Vowel Intelligibility in Clear and Conversational Speech for Cochlear Implant Users: A Preliminary Study

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This preliminary study examined vowel intelligibility in clear and conversational speech in 3 cochlear implant users. Monosyllabic words excised from sentences spoken clearly and conversationally by a single male talker were presented in quiet to 3 adult cochlear implant users for vowel identification. In a previous study (Ferguson & Kewley-Port, 2002), vowel intelligibility in noise was significantly higher in clear speech for young listeners with normal hearing; older adults with hearing loss, in contrast, showed no clear speech benefit for vowel identification in noise. In the present study, while 1 of the 3 implant users showed a clear speech benefit for vowel identification of 30 percentage points, vowel intelligibility scores in clear and conversational speech were within 2 percentage points of each other for the other 2 listeners. The intelligibility pattern for individual vowels in clear versus conversational speech also varied among the 3 cochlear implant users and differed from those observed in listeners with normal and impaired hearing identifying the same materials. These results suggest that the specific clear speech acoustic changes that lead to improved speech intelligibility for cochlear implant users may differ from those that are helpful for other listener groups. Further research is needed to determine which clear speech modifications provide an intelligibility benefit for cochlear implant users.

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"Clear speech" is one of several communication strategies that can improve communication for people with hearing loss (Crandell & Smaldino, 2002). Clear speech refers to a specific speaking style that occurs when a talker is told to speak as though conversing with a person with hearing loss (Ferguson & Kewley-Port, 2002). Several studies have shown that when talkers attempt to speak in a clear manner, definite changes to the pattern of their speech are produced. These changes result in a significant improvement in speech understanding by a variety of listener populations, including listeners with hearing impairment. If speech communication is viewed as a mutual event between a talker and a listener, clear speech can be considered a talker-driven communication strategy that the communication partners of listeners with hearing impairment can use to reduce speech perception difficulties. In contrast, other options, including assistive listening devices, speechreading, and environmental management, can be considered listener-driven strategies.

In a study measuring the clear speech effect (i.e., the intelligibility difference between ordinary conversational speech and clear speech) for sentence materials, Picheny, Durlach, and Braida (1985) reported a 17-percentage-point clear speech benefit for adults with hearing loss. The nonsense sentences recorded by Picheny et al. (1985) have been used in other clear speech studies with listeners with normal and impaired hearing, yielding similar results. For example, using sentences produced by one of the three talkers, Payton, Uchanski, and Braida (1994) found a clear speech benefit of 20 percentage points for listeners with normal hearing and 26 percentage points for listeners with hearing impairment under degraded listening conditions. Uchanski, Choi, Braida, Reed, and Durlach (1996), using all three talkers' speech materials from Picheny et al. (1985), found an average clear speech benefit of 16 percentage points for listeners with normal hearing in noise and 15 percentage points for listeners with hearing impairment in quiet. Studies using meaningful sentences have also shown clear speech benefits (Gagné, Querengesser, Folkeard, Munhall, & Masterson, 1995; Schum, 1996).

Clear speech studies have also been conducted using materials other than sentences. For example, Gagné, Masterson, Munhall, Bilida, and Querengesser (1994) used monosyllabic and bisyllabic words produced in isolation. The average clear speech benefit for listeners with normal hearing in a simulated sensorineural hearing loss condition was approximately 7 percentage points, which is smaller than the benefit found in previous studies using sentences. This finding was attributed to the absence of linguistic and contextual cues in isolated word stimuli as compared to sentences. More recently, Ferguson and Kewley-Port (2002) assessed vowel intelligibility in clear and conversational speech using words excised from sentences. In their experiment, both older listeners with hearing impairment and young listeners with normal hearing identified vowels in monosyllabic words presented in 12-talker babble. While no benefit was found for the listeners with hearing impairment, a 15 percentage point clear speech vowel intelligibility benefit was observed for the listeners with normal hearing. This result contrasted with studies showing similar clear speech intelligibility benefits for listeners with normal hearing and listeners with hearing impairment (e.g., Payton et al., 1994).

Ferguson and Kewley-Port (2002) explained this surprising result in terms of an interaction between the acoustic characteristics of vowels in clear speech and the high-frequency hearing losses of the listeners with hearing impairment. Compared to vowels in conversational speech, vowels in clear speech were longer in duration, consistent with earlier studies (e.g., Picheny, Durlach, & Braida, 1986). In addition, front vowels in clear speech had higher second formant (F2) values, while back vowels had lower F2 values, consistent with an expanded vowel space in clear speech. Regression analyses showed that only the front vowel F2 increase, and not the back vowel F2 decrease or the duration increase, was actually associated with the clear vowel intelligibility speech benefit for listeners with normal hearing. This suggested that not all clear speech acoustic features actually play a role in improving speech intelligibility. Furthermore, regression analyses for the older listeners with hearing impairment suggested that the front vowel F2 increase actually made the front vowels *less* intelligible in clear speech than in conversational speech. Because the listeners had high-frequency hearing loss, it appeared that raising F2 made the front vowels less audible in clear speech. The negative clear speech effect for front vowels (-10 percentage points) canceled the positive effect for back vowels (9 percentage points), consequently producing a zero overall clear speech vowel intelligibility effect. This finding suggested that the acoustic cues that make vowels more intelligible in clear speech might differ for populations of listeners with different hearing characteristics.

Cochlear implant users are another interesting listener population to be explored with respect to the clear speech effect. Many studies have demonstrated that cochlear implants deliver a wide range of improvement in speech perception performance. However, ultimately, the electrical hearing provided by a cochlear implant is very different from the acoustical hearing enjoyed by listeners with normal hearing. One important difference is the number of channels available for processing frequency information. Using a cochlear implant simulation, Friesen, Shannon, Baskent, and Wang (2001) showed that the performance of listeners with normal hearing improved as the number of channels increased to about 20. In contrast, the performance of actual cochlear implant users reached plateau at only four to seven channels. To date, only one published study has investigated the clear speech effect for cochlear implant users (Liu, Del Rio, Bradlow, & Zeng, 2004). While the results suggested that cochlear implant users benefit from clear speech in sentence identification, no data are available describing phoneme intelligibility in clear and conversational speech for this population. The goal of the current preliminary study was to assess the intelligibility of vowels in clear and conversational speech spoken by a single talker for cochlear implant users. The clear speech vowel intelligibility effect for three cochlear implant users was compared to that observed for other listener populations in an earlier investigation using the same materials (Ferguson & Kewley-Port, 2002).

METHODS

Listeners

Three postlingually deafened adult (61-73 years) users of Nucleus multichannel cochlear implants participated in this experiment. All listeners had at least 1 year of experience utilizing the SPEAK processing strategy and showed sentence recognition scores of approximately 90%. Demographic information about each listener is shown in Table 1. It should be noted that Listeners 1 and 2 each were initially implanted in the right ear, but stopped using these implants after receiving a new implant in the left ear. All listeners were informed of the study in detail and signed a consent form prior to testing. All procedures were reviewed and approved by a university Human Subjects Review committee.

Materials

Stimuli were 200 words consisting of 10 vowels (/i/, /ɪ/, /e/, /ɛ/, /æ/, /ɑ/, /ʌ/, /o/, /ʊ/, /u/) in /bVd/ context. These words were previously used by Ferguson and Kewley-Port (2002). Each word (e.g., bead, bid, bade) was originally centered in 1 of 12 neutral carrier sentences for recording. The test sentences were spoken

Table 1

Demographic Information for the Three Listeners

Listener	1	2	3
Age	61	62	73
Gender	Male	Female	Female
Etiology of hearing loss	Hereditary	Unknown	Otosclerosis
Age of onset of hearing loss	14	39	26
Age of onset of deafness	42	42	45
Age at implantation	47	47	48
Implanted ear	Left	Left	Left
Device	Nucleus N22	Nucleus 24	Nucleus N22
Processor	Esprit 3G	SPRINT	Esprit 3G
Processing strategy	SPEAK	SPEAK	SPEAK
Active electrodes	17	20	20
Sentence recognition score	86%[a]	92%[b]	92%[b]

[a]For recorded sentences from the Hearing in Noise Test (HINT; Nilsson, Soli, & Sullivan, 1994) presented at 70 dB SPL in quiet. [b]For recorded Bamford-Kowal-Bench (BKB) sentences (Bench, Kowal, & Bamford, 1979) presented at 70 dB SPL in quiet.

by a 59-year-old male audiologist who had extensive experience communicating with individuals with hearing impairment.

The sentences were recorded to digital audio tape, then low-pass filtered (8500 Hz) and digitized (16-bit A/D, 22050 Hz sampling rate). The /bVd/ test words were excised from the sentences using sound editing software (Cool Edit 96). Of the 200 test words, 100 were recorded under instructions to speak conversationally. For the other 100 words, the talker was instructed to speak as though he were talking to a person with hearing loss. The 100 test words in each speaking style corresponds to 10 tokens of each of the 10 vowels. To eliminate amplitude differences among vowels and between the two speaking styles, the average RMS amplitude was calculated across all test items. All test items were then scaled to this average amplitude using MATLAB. For the current experiment, test stimuli were resampled to a sample rate of 24414.125 Hz.

When Ferguson and Kewley-Port (2002) presented these materials to normal-hearing listeners in a background of 12-talker babble (signal-to-babble ratio [S/B] = -10 dB), vowels extracted from clear speech were significantly more intelligible than those extracted from conversational speech. They also reported significant acoustic differences between the clear and conversational vowels. The value of the first formant (F1), the amount of dynamic formant movement, and vowel duration were all significantly greater in clear speech than in conversational speech. The second formant (F2) was significantly higher in clear speech for front vowels (/i/, /ɪ/, /e/, /ɛ/, /æ/) and significantly lower in clear speech for back vowels.

Procedure

Listeners were tested individually in a double-wall sound-treated booth, seated in front of a computer monitor and keyboard. Test stimuli were presented in the sound field, via a speaker situated at approximately 45° azimuth on the side of the listener's implanted ear, that is, to the left. On each trial, a test word was played out by a Tucker-Davis Technologies (TDT) RP2.1 Enhanced Real-Time Processor. Test words were then attenuated (TDT PA5) to an overall presentation level of 70 dB SPL (measured at the position of the center of the listener's head). During the experiment, a list of 10 response categories was presented on the computer monitor. On each trial, the listener identified which vowel he or she heard by clicking on the response category corresponding to that vowel. Response categories corresponding to 10 vowels (/i/, /ɪ/, /ɵ/, /ɛ/, /æ/, /ɑ/, /ʌ/, /o/, /ʊ/, /u/) were presented on the computer monitor as keywords: (a) feet, thief, bead; (b) sit, rib, bid; (c) tape, raid, bade; (d) head, said, bed; (e) back, mass, bad; (f) pot, sod, bod; (g) cup, rug, bud; (h) rode, own, bode; (i) would, should, book; and (j) rude, news, booed.

For each listener, testing was completed in one 2-hour test session. Before experimental testing, listeners were familiarized with the vowel identification task

Table 2

Mean Percent Correct Vowel Intelligibility in Clear (CL) and Conversational (CON) Speech, and the Percentage Point Difference Between the Two Styles (DIFF) for Individual Listeners

Listener	CL	CON	DIFF
1	57.0	87.0	30.0
2	81.0	79.3	-2.0
3	79.0	80.0	1.0

through face-to-face training with feedback. Next, a 40-trial familiarization block of clear vowel tokens was presented with feedback at a comfortable sound level. For intelligibility testing, the 200 test stimuli were presented three times, producing 600 test trials divided into 6 blocks of 100 trials. Stimuli were randomized within each block and each listener received the 6 test blocks in random order. Feedback was not given during the test blocks.

RESULTS

Overall vowel intelligibility for each listener in each speaking style was obtained by averaging the percent correct scores of three blocks of 100 test stimuli in each style. These overall scores are presented in Table 2, along with the percentage point difference score (clear minus conversational) for each listener. Prior to statistical analysis, percent correct scores for individual vowels in each test block were converted to rationalized arcsine units (RAUs; Studebaker, 1985). The effects of listener, speaking style, and vowel were analyzed in a three-way repeated-measures analysis of variance (ANOVA) using Statistica (Statsoft, Inc., 2003).

All three main effects were significant [speaking style: $F(1, 60) = 22.08$, $p < .001$; vowel: $F(9, 60) = 12.6$, $p = .0001$; listener: $F(2, 60) = 4.63$, $p < .05$]. Averaged over the three listeners, vowels in clear speech were more intelligible than vowels in conversational speech, by an average of 9.8 percentage points. Overall intelligibility scores also varied among the vowels and among the three listeners. The speaking style by vowel interaction was significant [$F(9, 60) = 11.32$, $p = .0001$], indicating that the size of the clear speech benefit varied among the vowels. More interesting, however, are the two- and three-way interactions involving the listener factor. As Figure 1 illustrates, the style by listener interaction was significant [$F(2, 60) = 25.50$, $p < .001$]. While Listener 1, who showed the poorest performance in conversational speech among the three listeners, enjoyed a large clear speech vowel intelligibility benefit (30 percentage points, as seen in Table 2), the other two listeners showed essentially no effect of speaking style. Thus the significant clear speech benefit for vowels observed in this preliminary study of cochlear implant users can be attributed to the results of a single listener.

The significant three-way style by listener by vowel interaction [$F(19, 60) = 2.8$, $p < .01$], furthermore, suggests that the clear speech effect for individual vowels varied among the three listeners. This interaction is evident in Figure 2, which shows the intelligibility of individual vowels in clear and conversational speech for each listener. For Listener 1, the only listener to show an overall clear speech vowel intelligibility benefit, all but two vowels (the front vowel /ɪ/ and the back vowel /ʊ/) were more intelligible in clear speech. Listeners 2 and 3, who showed essentially no overall clear speech intelligibility effect, showed intelligibility patterns for individual vowels that were similar to each other, but quite different from Listener 1. For these two listeners, the front vowels /ɪ/ and /ɛ/ and the back vowel /ʌ/ were less intelligible in clear speech than in conversational speech. These negative clear speech effects apparently cancelled the clear speech benefit observed for other vowels (/i/, /ɛ/, /ʊ/, and /u/), yielding an overall clear speech effect of zero for these listeners.

DISCUSSION

The first goal of this study was to examine, in a very preliminary manner, whether vowels in clear speech are more intelligible than vowels in conversational speech for cochlear implant users. When averaged across the three listeners, the clear speech benefit for vowels was 9.8 percentage points. Averaging

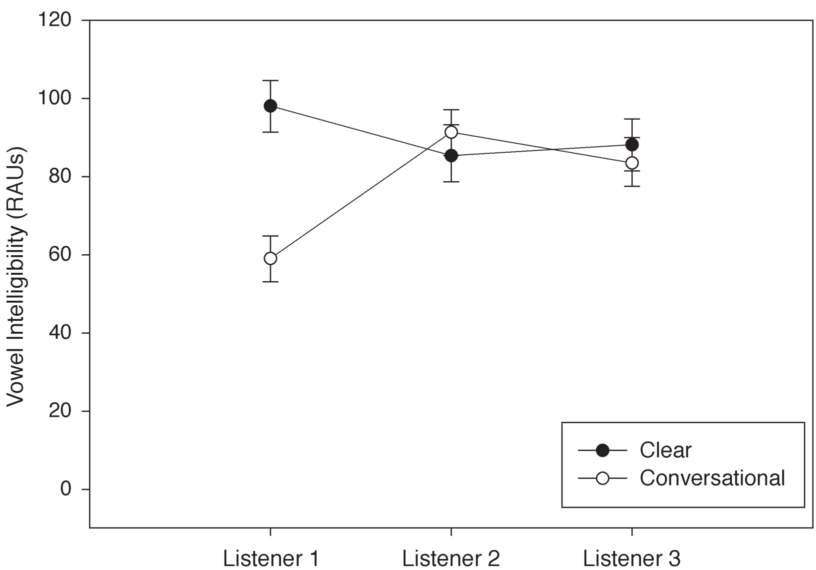

Figure 1. Mean overall vowel intelligibility in rationalized arcsine units (RAUs) for individual listeners. Error bars indicate 95% confidence intervals.

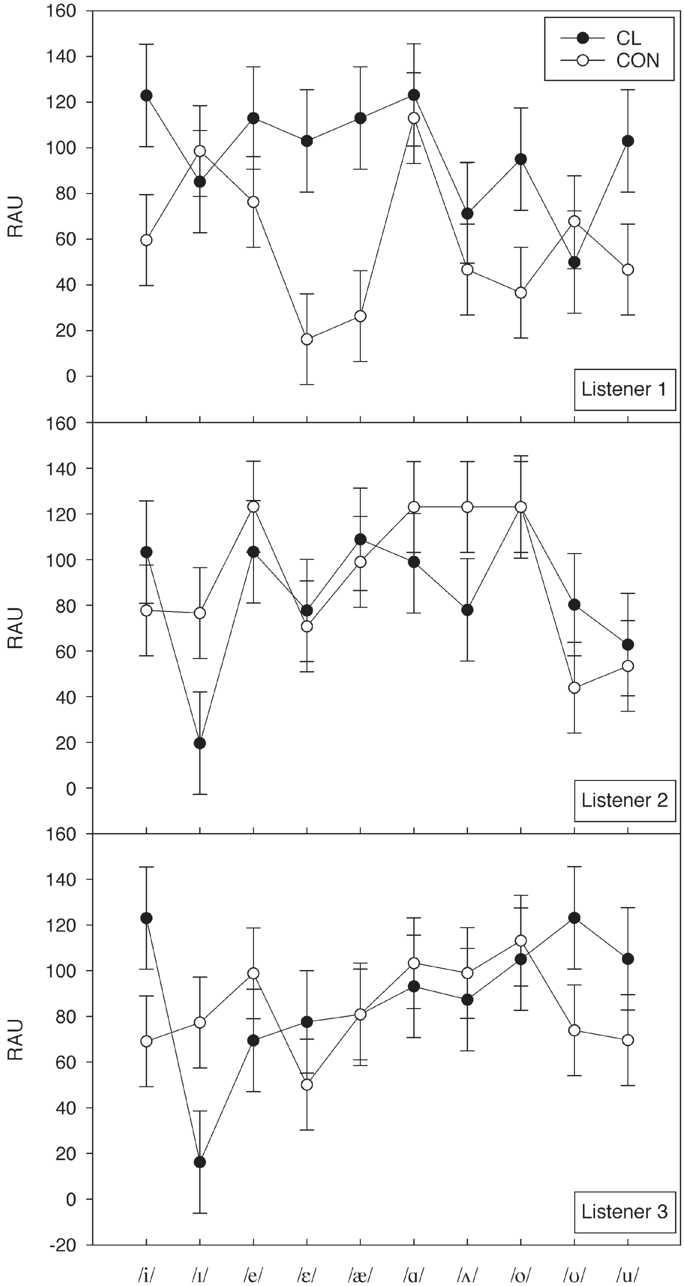

Figure 2. Intelligibility scores for individual vowels in rationalized arcsine units (RAUs) for individual listeners. Error bars indicate 95% confidence intervals.

performance in this way obscures a more important result, however: the clear speech benefit for vowels differed considerably among the three cochlear implant users. Listener 1 showed a clear speech advantage of 30 percentage points, while Listeners 2 and 3 showed negligible speaking style effects (-2 and 1 percentage points, respectively). These results can be compared to the clear speech benefit that Liu et al. (2004) found using sentence materials for 8 adult cochlear implant users. They reported an average 37.8 percentage point clear speech benefit for listeners who used a variety of processors and coding strategies and who identified sentences at a variety of signal-to-noise ratios. Examination of the bottom panel of Figure 8 from Liu et al. (2004), however, suggests that in quiet, the clear speech intelligibility advantage enjoyed by the cochlear implant users varied.

The current data can also be compared to those of Ferguson and Kewley-Port (2002), who presented identical speech materials in a background of 12-talker babble to 9 listeners with normal hearing (S/B = -10 dB) and to 9 listeners with hearing loss (S/B = -3 dB). The clear speech vowel benefit enjoyed here by Listener 1 (30 percentage points) is greater than that achieved by any of their listeners (the speaking style effect ranged between 10 and 24 percentage points for listeners with normal hearing and between -8 and 10 percentage points for listeners with hearing loss). Listeners 2 and 3, in contrast, fall within the range of the listeners with hearing loss tested by Ferguson and Kewley-Port (2002). Indeed, like Listeners 2 and 3, 4 of the listeners with hearing loss in the earlier study showed "essentially no difference between styles" (p. 267).

Figures 3 and 4 allow for a more detailed comparison of the current results for cochlear implant users to the results Ferguson and Kewley-Port (2002) observed for young listeners with normal hearing (YNH) and for older listeners with sloping sensorineural hearing loss (EHI). In the top panel of each figure, the clear speech benefit in percentage points was calculated for individual vowels using data given in Ferguson and Kewley-Port (2002). The bottom panels show results for the cochlear implant users tested here (coded in this figure as CI1, 2, and 3 for clarity). In the top panel of Figure 3 we see what Ferguson and Kewley-Port (2002) observed, that the clear speech effect for front vowels was quite different for the YNH and EHI listeners. In the bottom panel, it appears that the current Listener 1, who achieved a large overall clear speech intelligibility benefit, showed a pattern for individual vowels resembling that seen for YNH listeners. Listener 1's pattern for back vowels (see Figure 4) also resembles the pattern observed for YNH listeners, in that this listener achieved more consistently positive clear speech effects for these vowels. Although the overall clear speech vowel intelligibility benefit for Listeners 2 and 3 was similar to results reported by Ferguson and Kewley-Port (2002) for EHI listeners, their individual vowel patterns show very little resemblance to those of the EHI listeners.

To further explore the degree to which individual vowel patterns for the cochlear implant users resembled those of either the YNH or EHI listeners, vowel confusion matrices for clear and conversational speech were compared. The matrices for the YNH and EHI listeners represent new analyses of the data collected by Ferguson and Kewley-Port (2002). A summary of this comparison is shown in Table 3, which shows the percent correct performance score and the most frequent substitution error for each vowel in each speaking style for the YNH, EHI, and cochlear implant listeners. Solid boxes indicate vowels for which the clear

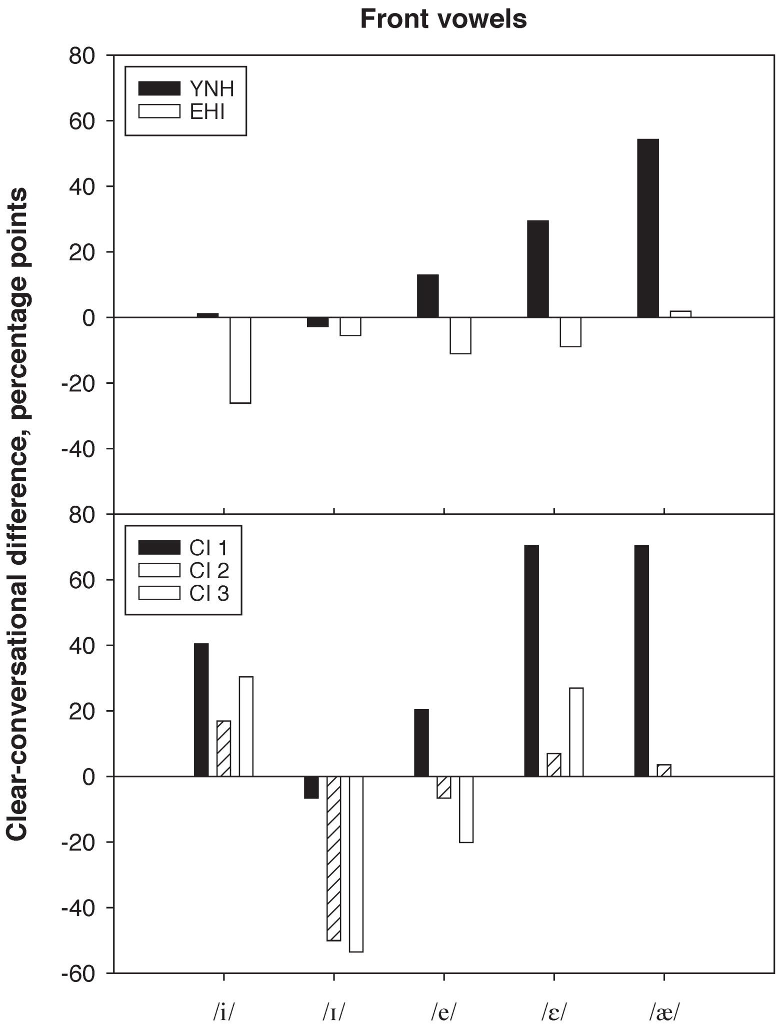

Figure 3. Clear minus conversational difference scores in percentage points for individual front vowels for listeners from Ferguson and Kewley-Port (2002; top) and for individual cochlear implant users (bottom).

versus conversational pattern for the EHI listeners differed from that for the YNH listeners; this occurred for all vowels except /æ/ and /u/. Dashed boxes indicate vowels for which one or more of the current cochlear implant users showed a pattern different from that shown by the YNH listeners. Note that in no case did the cochlear implant users show patterns that resembled those of the EHI listeners.

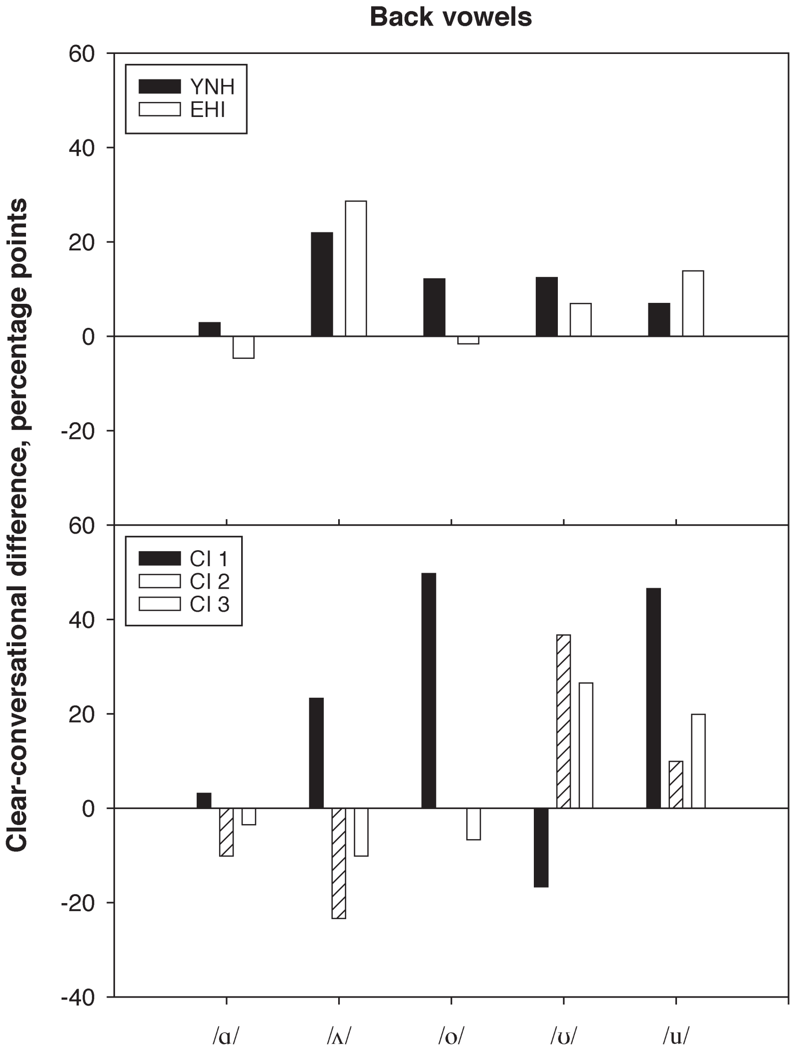

Figure 4. Clear minus conversational difference scores in percentage points for individual back vowels for listeners from Ferguson and Kewley-Port (2002; top) and for individual cochlear implant users (bottom).

Table 3

Mean Percent Correct Intelligibility and Modal Error Categories in Clear (CL) and Conversational (CON) Speech for Young Listeners With Normal Hearing (YNH), Elderly Listeners With Hearing Impairment (EHI)[a], and Three Cochlear Implant Users

	YNH		EHI		CI1		CI2		CI3	
	CON	CL	CON	CL	CON	CL	CON	CL	CON	CL
EE	91 /ɪ/	92 /ʊ/	***68***[b] /u/	***42*** /u/	**60** /ɪ/	**100** n/a	**70** /ɪ/	**100** n/a	**77** /e/	**93** n/a
IH	93 /ɛ/	90 /ɛ/	***59*** /ɛ/	***53*** /ʊ/	***90*** /ɛ/	***83*** /ɛ/	***77*** /ɛ/	***23*** /ɛ/	***77*** /ɛ/	***27*** /ɛ/
AY	**79** /i/	**91** /i/	***78*** /ɛ/	***67*** /ɛ/	**77** /ɪ/	**97** n/a	***90*** n/a	***70*** /i/	100 n/a	97 n/a
EH	**47** /ɪ/	**76** /ɪ/	***65*** /ɪ/	***56*** /e/	**23** /ɪ/	**93** /ɪ/	**50** /ɪ/	**77** /æ/	**70** /ɪ/	**77** /æ/
AE	**31** /ɛ/	**81** /ɛ/	78 /ɛ/	80 /ɛ/	**27** /ɛ/	**97** n/a	80 /ɛ/	80 /i/	90 /ɛ/	93 n/a

Continued on page 45

Table 3 *continued from page 44*

	YNH		EHI		CI1		CI2		CI3	
	CON	**CL**	**CON**	**CL**	**CON**	**CL**	**CON**	**CL**	**CON**	**CL**
AH	95 n/a	98 n/a	***91*** /æ/	***86*** /æ/	97 n/a	100 n/a	93 n/a	90 /i/	100 n/a	90 /i/
UH	**72** /ʌ/	**94** /ɑ/	**60** /ɛ/	**89** /ʊ/	**47** /ʊ/	**70** /ɑ/	**90** /ʊ/	**80** /ɑ/	100 n/a	90 /ɑ/
OH	**72** /u/	**84** /u/	89 /ʊ/	87 /ʌ/	**37** /u/	**87** /u/	***97*** n/a	***90*** /u/	100 n/a	100 n/a
UU	**69** /u/	**81** /u/	**81** /u/	**88** /u/	***67*** /ʌ/	***50*** /ʌ/	**73** /ʌ/	**100** /ʌ/	**43** /ʌ/	**80** /ʌ/
OO	**68** /ʊ/	**75** /ʊ/	**69** /ʊ/	**83** /ʊ/	**47** /ʊ/, /o/	**93** /ʊ/	**70** /ʊ/	**90** n/a	**53** /o/	**63** /o/
MEAN:	**71.7**	**86.2**	73.8	73.1	**57.2**	**87**	79	80	81	81

[a]YNH and EHI data represent new analyses of data collected by Ferguson and Kewley-Port (2002). [b]Boldface indicates vowels for which the CL score exceeded the CON score by ≥5 percentage points; italicized boldface indicates that the CON score exceeded the CL score by that criterion.

As seen in Figures 3 and 4, Table 3 suggests that for most vowels, Listener 1 behaved much like the YNH listeners, while Listeners 2 and 3 showed unique individual vowel patterns.

The finding that one of the current cochlear implant users behaved very much like listeners with normal hearing is consistent with studies such as Kirk, Tye-Murray, and Hurtig (1992) and Iverson, Smith, and Evans (2006). While the cochlear implant users in the latter study used much more advanced technology than those in the earlier study, both reported that cochlear implant users used vowel acoustic cues in a manner similar to listeners with normal hearing. In Kirk et al. (1992), this was manifested by performance declines of similar magnitude when either steady-state or durational information was removed from the vowel stimuli. In Iverson et al. (2006), cochlear implant users and listeners with normal hearing chose similar "best" vowels in a method-of-adjustment task involving multiple acoustic dimensions. Other method-of-adjustment studies, however, showed very large differences among the vowel spaces chosen by individual cochlear implant users (Harnsberger et al., 2001; Svirsky, Silveira, Neuburger, Teoh, & Suarez, 2004). This is consistent with the large individual differences seen among our three cochlear implant users.

Regression analyses in Ferguson and Kewley-Port (2002) indicated that the acoustic cues associated with improved vowel intelligibility in clear speech for the listeners with hearing loss differed from those that made vowels more intelligible for listeners with normal hearing. The divergence in individual vowel patterns among the three present listeners suggests that cochlear implant users also may need different clear speech acoustic changes to achieve improved vowel intelligibility. This is not all that surprising considering the limited number of spectral channels available to most cochlear implant users (e.g., Friesen et al., 2001) and the importance of spectral information for accurate vowel identification (Xu, Thompson, & Pfingst, 2005). To understand the effect of clear speech on vowel intelligibility for cochlear implant users, more research regarding the relationship between acoustic characteristics and vowel intelligibility, as well as patterns of acoustic information transmission by cochlear implants, is necessary. In this work, researchers will need to remember that cochlear implant listeners are a study population who may show great variance in intelligibility performance depending on a number of factors related to individual pathology and implant options.

CONCLUSION

The current preliminary study was mainly focused on determining how well naturally-produced clear speech would improve the vowel identification performance of three cochlear implant users. The clear speech vowel intelligibility benefit for these listeners was also compared to that enjoyed by listeners with normal hearing and listeners with hearing impairment in an earlier study (Ferguson

son & Kewley-Port, 2002). The results suggest that for clear speech to actually be more intelligible, cochlear implant users require clear speech acoustic changes that are different from those changes shown to benefit listeners with normal hearing. Of course, the small sample size makes it impossible to generalize the findings from this study to the clear speech effect in vowel identification by cochlear implant users; future studies clearly are needed using much larger listener groups. However, the enormous clear speech vowel intelligibility benefit observed for one of the listeners does suggest that asking frequent communication partners to speak clearly will be an effective communicative strategy for some cochlear implant users to enhance their speech understanding.

ACKNOWLEDGMENTS

This research was conducted as part of a master's degree project by the second author. The authors gratefully acknowledge Lisa Cowdrey for her assistance with participant recruitment and two anonymous reviewers for their helpful comments on an earlier version of this manuscript.

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