encode and process specific features of speech, especially under adverse listening conditions.

A number of studies have suggested that older adults who use CIs perform as well as younger adults with CIs on some speech perception tasks. For example, studies involving word recognition tasks have demonstrated no difference in outcomes for younger and older

implanted adults (Hay-McCutcheon, Pisoni, & Kirk, 2005; Noble, Tyler, Dunn, & Bhullar, 2009; Ruffin et al., 2007). However, recent research has suggested that with increasing age, there might be specific aspects of speech that are more difficult to perceive. Specifically, Lee, Freedland, and Runge (2012) examined physiological and psychophysical forward-masking recovery rates and discovered that although no differences were found between younger and older adults with CIs for the physiological recovery rates, psychophysical recovery rates were significantly slower in the older adults with CIs than in the younger adults with CIs.

Also, differences in performance across age have been demonstrated through the use of a CI simulation analysis. Schwartz, Chatterjee, and Gordon-Salant (2008) demonstrated that age had a significant impact on the identification of spectrally degraded vowels. In their study, vowels were processed through a continuous interleaves sampling (CIS) CI simulation program that filtered the signals through a number of spectral channels and spectrally shifted the vowels to higher frequencies. This processing simulated the filtering of speech that occurs in CI speech processing strategies and the differences in the insertion depth of the electrode array within the cochlea. Schwartz et al. (2008) found that older adults with normal hearing identified significantly fewer processed vowels compared with younger adults. Moreover, as the spectral shift of the vowels increased, or as the reliance on temporal cues increased, the number of processed vowels identified by the older adults decreased even further.

The reliance on temporal cues for speech recognition could affect performance on frequency identification and discrimination tasks to a larger extent in older, compared with younger, CI recipients. Older CI recipients who rely heavily on temporal cues for speech recognition could be more adversely affected by current speech processing strategies than their younger counterparts. Evidence from CI simulation studies involving young listeners with normal hearing suggests that as the spectral processing of speech declines, listeners rely more on temporal cues for vowel recognition (Nie, Barco, & Zeng, 2006; Xu, Thompson, & Pfingst, 2005). It is likely, therefore, that older CI recipients would also perform more poorly than younger adults on tasks that require encoding of formant information in vowel recognition, because of older adults' poorer temporal resolution processing.

Another factor to consider when examining the identification of similar speech items in adults with profound deafness is the use of a hearing aid (HA) in conjunction with a CI. Evidence from CI recipients has suggested that through the use of bimodal hearing (i.e., unilateral cochlear implant and a contralateral hearing aid), individuals can achieve improved speech perception. Yoon, Li, and Fu (2012) found that CI recipients who use a contralateral HA that provided aided pure-tone averages (PTAs) ≥ 55 dB were much more successful at vowel identification and sentence recognition in noise than bimodal users who had aided PTAs < 55 dB. Additionally, Dunn, Tyler, and Witt (2005) demonstrated that seven of 11 individuals who used bimodal hearing were significantly better at identifying City University of New York (CUNY) sentences in the presence of multitalker speech babble compared with when they used their CI alone. Finally, Dorman, Gifford, Spahr, and McKarns (2008) revealed that the identification of single-syllable words and sentences in quiet and in noise was significantly improved when individuals used both their HA and CI

compared with when they used either device alone. Presumably, the added spectral information provided through a CI and/or the mere use of bilateral stimulation provided additional cues for these individuals that resulted in improved performance. These cues might also benefit individuals when they are required to identify groups of speech tokens that are acoustically similar.

The goal of the present study was to determine how aging and the degree of residual hearing prior to implantation affect vowel identification in adults who use HAs and/or CIs. Instead of presenting random isolated vowels for identification, we used sets of vowels that were either acoustically similar or acoustically dissimilar, to help us identify how acoustic–phonetic confusability among a small set of test signals affects perception in this population of adults. Previous research has found that perception of isolated random vowels was affected by acoustic similarity (Turner & Henn, 1989).

For this study, we expected that all adults would have more difficulty identifying vowels in a group of acoustically similar vowels than acoustically dissimilar vowels. For older adults, however, we predicted that these listeners would have more difficulty identifying acoustically similar vowels than do younger adult CI recipients. Our hypothesis is based on earlier findings showing that acoustic similarity affects recognition performance and that older adults have more difficulty processing temporal cues of speech. Older adults with CIs require more explicit controlled processing of degraded test items than younger adults. We also predicted that the acoustic cues provided through an HA could improve the identification of acoustically confusable vowels for adults who use CIs, and that greater residual hearing prior to implantation would result in better performance.

Method

Participants

This study was carried out according to basic ethical standards for the protection of human research subjects and was approved by the institutional review boards at Indiana University School of Medicine and The University of Alabama. For this study, we recruited 40 adults with postlingual deafness who received a CI at the Department of Otolaryngology—Head and Neck Surgery at the Indiana University School of Medicine. Twenty of these participants used an HA in the opposite ear to their CI (i.e., bimodal stimulation). The demographic data for the study participants are summarized in Table 1. The mean age at test was 61.17 years (± 11.58 years), with a mean duration of CI use of 4.2 years (± 3.71 years). All participants had at least 6 months of experience with their CI prior to testing and wore their implant for the majority of their waking hours. In addition, all study participants used current speech processing strategies (i.e., Spectral Peak [SPEAK]; Advanced Combination Encoder [ACE]; Continuous Interleaved Sampling [CIS]; Multiple Pulsatile Sampler [MPS]). Throughout the testing session, the hearing devices were set at everyday listening/volume levels.

Table 2 displays the participants' sound field audiometric thresholds. Due to time constraints, we could not obtain audiometric thresholds on one participant (AAV). All of the remaining study participants had their thresholds checked within 1 year of testing, except

one (ABL) who had thresholds obtained within 2 years of testing. All behavioral thresholds were deemed to be stable for at least 6 months prior to the testing session. Multiple regression analyses revealed no significant differences across age for each of the pure-tone frequencies tested.

Several researchers have examined the role of low-frequency residual hearing on speech perception performance prior to implantation. Ching et al. (2004) and Gifford et al. (2007) suggested that the behavioral threshold at 250 Hz prior to implantation might be important for predicting postimplantation performance. Considering the importance of low-frequency information for vowel identification, both traditional measures of residual hearing (i.e., pure-tone frequency threshold average at 500 Hz, 1000 Hz, and 2000 Hz) and a separate measure of low-frequency residual hearing (LF-PTA; i.e., pure-tone frequency threshold average of 250 Hz, 500 Hz, and 1000 Hz) at the better-hearing ear prior to implantation were obtained in the current study to assess the possible role of low-frequency residual hearing for vowel identification and speech recognition. These PTAs are displayed in Table 1.

Stimuli and Procedure

Vowel identification—The vowel stimuli were originally generated by Cleary (1996). Eight isolated steady-state sustained vowels, four acoustically dissimilar or “far” vowels (i.e., [i], [u], [A], and [æ]), and four acoustically similar or “near” vowels (i.e., [I], [ʊ], [ʌ], and [ɛ]) were created. Each vowel was edited from natural speech tokens obtained from one male speaker who produced the vowels in isolation. The recordings were made in a single-walled IAC sound booth using a Shure (SM98) microphone. A 16-bit analog-to-digital conversion of the speech was conducted using Tucker-Davis Technologies (TDT) System II equipment with a sampling rate of 22.05 kHz and an anti-aliasing filter of 10.4 kHz. The TDT system was controlled using a customized speech acquisition program (Dedina, 1987; Hernandez, 1995). For each vowel token, 300 ms of the sample was selected from the center of the original speech waveform. The first and last 50 ms of each sample were then ramped on and off to mimic the natural onset and offset of speech. The amplitude of each .wav file was then normalized to use 80% of the available bit space using SoundEdit16 (Version 2) software. Spectral analyses of the vowels were also conducted using Waves+ digital signal processing software (Entropic, San Diego, CA). Table 3 displays the formant frequencies for each of the eight vowel tokens obtained at approximately 145 ms after onset.

The results of the spectral analyses were used to assign the vowels into two distinct groups: vowels that were acoustically dissimilar (i.e., far vowels) and vowels that were acoustically similar (i.e., near vowels) in the vowel space. The formant frequencies were converted to Bark values using the following equation in radians from Zwicker and Terhardt (1980):

$$B = 13 \arctan(0.76f) + 3.5 \arctan(f/7.5)^2, \quad (1)$$

where f = frequency in kHz. The differences in the Bark values of F1 and F0 and of F3 and F2 for each of the vowels are plotted in Figure 1, adapted from Cleary (1996). The vowels were then assigned into two groups based on their acoustic similarity. From Figure 1, it can be observed that the vowels [i], [u], [A], and [æ] comprise the outer quadrilateral or far vowels, and [I], [ʊ], [ʌ], and [ɛ] comprise the inner quadrilateral or near vowels.

For the two sets of vowels (i.e., acoustically similar and acoustically distinct), the vowel stimuli were presented to the participants in a four-choice response format. All eight vowels were also presented to the participants using an eight-choice response format. These three listening tasks were presented using a Dell 1707 FPT computer monitor and a MacMini 1.42 GHz Power PC G4 computer. The software programming tool PsyScript 5.5d3 was used to generate all of the experimental tasks. The stimuli were presented to the listener at 65 dB SPL via two Advent AV570 speakers each placed at 45° azimuth.

Each vowel identification task consisted of two phases, a familiarization phase and a testing phase. In the first phase, participants were familiarized with the four vowel sounds for each of the two groups by selecting a word presented on the computer monitor in hVd format that corresponded to a particular vowel (i.e., *heed*, *who'd*, *hawd*, and *had* for the far vowels and *hid*, *hood*, *head*, and *hud* for the near vowels) while listening to the stimuli. Participants were allowed to listen to each vowel twice before proceeding to the test phase. During the test phase, the participants selected the hVd word that corresponded to the presented vowel token. A crosshair was presented in the center of the computer screen prior to each trial to prepare the listener for the upcoming stimulus presentation. Each vowel was presented over the loudspeaker four times in a random order during the test phase. No feedback was provided to the listeners. A percentage correct score was calculated from the raw scores and used as the dependent measure in the statistical analyses.

Speech perception—One 50-word list from the Consonant-Nucleus-Consonant (CNC) word recognition test (Peterson & Lehiste, 1962) was presented to all study participants in a sound-treated booth at 65 dB SPL. In addition, two lists containing 10 sentences each from the Hearing in Noise Test (HINT) sentence test (Nilsson, Soli, & Sullivan, 1994) were presented in quiet and in noise (i.e., +5 dB signal-to-noise ratio [SNR]), and participants were asked to repeat out loud the sentences they heard to the experimenter. The standard procedure for the HINT test (i.e., determining a sentence reception threshold in noise) was not used. The CNC word test was always administered first, followed by the HINT sentence test. All study participants were instructed to repeat the stimuli they heard, and guessing was encouraged. Percentage correct scores were obtained for both tests as the dependent measures.

Data Analyses

We used analysis of covariance (ANCOVA) and analysis of variance (ANOVA) repeated measures mixed-effect models to assess the relations among device use, chronological age, PTA, and LF-PTA on the vowel identification task and the two word recognition tasks. The ANCOVA and ANOVA models were carried out using SAS for Windows (Version 9.1). In addition, Pearson correlation coefficients were computed, using the SPSS software, to determine significant associations between the dependent and independent variables.

Results

Vowel Identification Results

The vowel identification results are presented in Figure 2. Percent correct identification is shown as a function of the test conditions (i.e., far vowels, near vowels, and all eight vowels). In this figure, and in the box plot figures that follow, the horizontal edges of each box represent the 25th and 75th percentiles, and the solid line within the box represents the median. The whiskers represent the 10th and 90th percentiles, and the solid circles show the suspected outliers. Analysis of the raw scores revealed that all of the participants (i.e., 40 out of 40) displayed better performance on the far-vowel condition than on the combined eight-vowel condition, and 35 out of the 40 participants performed better on the near-vowel condition than on the combined eight-vowel condition. Paired-samples *t* tests indicated that the mean vowel identification for the far-vowel set was significantly greater than both the near-vowel set, $t(40) = 7.78, p < .0001$, and the eight-vowel set, $t(40) = 15.04, p < .0001$. Effect sizes for these outcomes were large. Specifically, for the far-vowel and near-vowel comparison, the Cohen's *d* effect size was 1.38, and for the far-vowel and eight-vowel comparison, the Cohen's *d* effect size was 2.76. In addition, identification of the four near vowels was significantly better than identification of all eight vowels, $t(40) = 6.38, p < .0001$, with a Cohen's *d* effect size of 0.86.

Correlations among the vowel identification scores are shown in Figure 3. The top panel displays the correlation between the far-vowel and combined eight-vowel data, and the bottom panel shows the correlation for the near-vowel and the eight-vowel findings. Only a moderate correlation was observed for the results from the far-vowel and eight-vowel conditions (i.e., $r = .417, p = .007$). This outcome may be due to the ceiling effects that were found for the results from the far-vowel condition. A stronger correlation was found for the results from the near-vowel and combined eight-vowel identification tasks (i.e., $r = .675, p < .0001$).

Statistical Analyses: Vowel Identification Results

Tables 4, 5, and 6 provide the data generated from the ANOVA mixed-model analyses. The results from the far- and near-vowel identification tasks shown in Tables 4 and 5, respectively, revealed no significant differences in vowel identification between the two different device-type groups (i.e., CI alone and CI + HA). In addition, no other effects were indicated for any of the variables except for the PTA in the far-vowel condition, $F(1, 36) = 3.99, p = .05$. For this variable, the β estimate indicated that for every 1-dB increase in PTA, the identification of vowels in this condition deteriorated by 0.28%.

Analyses of the data presented in Table 6 for the eight-vowel condition indicated that adults who used bimodal stimulation (i.e., CI + HA) performed significantly better than adults who used the CI only, $F(1, 36) = 3.53, p = .02$. In addition, in this condition, main effects were observed for the PTA prior to implantation, $F(1, 36) = 4.57, p = .04$, and the age of the participant at testing, $F(1, 36) = 4.73, p = .04$. The β estimate indicated that for every 1-dB increase in PTA, performance declined by 0.41 percentage points, and for every 1-year increase in chronological age, performance decreased by 0.47 percentage points. These data

suggest that when listeners are forced to identify vowels under challenging acoustic conditions, their performance deteriorates, especially in older adults.

Analysis of Errors: Combined Eight-Vowel Task

A more detailed examination of the errors made in the combined eight-vowel condition is presented in Figure 4. This figure shows the percent correct identification for the acoustically similar and acoustically dissimilar vowels in the eight-vowel identification task. A one-way ANOVA revealed a highly significant difference in the means for the acoustically similar and acoustically dissimilar vowels, $F(1, 78) = 44.69, p < .0001$. In addition, identification of both the far vowels and the near vowels in the combined eight-vowel condition was significantly lower than identification of the four vowels in the far-vowel condition, $F(1, 78) = 34.0, p < .0001$, and the four vowels in the near-vowel condition, $F(1, 78) = 44.28, p < .0001$, when presented separately. The Cohen's d effect size between the far- and near-vowel outcomes within the combined eight-vowel condition was 1.49, which is similar to the effect size observed for these vowel identification conditions when presented individually (i.e., 1.38). Overall, these findings suggest that acoustic similarity has a negative impact on the ability to identify isolated vowels.

Speech Perception Results

Figure 5 displays the results from the speech perception tests. Percent correct word identification score is shown as a function of the type of test (i.e., CNC, HINT, HINT +5 SNR). Paired-samples t tests revealed significant differences between the means of the CNC and HINT tests in quiet results, $t(39) = -12.27, p < .0001$, and the HINT in quiet scores and the HINT sentences presented at a 5 dB SNR, $t(39) = 6.38, p < .0001$. No significant differences were observed between the means for the HINT +5 SNR scores and the CNC scores.

Statistical Analyses: Speech Perception Tests Results

For analyses purposes, the HINT scores were arcsine-transformed using the rationalized arcsine transform equation for small sets outlined in Sherbecoe and Studebaker (2004). ANCOVA mixed models revealed that the PTA prior to implantation affected the HINT in quiet scores, $F(1, 36) = 3.89, p = .05$, with every 1-dB decrement in PTA resulting in a 0.48 percentage point decrease in the HINT score. No other significant findings were revealed for the HINT analyses.

ANCOVA mixed-model analyses for the CNC results revealed significant differences between the unilateral CI recipients and the bimodal stimulation participants, $F(1, 36) = 3.61, p = .02$, when analyzing the outcomes using the model that included the PTA variable. Main effects revealed that the PTA, $F(1, 36) = 10.33, p = .003$, prior to implantation affected performance. For every 1-dB increase in PTA, the CNC scores decreased by 0.75 percentage points. However, when we analyzed the outcomes using the LF-PTA variable, significant overall differences in performance between the two experimental groups were not revealed. For this analysis, however, it was revealed that the LF-PTA prior to implantation affected performance, $F(1, 34) = 8.30, p = .007$. Additionally, an interaction between LF-PTA and the device was found, $F(1, 34) = 4.17, p = .05$, with this variable affecting the outcomes

from the bimodal users but not the unilateral CI recipients. The outcomes from the CNC analyses are provided in Tables 7 and 8.

Correlational Analyses: Speech Perception and Vowel Identification Scores

Pearson correlations using the CNC and vowel identification results are shown in Figure 6. Figure 7 shows the correlation results for the HINT in quiet and the HINT +5 SNR results with the vowel identification scores. The data shown in both figures demonstrate that as vowel identification becomes more challenging, the correlation between the speech perception scores and vowel identification becomes poorer. Specifically, strong correlations were found between the speech perception scores and the far-vowel identification scores ($r_s = .623-.673$). Moderate correlations were observed between the speech perception scores and the near-vowel identification scores ($r_s = .405-.417$), and even weaker correlations were observed between the speech perception scores and the performance on the eight-vowel task ($r_s = .203-.437$).

Discussion

The results obtained in this study suggest that as the acoustic properties of a group of vowels become more similar, vowel identification declines. Performance declined more for the acoustically confusable near-vowel condition compared with the acoustically dissimilar far-vowel condition, and the poorest performance was observed when listeners were asked to identify vowels from a group of eight vowels. In fact, all of the listeners performed more poorly on the combined eight-vowel task compared with the far-vowel identification task, and 35 of the 40 listeners performed more poorly on the eight-vowel condition compared with the near-vowel condition.

We found that age, the degree of residual hearing, and the use of an HA were all factors that contributed to performance in the specific listening conditions. Although we found that chronological age did not affect performance when participants identified vowels in the four-vowel acoustically distinct or acoustically similar conditions, we found age to have a significant effect when the participants identified vowels in the eight-vowel condition. It is clear that this more challenging vowel identification task taxed the individual listeners' processing resources, resulting in poorer performance for the same set of signals. In addition, the use of a contralateral HA also was related to the identification of vowels in the eight-vowel condition. Finally, the degree of residual hearing prior to implantation was related to performance on the acoustically similar vowel identification task and to the most challenging listening task (i.e., identification of vowels in the eight-vowel condition).

Acoustic Similarity and Aging

Our results provide evidence that the effects of aging, along with the acoustic properties of the signal, result in poorer performance for specific listening conditions in adults who use CIs. Specifically, older CI recipients showed poorer performance when they identified isolated vowels in the combined eight-vowel condition. These effects were observed despite the fact that no significant differences in hearing sensitivity were present among the participants, regardless of age. This finding replicates the earlier results of Schwartz et al.

(2008), who reported that older adults with normal hearing had poorer vowel identification than younger adults. They found that as the spectral features of vowels were degraded, vowel identification by older adults was poorer compared to the vowel identification by younger adults. It is possible, therefore, that with increasing age, temporal processing strategies are less effective, and retrieval of phonological representations in long-term memory is not as automatic as it is for younger adults.

Although not directly evaluated in this study, the ease of language understanding (ELU) model proposed by Ronnberg et al. (2008) may help to explain the findings associated with the perception of acoustically similar items for older adults who use CIs. Specifically, the ELU model proposes that an incoming multimodal speech signal consisting of phonological, semantic, syntactical, and prosodic cues will be automatically bound together within the central nervous system. During optimal listening conditions, the lexical representation of the signal will be immediately accessed in long-term memory via implicit automatic processing operations. Under more challenging listening conditions (e.g., acoustic confusions, use of an HA or a CI, aging), the information will not be automatically accessed in long-term memory, and a resultant mismatch can occur. When a mismatch occurs, the listener will need to predict and infer the meaning of the signal using explicit controlled processing and other sources of knowledge in long-term memory.

Using the ELU model as a framework, the present findings suggest that for all participants, the acoustic cues encoded in the degraded vowels were sufficiently confusable, forcing the listeners to make inferences about the vowels' identity based on their knowledge in long-term memory. With increasing age, these effects might become more apparent. Specifically, our data revealed that increasing age was a significant factor when listeners were asked to identify vowels in the combined eight-vowel task. This result might suggest that when the listening conditions become suboptimal, older CI recipients will have more difficulty compared to younger listeners accessing items due to poorer temporal processing, and consequently, more top-down knowledge-based inferences will be made about the incoming signals. Further work will be required, however, to demonstrate the validity of this theoretical framework and its application to the identification of acoustically similar speech items.

Bimodal Stimulation

In the most challenging listening condition, the combined eight-vowel identification task, the use of an HA significantly helped with identification. Most likely, the additional acoustic cues provided via the HA helped to increase the ease with which the vowels were identified in this listening condition. This finding supports previous findings that have suggested improved performance with the use of bimodal stimulation.

Better outcomes with the use of bimodal stimulation have been observed for a variety of listening tasks, including sentence recognition in noise; the perception of suprasegmental features of speech; the identification of vowels, consonants, words, syllable stress, and word emphasis; and the localization of sounds (Most, Harel, Shpak, & Luntz, 2011; Neuman & Svirsky, 2013; Perreau, Bentler, & Tyler, 2013; Potts, Skinner, Litovsky, Strube, & Kuk, 2009; Yoon et al., 2012; Zhang, Dorman, Fu, & Spahr, 2012). In addition, Yoon et al.

(2012) found that individuals who had aided PTAs ≥ 55 dB with their HAs had better outcomes on the vowel feature analyses (i.e., F1 height, F2 place, and duration) compared with individuals who had aided PTAs < 55 dB. Finally, it has been found that performance on some tasks can be improved through auditory training (Zhang et al., 2012). Specifically, Zhang et al. (2012) discovered that after 4 weeks of training (60 min per day for 5 days per week), individuals improved their performance on the identification of vowels, consonants, and sentences, and these improvements were sustained for 1 month following training.

Unlike the studies discussed above, which used a within-subject design, the current study was performed using a between-subject design. By examining performance using the everyday devices and settings, we demonstrated that the spectral information provided via an HA is capable of improving performance in challenging listening conditions across participants. Our results, therefore, extend the findings outlined above by demonstrating that for challenging listening tasks, the use of an HA in conjunction with a CI is beneficial.

Degree of Residual Hearing

Previous research has found that individuals with a greater degree of residual hearing prior to implantation perform better on a wide range of speech perception tasks compared with individuals with less residual hearing (Francis, Yeagle, Bowditch, & Niparko, 2005; Gantz, Woodworth, Knutson, Abbas, & Tyler, 1993; Gomaa, Rubinstein, Lowder, Tyler, & Gantz, 2003). Additionally, several researchers have examined the role of low-frequency residual hearing prior to implantation on speech perception performance (Ching, Incerti, & Hill, 2004; Gifford, Dorman, McKarns, & Spahr, 2007). Considering the importance of residual hearing prior to implantation for vowel identification, both conventional measures of residual hearing (i.e., pure-tone frequency threshold average at 500 Hz, 1000 Hz, and 2000 Hz) and an additional measure of low-frequency residual hearing (i.e., pure-tone frequency threshold average of 250 Hz, 500 Hz, and 1000 Hz) were obtained in the current study.

In agreement with previous work, the present results revealed that the degree of residual hearing prior to implantation affected word identification skills and the identification of acoustically similar and dissimilar vowels. In addition, our results suggest that the degree of residual hearing at 250 Hz was particularly important for identification of the CNC words (see Tables 7 and 8).

As mentioned previously, Yoon et al. (2012) demonstrated that better aided PTA resulted in better performance. To understand the importance of aided hearing for the identification of acoustically similar items, therefore, future studies should examine how aided PTA affects speech perception. It is suspected, based on the previous findings from Yoon et al., that individuals with better aided PTAs will have better vowel identification than individuals with poorer aided PTAs.

Vowel Identification and Word Recognition

The results from the vowel identification and word recognition tasks revealed that as the vowels became more acoustically confusable, the correlations between word and vowel identification became weaker. Specifically, the correlations of the acoustically dissimilar

vowels with the word recognition scores were quite strong ($r_s = .62$ and better). However, as the vowels became more acoustically confusable (i.e., near vowels and all eight vowels), the correlation between the results for the vowel and word recognition tasks became weaker. It is unclear why the correlation between word identification and vowel perception became poorer as the vowels became more acoustically confusable. Perhaps the poorer coding of the vowel spectral cues at the periphery, the poorer processing of these spectral cues through the auditory pathway, or a combination of these factors might have contributed to these weaker correlations.

Conclusions

The results of this study with 40 adults who use CIs suggest that the acoustic similarity of isolated vowels affects vowel identification performance and is correlated with measures of spoken word recognition in isolation and in sentences. Under the most challenging listening condition (i.e., identification of all eight vowels), older CI recipients experienced more difficulties identifying acoustically confusable isolated vowels than their younger counterparts. The use of a contralateral hearing aid also affected word and vowel identification performance in the combined eight-vowel condition. In addition, the degree of residual hearing prior to implantation affected vowel identification (i.e., acoustically dissimilar vowels and combined eight-vowel task) and word recognition (i.e., HINT in quiet and CNC test). Finally, moderate correlations were found between word recognition—in both isolation (i.e., CNC data) and sentences (i.e., HINT data)—and vowel identification, suggesting close associations between acoustic-phonetic similarity and the processing operations used in spoken word recognition. Weaker correlations were observed between word recognition and the eight-vowel identification task. Further work is required to understand this poorer correlation between word recognition and vowel identification.

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Figure 1.

The differences in the Bark values of F1 and F0 and of F3 and F2 for each of the vowels are plotted (adapted from Cleary, 1996). Two groups of vowels are displayed based on their acoustic similarity. The vowels [i], [u], [α], and [æ] comprise the outer quadrilateral or “far vowels,” and [ɪ], [ʊ], [ʌ], and [ɛ] comprise the inner quadrilateral or “near vowels.”

Figure 2.

Vowel identification results. The percent correct identification is shown as a function of the vowel group (i.e., far, near, all). The horizontal edges of each box represent the 25th and 75th percentiles, and the solid line within the box represents the median. The whiskers represent the 10th and 90th percentiles, and the solid circles show the suspected outliers.

Figure 3.

Pearson correlation results for the vowel identification tasks. Top panel: Correlation data for the results from the acoustically dissimilar vowel listening task with the results from the combined eight-vowel listening task. Bottom panel: Correlation data for the acoustically similar vowel identification task and the combined eight-vowel task. Within each panel, the solid circles represent individual data points, and the solid line is the linear regression line through the data.

Figure 4.

The percent correct identification for the acoustically similar and acoustically distinct vowels that comprised the eight-vowel identification task. The horizontal edges of each box represent the 25th and 75th percentiles, and the solid line within the box represents the median. The whiskers represent the 10th and 90th percentiles, and the solid circles show the suspected outliers.

Figure 5.

Box plots displaying the results from the Consonant-Nucleus-Consonant (CNC) and Hearing in Noise Test (HINT) word recognition tests in quiet (Q) and +5 signal-to-noise ratio [+5]). The horizontal edges of each box represent the 25th and 75th percentiles, and the solid line within the box represents the median. The whiskers represent the 10th and 90th percentiles, and the solid circles show the suspected outliers.

Figure 6.

Pearson correlation results for the CNC word recognition task and the vowel identification task. Left panel: Correlation data for the results from the CNC test and the acoustically dissimilar vowel listening task. Middle panel: Correlation data for the CNC results and the acoustically similar vowel identification task. Right panel: Correlation data for the CNC results and the combined eight-vowel listening task. Within each panel, the solid circles represent individual data points, and the solid line is the linear regression line through the data.

Figure 7.

Pearson correlation results for the HINT sentences and the vowel identification tasks. Top panels (left to right): Correlation results for the HINT in quiet results and the results from the far-vowel, near-vowel, and combined eight-vowel listening tasks. Bottom panels (left to right): Correlation data for the HINT +5 SNR results and the results from the far-vowel, near-vowel, and combined 8-vowel listening tasks. Within each panel, the solid circles represent individual data points, and the solid line is the linear regression line through the data.

Table 1

Demographics for cochlear implant (CI) recipients.

Participant ID	Age at testing (years)	Implant model	Duration of CI use (years)	PTA (dB HL)	LF-PTA (dB HL)
AAX1	30.4	N24-CI24RE (CA)	2.1	112	98
ABW1	38.5	N24-CI24RE (CA)	0.6	95	97
ABS1	43.7	N24-CI24RE (CA)	2.6	100	87
ABQ1	44.8	N24-CI24RE (CA)	0.6	83	73
ABF1	48.4	ME-Combi 40+ H	4.4	80	80
AAP1	48.9	N22-CI22M	15.6	120	120
ABE1	48.9	N24-CI24RE (ST)	2.5	77	52
AAV1	49.7	N22-CI22M	17.4	110	98
ABH1	52.4	N24-CI24R (CA)	3.2	97	98
AAK1	52.5	N24-CI24R (CS)	3.9	112	117
AAG1	54.7	N24-CI24R (CS)	4.9	105	83
ABV1	54.8	N24-CI24RE (CA)	2.1	80	82
AAV1	55.3	N24-CI24M	10.1	105	83
AAN1	56.3	N24-CI24R (CS)	4.2	92	92
AAU1	57.6	N24-CI24RE (CA)	0.9	100	88
ABN1	57.7	CL-HiRes 90K	2.6	92	83
AAM1	58.0	ME-Combi 40+ H	2.7	100	82
ABA1	59.7	N24-CI24R (CS)	5.8	87	73
ABD1	59.7	CL-HiRes 90K	2.9	78	55
AAS1	61.1	ME-Combi 40+ H	3.5	107	97
ABU1	61.7	CL-HiRes 90K	2.9	108	107
ABO1	62.7	N24-CI24RE (CA)	1.7	108	87
ABL1	64.4	N24-CI24R (CS)	4.9	90	90
ABI1	64.5	N24-CI24RE (CA)	2.1	110	108
ABG1	64.8	ME-Combi 40+ H	3.1	93	93
AAW1	66.9	N24-CI24RE (CA)	1.2	92	90
AAQ1	68.7	CL-HiFocus	7.1	95	83
ABM1	69.6	N24-CI24RE (CA)	2.6	88	60
ABC1	70.4	N24-CI24RE (CA)	1.2	82	55
ABJ1	70.4	N24-CI24RE (CA)	0.5	105	105
ABR1	70.7	CL-HiRes 90K	2.3	113	108
ABT1	71.0	CL-HiRes 90K	1.2	107	97
AAD1	72.7	ME-Combi 40+ H	2.4	87	62
ABB1	73.5	ME-Combi 40+ HS	7.2	93	73
ABK1	73.7	ME-Combi 40+ H	8.0	78	72
AAL1	73.8	N24-CI24RE (CA)	0.7	62	33
AAR1	74.2	N24-CI24M	9.2	98	77
AAT1	77.4	N24-CI24RE (CA)	3.8	107	82
AAH1	80.8	N24-CI24R (CS)	5.4	108	102

Participant ID	Age at testing (years)	Implant model	Duration of CI use (years)	PTA (dB HL)	LF-PTA (dB HL)
AAO1	81.8	ME-Combi 40+ H	3.0	77	80
<i>M</i>	61.17		4.2	95.8	84.7
<i>SD</i>	11.58		3.71	13.15	18.45

Note. CI = cochlear implant; PTA = pure-tone average; LF = low frequency.

Table 2

Participants' sound field audiometric thresholds.

Participant ID	Age	250 Hz	500 Hz	1000 Hz	2000 Hz	3000 Hz	4000 Hz
AAX1	30.4	16	24	22	18	26	28
ABW1	38.5	28	30	24	30	34	24
ABS1	43.7	35	30	10	25	25	25
ABQ1	44.8	15	25	25	30		25
ABF1	48.4	14	22	20	22	26	22
AAP1	48.9	32	30	36	40		42
ABE1	48.9	20	25	15	15	30	30
AAV1	49.7	36	42	40	36		40
ABH1	52.4	42	48	38	32		32
AAK1	52.5	25	25	25	20	25	20
AAG1	54.7	18	30	24	24		22
ABV1	54.8	25	40	30	25		30
AAV1	55.3						
AAN1	56.3	30	40	35	30	30	35
AAU1	57.6	22	20	16	20	22	24
ABN1	57.7	40	30	25	35	50	50
AAM1	58.0	20	30	25	25		30
ABA1	59.7	18	20	20	17	15	15
ABD1	59.7	28	36	34	28		34
AAS1	61.1	20	24	20	24	26	24
ABU1	61.7	40	20	25	25		30
ABO1	62.7	30	35	30	35		40
ABL1	64.4	40	40	35	25	40	30
ABI1	64.5	22	36	26	26	26	30
ABG1	64.8	25	30	25	25	25	35
AAW1	66.9	24	30	30	28	28	36
AAQ1	68.7	28	22	22	24	32	36
ABM1	69.6	12	24	24	20	26	28
ABC1	70.4	26	32	30	30		30
ABJ1	70.4	30	30	25	30	30	20
ABR1	70.7	24	30	25	18	30	30
ABT1	71.0	30	35	35	20	25	25
AAD1	72.7	20	32	30	26		36
ABB1	73.5	25	35	35	35	40	35
ABK1	73.7	35	30	20	35	45	35
AAL1	73.8	35	45	45	50		50
AAR1	74.2	34	44	35	32		30
AAT1	77.4	15	35	25	20		25
AAH1	80.8	30	36	34	32	36	38

Participant ID	Age	250 Hz	500 Hz	1000 Hz	2000 Hz	3000 Hz	4000 Hz
AAO1	81.8	16	28	18	22	22	22
<i>M</i>	61.17	26.28	31.28	27.13	27.03	29.75	30.59
<i>SD</i>	11.58	8.07	7.17	7.44	7.09	7.85	7.70

Note. Cells in the AAV1 row are blank because testing of AAV was not conducted due to time constraints.

Table 3

Fundamental and formant frequencies for vowel stimuli (in Hz; adapted from Cleary, 1996).

Vowel (as in)	F0	F1	F2	F3
[i] <i>heed</i>	130	263	2206	3071
[u] <i>who'd</i>	138	287	771	2290
[æ] <i>had</i>	124	634	1767	2613
[ɑ] <i>hawd</i>	127	604	924	2662
[ʌ] <i>hud</i>	125	604	1257	2670
[ɛ] <i>head</i>	124	609	1655	2458
[ɪ] <i>hid</i>	131	364	1922	2586
[o] <i>hood</i>	134	438	1101	2470

Table 4

Analyses of variance (ANOVAs) for identification of acoustically distinct vowels.

Variable	LS mean	df	F	Probability	β estimate	SE	t (probability)
$R^2 = .11$, power = 0.08							
Device							
CI + HA	95.00	36	1.44	0.25			
Unilateral	93.44						
Main effects							
Device		1	0.20	0.66			
PTA		1	3.99	0.05*			
Test age		1	0.99	0.33			
Parameters							
Device					1.56	3.53	0.44 (0.66)
PTA					-0.28	0.14	-2.00 (0.05)*
Test age					-0.16	0.16	-0.99 (0.33)
$R^2 = .02$, power = 0.06							
Device							
CI + HA	94.72	36	0.27	0.85			
Unilateral	93.72						
Main effects							
Device		1	0.07	0.79			
LF-PTA		1	0.52	0.48			
Test age		1	0.38	0.54			
Parameters							
Device					1.00	3.70	0.27 (0.79)
LF-PTA					-0.07	0.10	-0.72 (0.48)
Test age					-0.10	0.16	-0.62 (0.54)

Note. LS = least squares.

*
 $p = .05$.

Table 5

ANOVAs for identification of acoustically similar vowels.

Variable	LS mean	df	F	Probability	β estimate	SE	t (probability)
$R^2 = .09$, power = 0.16							
Device							
CI + HA	75.44	36	1.15	0.34			
Unilateral	69.25						
Main effects							
Device		1	0.91	0.35			
PTA		1	2.63	0.11			
Test age		1	0.57	0.46			
Parameters							
Device					6.19	6.48	0.96 (0.35)
PTA					-0.42	0.26	-1.62 (0.11)
Test age					-0.22	0.29	-0.76 (0.46)
$R^2 = .06$, power = 0.13							
Device							
CI + HA	74.85	36	0.75	0.53			
Unilateral	69.84						
Main effects							
Device		1	0.58	0.45			
LF-PTA		1	1.46	0.23			
Test age		1	0.35	0.56			
Parameters							
					5.01	6.60	0.76 (0.45)
Device					-0.22	0.18	-1.21 (0.23)
LF-PTA					-0.17	0.29	-0.59 (0.56)
Test age					5.01	6.60	0.76 (0.45)

Table 6

ANOVAs for the eight-vowel condition.

Variable	LS mean	df	F	Probability	β estimate	SE	t (probability)
$R^2 = .23$, power = 0.10							
Device							
CI + HA	62.16	36	3.53	0.02*			
Unilateral	51.74						
Main effects							
Device		1	4.58	0.04*			
PTA		1	4.57	0.04*			
Test age		1	4.73	0.04*			
Parameters							
Device					10.42	4.87	2.14 (0.04)*
PTA					-0.41	0.19	-2.14 (0.04)*
Test age					-0.47	0.22	-2.17 (0.04)*
$R^2 = .18$, power = 0.49							
Device							
CI + HA	61.59	36	2.67	0.06			
Unilateral	52.31						
Main effects							
Device		1	3.41	0.07			
LF-PTA		1	2.32	0.14			
Test age		1	3.69	0.06			
Parameters							
Device					9.28	5.02	1.85 (0.07)
LF-PTA					-0.21	0.14	-1.52 (0.14)
Test age					-0.42	0.22	-1.92 (0.06)

*
 $p = .05$.

Table 7

Analyses of covariance (ANCOVAs) for the CNC test.

Variable	LS mean	df	F	Probability	β estimate	SE	t (probability)
$R^2 = .23$, power = 0.09							
Device							
CI + HA	68.94	36	3.61	.02*			
Unilateral	72.12						
Main effects							
Device		1	0.29	.59			
PTA		1	10.33	.002**			
Test age		1	0.67	.42			
Parameters							
Device					-3.17	5.87	-0.54 (0.59)
PTA					-0.75	0.23	-3.21 (0.002)**
Test Age					-0.22	0.26	-0.82 (0.42)
$R^2 = .23$, power = 0.16							
Device							
CI + HA	67.41	34	1.99	.11			
Unilateral	72.97						
Main effects							
Device			2.97	.09			
LF-PTA			8.30	.007**			
Test age			0.57	.46			
LF-PTA $\times$ Device			4.17	.05			
Test Age $\times$ Device			0.80	.38			

*
 $p = .05$.**
 $p < .001$.

Table 8

ANCOVAs for the CNC test: Slopes (device).

Variable	<i>df</i>	<i>F</i>	Probability	<i>R</i> ²	β estimate	<i>SE</i>	<i>t</i> (probability)
CI + HA							
Overall model	1	4.28	0.03	.33			
Main effects							
LF-PTA	1	8.46	0.01*				
Test age	1	1.07	0.31				
Parameters							
LF-PTA					-0.91	0.31	-2.91 (0.01)*
Test age					-0.46	0.44	-1.03 (0.31)
Unilateral							
Overall model	1	0.34	0.72	.04*			
Main effects							
LF-PTA	1	0.60	0.45				
Test age	1	0.01	0.91				
Parameters							
LF-PTA					-0.16	0.20	-0.77 (0.45)
Test age					0.04	0.34	0.12 (0.91)

*
p = .05.