Effects of Vowel Context on the Recognition of Initial and Medial Consonants by Cochlear Implant Users

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Objective: **Scores on consonant-recognition tests are widely used as an index of speech-perception ability in cochlear implant (CI) users. The consonant stimuli in these tests are typically presented in the /ɑ/ vowel context, even though consonants in conversational speech occur in many other contexts. For this reason, it would be useful to know whether vowel context has any systematic effect on consonant recognition in this population. The purpose of the present study was to compare consonant recognition for the /ɑ, i/, and /u/ vowel contexts for consonants presented in both initial (Cv) and medial (vCv) positions.**

Design: **Twenty adult CI users with one of three different implanted devices underwent consonant-confusion testing. Twelve stimulus conditions that differed according to vowel context (/ɑ, i, u/), consonant position (Cv, vCv), and talker gender (male, female) were assessed in each subject.**

Results: **Mean percent-correct consonant-recognition scores were slightly (5 to 8%) higher for the /ɑ/ and /u/ vowel contexts than for the /i/ vowel context for both initial and medial consonants. This general pattern was observed for both male and female talkers, for subjects with better and poorer average consonant-recognition performance, and for subjects using low, medium, and high stimulation rates in their speech processors. In contrast to the mean data, many individual subjects demonstrated large effects of vowel context. For 10 of 20 subjects, consonant-recognition scores varied by 15% or more across vowel contexts in one or more stimulus conditions. Similar to the mean data, these differences generally reflected better performance for the /ɑ/ and /u/ vowel contexts than for the /i/ vowel context. An analysis of consonant features showed that overall performance was best for the voicing feature, followed by the manner and place features, and that the place feature showed the strongest effect of vowel context. Vowel-context effects were strongest for the six consonants /d, j, n, k, m/, and /l/. For three of these consonants (/j, n, k/), the back vowels /ɑ/ and /u/ produced substantially (30 to 35%) higher mean scores than the front vowel /i/. For each of the remaining three consonants, a unique pattern was observed in which a different single vowel produced substantially higher scores than the others. Several additional consonants (/s, g, w, b/, and /ð/) showed strong context effects in either the initial consonant or medial consonant position. Overall, voiceless stop, nasal, and glide-liquid consonants showed the strongest effects of vowel context, whereas the voiceless fricative and voiceless affricate consonants were least affected. Consistent with the feature analysis, a qualitative assessment of phoneme errors for the six key consonants indicated that vowel-context effects stem primarily from changes in the number of place-of-articulation errors made in each context.**

Conclusions: **Vowel context has small but significant effects on consonant-recognition scores for the "average" CI listener, with the back vowels /ɑ/ and /u/ producing better performance than the front vowel /i/. In contrast to the average results, however, the effects of vowel context are sizable in some individual subjects. This suggests that it may be beneficial to assess consonant recognition using two vowels, such as /ɑ/ and /i/, which produce better and poorer performance, respectively. The present results underscore previous findings that poor transmission of spectral speech cues limits consonant-recognition performance in CI users. Spectral cue transmission may be hindered not only by poor spectral resolution in these listeners but also by the brief duration and dynamic nature of consonant place-of-articulation cues.**

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Tests of consonant recognition are used extensively to evaluate the speech-perception abilities of cochlear implant (CI) recipients. Typically, the consonant stimuli in these tests are presented in an /ɑCɑ/ context, which samples only one of many possible vowel contexts that occur in conversational speech. From a theoretical standpoint, it would be preferable to assess consonant recognition in several different vowel contexts; however, testing with multiple vowel contexts extends test time beyond what is practical for many clinical and research applications. For this reason, it would be helpful to know whether the use of differing vowel contexts results in similar or substantially different estimates of consonant recognition in CI listeners.

To anticipate the possible effects of vowel context on consonant identification in CI users, it is useful to consider the key features of vowels themselves. Vowels are distinguished acoustically and perceptu-

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ally from one another primarily on the basis of their first formant (F1) and second formant (F2) frequencies, with third formant (F3) frequency and duration providing additional cues. The frequency of F1 is determined by the height of the tongue during vowel articulation, with high tongue positions producing low F1 frequencies and low tongue positions producing high F1 frequencies. The frequency of F2 is determined by the point of maximal constriction in the vocal tract, with back constrictions producing low F2 frequencies and front constrictions producing high F2 frequencies. In the present study, we consider vowel-context effects for the three vowels /ɑ, i/, and /u/. These vowels have formants that differ maximally from one another in the F1 and/or F2 domains, thereby occupying three corners of the vowel quadrilateral. For a male speaker, typical F1 and F2 frequencies are 270 and 2290 Hz for /i/, 730 and 1090 Hz for /ɑ/, and 300 and 870 Hz for /u/ (Peterson & Barney, 1952).

Consonant identification involves the use of multiple acoustic cues that convey information about voicing, manner of articulation, and place of articulation. Voicing and manner cues are conveyed primarily in the temporal domain with possible contributions of spectral cues, whereas place cues are coded in the spectral domain (e.g., van Tasell, Greenfield, Logemann, et al., 1992; Xu, Thompson, & Pfingst, 2005). Of the three types of cues, place cues are likely to be most affected by the formant frequencies of the surrounding vowels and, therefore, most sensitive to vowel context. Such cues include dynamic changes in vowel formant frequencies that occur during vowel–consonant and consonant–vowel transitions. The direction and frequency extent of formant transitions vary according to the formant frequencies of the preceding or following vowel; thus, formant transition cues to consonant identity may be enhanced or degraded by changes in vowel context. This effect may be especially strong in CI users, who have poorer spectral resolution than normal-hearing listeners, and it may also vary among individual CI users with different degrees of spectral degradation.

The effect of vowel context on consonant recognition in CI listeners has not been directly evaluated in previous studies. However, an observation by Loizou et al. (2000) suggests that vowel context may significantly impact consonant perception in this population. Loizou and colleagues reported that use of higher stimulation rates in CI speech processors led to larger improvements in consonant recognition for consonants in the /iCi/ and /uCu/ contexts than for those in the /ɑCɑ/ context. This led them to propose that /ɑCɑ/ stimuli are less sensitive than /iCi/ and /uCu/ stimuli to performance differences that occur with parametric changes in speech-processing strategies. Their observation also suggests that overall consonant identification may vary with the identity of the preceding and following vowels. The stimuli used by Loizou and colleagues were a subset of the consonant stimuli described by Shannon et al. (1999), representing a single female talker.

The purpose of the present study was to systematically evaluate the effects of vowel context on consonant recognition in a relatively large sample of CI users. Vowel context was assessed both for initial (Cv) and medial (vCv) consonants using the full set of stimuli described by Shannon et al. (1999). Five male and five female talkers are included in the stimulus set, which made it possible to compare overall performance for male and female talkers and to determine whether the effects of vowel context varied with talker gender. As described below, the data were analyzed for both group and individual performance and for overall consonant recognition as well as recognition of specific phonemes.

Methods

Subjects

Subjects were 20 postlingually deafened adults with CIs. Six subjects used a Clarion v1.2 CI with the continuous interleaved sampling (CIS) or paired pulsatile stimulation (PPS) speech-processing strategy; seven used a Clarion CII CI with the CIS, PPS, or HiResolution (HiRes) speech-processing strategy; five used a Nucleus-22 CI with the spectral peak (SPEAK) speech-processing strategy; and two used a Nucleus-24 CI with the advanced combination encoder (ACE) strategy. Table 1 provides relevant information about each subject, including gender, age at the time of testing, cause of deafness, duration of deafness before implantation, duration of CI use, device, speech-processing strategy, and stimulation rate used with that strategy. The next to last column in Table 1 shows each subject's average consonant-recognition score for all conditions tested in the present study. The last column shows each subject's scores on a vowel-recognition task, which is described below. Consonant-recognition scores range from 34 to 82%, and vowel-recognition scores range from 34 to 83%. Thus, a wide range of speech-recognition performance is represented by this sample of subjects.

Stimuli

Stimuli were initial and medial consonants in three vowel contexts (/ɑ, i/, and /u/) from the stimulus set of Shannon et al. (1999), spoken by five male and five female talkers. Stimuli in this database are digitized at a sampling rate of 44.1 kHz with 16 bits of amplitude resolution.

The 19 consonants tested were /p, t, k, b, d, g, tʃ, f, s, ʃ, v, z, ð, m, n, r, l, w/, and /j/. These consonants

TABLE 1. Description of subjects

Code	M/F	Age	Etiology	Yrs deaf	Yrs CI use	Device	Strategy	Stim rate (pps)	% consonants	% vowels
C03	F	53	Hereditary SNHL	27	4	Clarion v1.2	CIS	812.5	82	88
C05	M	46	Unknown	<1	4.5	Clarion v1.2	CIS	812.5	80	91
C07	F	61	Hereditary SNHL	35	3	Clarion v1.2	PPS	1444.4	65	87
C16	F	48	Progressive SNHL	13	0.9	Clarion v1.2	PPS	866.7	72	88
C18	M	68	Otosclerosis	33	1.6	Clarion v1.2	PPS	1444.4	52	65
C19	M	63	Progressive SNHL	32	0.8	Clarion v1.2	PPS	1444.4	59	59
D01	M	56	Unknown	26	2.4	Clarion CII	HiRes	2900	56	90
D02	F	52	Unknown	1	0.6	Clarion CII	HiRes	5156	66	92
D03	M	59	Polio	7	1.1	Clarion CII	HiRes	2900	34	62
D05	F	71	Unknown	3	0.3	Clarion CII	CIS	812.5	66	46
D08	F	51	Otosclerosis	13	0.1	Clarion CII	PPS	1625	52	61
D10	F	60	Unknown	8	1.6	Clarion CII	HiRes	2486	83	80
D11	M	72	Unknown	15	0.6	Clarion CII	HiRes	5156	39	57
N12	M	52	Progressive SNHL	8	11.8	Nucleus-22	SPEAK	250	61	77
N13	M	65	Progressive SNHL	4	12.2	Nucleus-22	SPEAK	250	64	75
N14	M	57	Progressive SNHL	1	8.2	Nucleus-22	SPEAK	250	57	90
N32	M	34	Maternal rubella	<1	4.7	Nucleus-22	SPEAK	250	62	86
N34	F	56	Mumps; progressive SNHL	9	2.6	Nucleus-22	SPEAK	250	35	52
P04	F	76	Otosclerosis	22	1	Nucleus-24	ACE	900	61	85
P07	F	68	Unknown	3	2.9	Nucleus-24	ACE	720	50	36

Subject code, gender, age, etiology of hearing loss (HL), duration of severe-to-profound bilateral HL prior to implantation, years of cochlear implant (CI) use, device, processing strategy, stimulation rate used in clinical map (pulses/s), average percent-correct consonant recognition for all conditions tested in the present study, and percent-correct vowel recognition for 11 vowels spoken by three male talkers in an /hVd/ context.

were identified with relatively high accuracy by the normal-hearing subjects in Shannon's study. The consonants /v/ and /ð/ had the lowest identification rates (91.3 and 89.2%, respectively) because of confusions with one another; each of the remaining 17 consonants had identification rates exceeding 95.3%. The consonant /dʒ/, which is included in the database, was excluded from the present study because of mispronunciations in the tokens produced by one male and one female talker (Shannon, personal communication).

Consonant-confusion testing was conducted in a sound-isolated room with the subject seated approximately 1 m in front of a pair of high-quality loudspeakers and a video screen. Consonant stimuli were played out from computer memory, amplified, low-pass filtered at half the digitization rate, attenuated, and presented through the speakers at a level of 60 dBA. Data for each of the six conditions (3 vowel contexts $\times$ 2 consonant positions) were collected from each subject in three to six test sessions, depending on the subject's pace in performing the task. Each session lasted approximately 2 hr. Test order for the six (consonant position $\times$ vowel context) stimulus conditions was randomized across subjects. For each condition, the data for male and female talkers were collected separately but within the same test session. The order of testing male and female talkers was alternated in sequential test sessions, so that if the male talker was presented first in one session, the female talker was tested first in the next session.

Data collection for each new stimulus set (combination of consonant position, vowel context, and talker gender) included three separate procedures: familiarization, practice, and testing. Familiarization was accomplished by playing each of the 19 consonants for one talker (male talker "m2" or female talker "w2") three times in succession, with the consonant's identity displayed on the video screen. For the practice and testing procedures, the stimulus was presented once on each trial, with the listener using a computer mouse to select the desired response from a list of possible alternatives displayed on the video screen. Correct-answer feedback was provided immediately after each response. Practice was accomplished by having the subject complete this task for a short block of stimuli that included two trials for each phoneme (38 stimuli), presented in random order. All five (male or female) talkers were sampled in each practice block; however, only two talkers were sampled per phoneme. Testing used the same procedures as the practice session but used longer stimulus blocks, with each block including five trials per phoneme (one for each talker, for a total of 95 stimuli) presented in random order. Testing continued until three test blocks were obtained with less than 10% range in scores, and these three blocks were used in subsequent analyses. For all subjects and conditions, the 10% criterion was met after completion of four test blocks.

For each subject, a merged confusion matrix was compiled for each of the 12 stimulus conditions

TABLE 2. Consonant feature categories

Category No.	Voicing	Manner	Place
1	/b, d, g, v, z, ð, m, n, r, l, j. w/ (voiced)	/p, t, k, b, d, g/ (stops)	/p, b, f, v, m, w/ (front)
2	/p, t, k, tʃ, f, s, ʃ/(voiceless)	/tʃ, f, s, ʃ, v, z, ð/(fricatives, affricates)	/t, d, s, ð, z, n, l/ (mid)
3		/m, n/ (nasals)	/k, g,ʃ, tʃ, r, j/ (back)
4		/r, l, w, j/ (glide-liquids)	

(2 talker genders × 2 consonant positions × 3 vowel contexts), and an overall percent-correct score was computed for each matrix. In addition, information-transmission analyses (Miller & Nicely, 1955) were applied to each merged matrix to determine the proportion of transmitted information (TI) for the consonant features of voicing, manner, and place of articulation. The feature categories used for this analysis are shown in Table 2.

Level Calibration

Consonant stimuli were normalized in level by equating the root mean square (RMS) amplitudes of the steady-state segments of the initial (vCv stimuli) or final (Cv stimuli) vowels. A 10-sec noise having the same RMS amplitude as the vowel segments was used to measure sound level at the approximate location of the subject's head and to compute an attenuation factor that produced sound levels of 60 dBA during the vowel segments.

Speech-Processor Settings

Subjects used their own speech processors and clinical speech-processor programs ("maps") for all testing. The need for map adjustments was discussed with each subject before the start of the study. A few subjects required remapping and were referred to their clinical audiologist for this purpose. The majority were experienced CI users with stable maps, and declined to have adjustments made. The average time delay between a subject's most recent map adjustment and the start of testing was 6.5 mo. Speech-processor maps were not altered during the course of the study because doing so might have influenced consonant perception, thereby confounding the study results.

Sensitivity and volume settings were set in a systematic manner according to device. The Nucleus-22 processor only has a sensitivity control. Subjects using this device adjusted the sensitivity setting to a level producing comfortable loudness during the familiarization task for the first set of stimuli. The Nucleus-24 and Clarion body-worn devices have both sensitivity and volume controls. Subjects with these devices used a fixed sensitivity setting (8 for Nucleus-24, 10:30 for Clarion/S-Series, and 11:00 for Clarion/PSP) and adjusted the volume control to produce comfortable loudness during the first familiarization task. Four Clarion users who used behind the ear processors (C03, C05, C07, and D03) found their preprogrammed volume/sensitivity settings to produce comfortable loudness, and made no adjustments. Once sensitivity and volume settings had been adjusted during the first data-collection session, they were held constant for the remainder of the study.

Vowel-Recognition Testing

As part of a larger project, subjects in this study were also tested on a vowel-recognition task. A subset of these data for the vowels /ɑ, i/, and /u/ were analyzed for comparison with the consonant-recognition data. Vowel stimuli were 11 medial vowels presented in an /hVd/ context, taken from the stimulus set of Hillenbrand et al. (1995). The vowels tested were those in the words *had*, *hod*, *head*, *hayed*, *heard*, *hid*, *heed*, *hoed*, *hood*, *hud*, and *who'd*. Six tokens representing six different male talkers were presented for each vowel. The procedures used to obtain the vowel-recognition data were similar to those described above for consonant recognition, except that practice and standard blocks of stimuli incorporated 33 and 66 stimuli, respectively.

RESULTS

Group Data, Percent-Correct Results

Initial Consonants • Figure 1 shows the average percent-correct scores achieved by all subjects for the initial consonant stimuli. The scores for female and male talkers are shown separately in the left and center panels, respectively, and the combined scores for female and male talkers are shown in the right panel. In general, performance was poorer for consonants presented in the /i/ vowel context than for consonants presented in the /ɑ/ or /u/ contexts.

A two-way (vowel context × talker gender) repeated-measures analysis of variance (ANOVA) was used to evaluate the data in more detail.* The ANOVA confirmed a significant main effect of vowel context ($F[2,38] = 17.2$, $p < 0.001$) and also revealed a significant interaction between vowel context and talker gender ($F[2,38] = 13.3$, $p < 0.001$). For female talkers,

*Although it is common practice to apply a rationalized arcsine transformation to percent-correct data, the distribution of scores in this data set did not warrant the use of such a transformation.

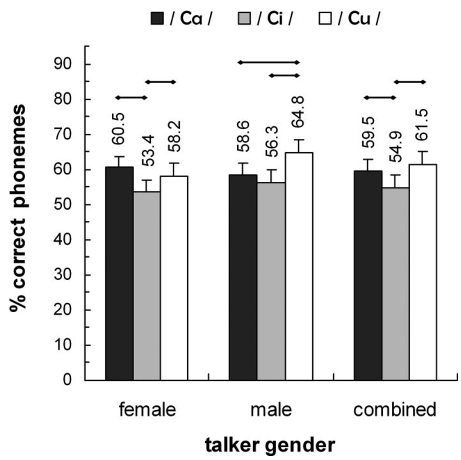


Figure 1. Mean consonant-recognition scores for the initial consonant stimuli, plotted as a function of vowel context and talker gender. Error bars represent 1 SE of the mean. Horizontal bars indicate pairs of mean scores that are significantly different from one another (p < 0.05).

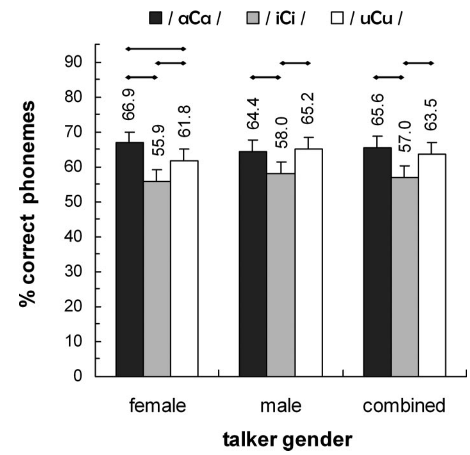


Figure 2. Mean consonant-recognition scores for the medial consonant stimuli, plotted as a function of vowel context and talker gender. Error bars represent 1 SE of the mean. Horizontal bars indicate pairs of mean scores that are significantly different from one another (p < 0.05).

scores for the /ɑ/ and /u/ contexts were significantly higher than scores for the /i/ context (Holm-Sidak multiple-comparison post hoc tests, $p < 0.05$) but were not different from each other. For male talkers, scores for the /u/ context were significantly higher than those for the /ɑ/ and /i/ contexts (Holm-Sidak test, $p < 0.001$), whereas scores for the /ɑ/ and /i/ contexts were not significantly different. Overall performance for the male talkers was significantly higher than for the female talkers ($F[1,38] = 10.1$, $p < 0.01$), but the absolute difference in scores was only 2.5% (59.9% for males versus 57.4% for females).

Although the data shown in Figure 1 reveal statistically significant effects of vowel context on initial consonant recognition, it should be noted that the mean differences attributable to vowel context were relatively modest. Maximum differences were 7.1% for female talkers (60.5% for /ɑ/ versus 53.4% for /i/), 8.5% for male talkers (64.8% for /u/ versus 56.3 for /i/), and 6.6% for female and male talkers combined (61.5% for /u/ versus 54.9% for /i/).

Medial consonants • Figure 2 shows the mean percent-correct scores for medial consonant recognition, displayed in the same format used in Figure 1. Similar to the initial consonants, there was a trend for mean scores for the /i/ vowel context to be slightly poorer than mean scores for the /ɑ/ and /u/ contexts.

A two-way (vowel context × talker gender) ANOVA again confirmed the main effect of vowel context ($F[2,38] = 16.6$ $p < 0.001$) and indicated a significant interaction between vowel context and talker gender ($F[2,38] = 10.4$, $p < 0.001$). For female talkers, there were significant differences between the scores for each of the three vowel contexts: the /ɑ/ context yielded the best performance, followed by the /u/ context and then the /i/ context (Holm-Sidak multiple-comparison post hoc tests, $p < 0.01$). For male talkers, the /ɑ/ and /u/ vowel contexts did not produce significantly different performance, but both yielded better performance than the /i/ context (Holm-Sidak test, $p < 0.005$). There was no difference between the average performance for female and male talkers for medial consonants.

Mean performance differences attributable to vowel context were slightly larger for the medial consonants as compared to the initial consonants. Maximum differences were 11.0% for female talkers (66.9% for /ɑ/ versus 55.9% for /i/), 7.2% for male talkers (65.2% for /u/ versus 58.0% for /i/), and 8.6% for female and male talkers combined (65.6% for /ɑ/ versus 57.0% for /i/).

Analysis by stimulation rate • As indicated earlier, Loizou et al. (2000) observed greater improvements in medial consonant recognition with increasing stimulation rate when consonants were presented in the /i/ or /u/ context compared with the /ɑ/ context. This led us to speculate that the effects of vowel context on consonant-recognition scores might vary with stimulation rate. To assess this possibility, we divided subjects into three groups according to the stimulation rate used in their clinical speech processors: low stimulation rate (<500 pps per channel), moderate stimulation rate (500 to 1000 pps per channel), and high stimulation rate (>1000 pps per channel). The groups included five, six, and nine subjects, respectively (Table 1).

Separate two-way (stimulation rate × vowel context) repeated-measures ANOVAs were applied to the data for each of four stimulation conditions (initial female, initial male, medial female, and medial male). None of the four ANOVAs yielded significant interaction terms, indicating that the effects of vowel context did not differ systematically

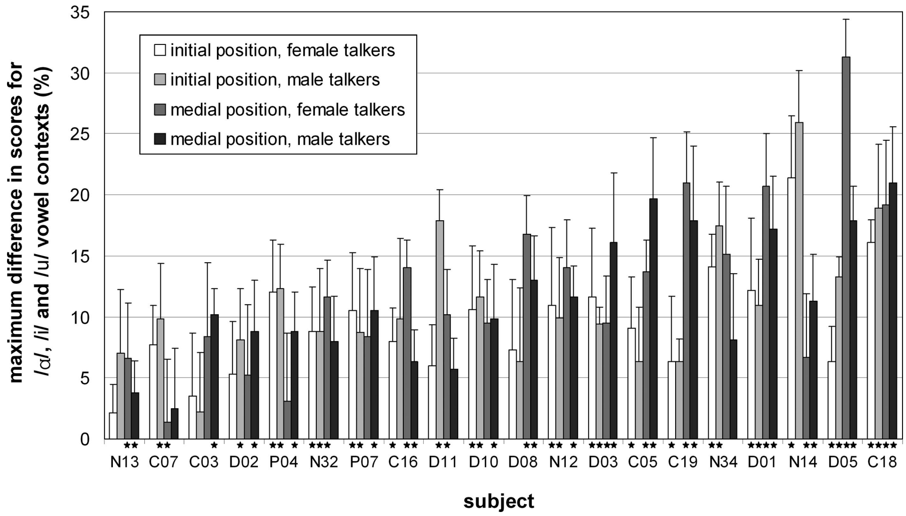


Figure 3. Maximum difference in individual subjects' consonant-recognition scores attributable to vowel context. Individual subjects' data are ordered according to the average maximum difference across the four stimulus conditions shown. Error bars represent the root-mean-square standard deviation of the two scores producing the maximum difference. Stars below individual bars indicate that the differences represented by those bars are significantly greater than zero.

with the stimulation rate used in subjects' speech processors. However, the relatively small size of our groups may have precluded us from identifying small effects of stimulation rate.

Analysis by overall performance • To determine whether the effects of vowel context were similar for subjects with poorer overall performance and subjects with better overall performance, we divided subjects into two groups according to their average consonant-recognition scores across all conditions (next to last column in Table 1). Nine subjects were included in the group with poorer performance (average scores <60%), and 11 subjects were included in the group with better performance (average scores >60%).

Similar to the analysis for stimulation rate, separate two-way (performance × vowel context) repeated-measures ANOVAs were performed for each of the four stimulus conditions (initial female, initial male, medial female, and medial male). Once again, the four ANOVAs all failed to produce a significant interaction term, indicating that the average effects of vowel context on consonant recognition were similar for the better-performing and poorer-performing subjects.

Possible order effects • Although the order of testing different stimulus conditions was randomized across subjects, order effects could still have been partly or wholly responsible for the apparent effects of vowel context exhibited in Figures 1 and 2. To evaluate this possibility, a one-way (test order) repeated-measures ANOVA was applied to the percent-correct data for each of the four stimulus conditions represented in those figures (initial female, initial male, medial female, and medial male). None of the four ANOVAs yielded a significant effect of test order ($p > 0.05$), indicating that the order of testing did not systematically influence the percent-correct scores.

Individual Data, Percent-Correct Results

The results presented thus far indicate that vowel context has small but significant effects on the consonant-recognition scores of an average CI user. Mean performance differences associated with vowel context were generally less than 10% for a given combination of consonant position (initial, medial) and talker gender (female, male). Importantly, examination of the data for individual subjects sometimes revealed much larger effects of vowel context.

Maximum-difference scores • Figure 3 shows maximum-difference scores attributable to vowel context for each subject and stimulus condition. To illustrate how these values were obtained, consider the data for subject N13, shown at the far left of the figure. For the initial-female condition, this subject scored 56.1% correct for the /Cu/ stimuli, 54.7% for the /Cɑ/ stimuli, and 54.0% for the /Ci/ stimuli. A maximum-difference score of 2.1% was plotted (leftmost bar in the figure), corresponding to the difference between the highest and lowest scores. Corresponding maximum-difference scores for the three remaining stimulus conditions (initial male, medial female, and medial male) were plotted in the adjacent bars. Similar data are plotted in Figure 3 for the other 19 subjects, with subjects arranged along the abscissa in increasing order of their average difference scores. Small stars are shown below each bar for which the maximum-difference score was significantly greater than zero (t-test on individual block scores, $p < 0.05$).†

Ten of 20 subjects exhibited maximum-difference scores of 15% or greater for at least one of the four stimulus conditions, and four of these subjects (C19, D01, D05, and C18) had at least one score of 20% or

†The Mann–Whitney rank sum test was applied for 7 of the 80 comparisons for which the normality of variance assumption was not met.

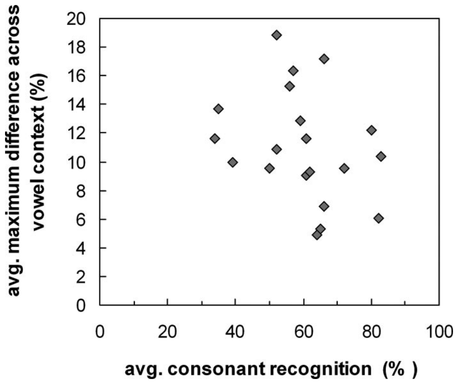


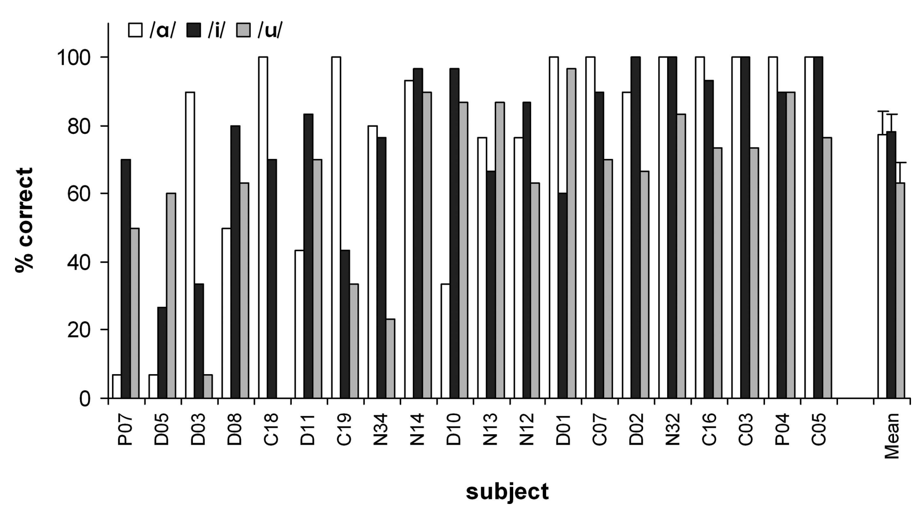
Figure 4. Average maximum difference in scores across vowel contexts (average value of the four vertical bars shown for each subject in Fig. 3) plotted as a function of overall consonant recognition (next to last column in Table 1).

greater. Most of the 10 subjects with large maximum-difference scores for one stimulus condition showed much smaller maximum-difference scores for other stimulus conditions; however, the particular stimulus conditions that produced larger and smaller maximum-difference scores varied across subjects. All together, 18 of 80 maximum-difference scores exceeded 15%. In 8 of these 18 cases, the highest consonant-recognition score was achieved for the /ɑ/ vowel context, and the lowest score was achieved for the /i/ vowel context. In another eight cases, the highest score was achieved for the /u/ vowel context, and the lowest score was achieved for the /i/ vowel context. In the remaining two cases, the highest score was achieved for the /u/ vowel context, and the lowest score was achieved for the /ɑ/ vowel context. Not unexpectedly, these patterns of differences attributable to vowel context are consistent with the group patterns illustrated in Figures 1 and 2, generally reflecting higher scores for the /ɑ/ and /u/ contexts than for the /i/ context.

To determine whether there was a relationship between the magnitude of maximum-difference scores in Figure 3 and overall performance, the average maximum-difference scores (mean value of the four vertical bars for each subject in Fig. 3) were compared with the average consonant-recognition scores for all stimulus conditions (next to last column in Table 1). A scatterplot of these data is shown in Figure 4. This plot indicates that there was no systematic relationship between subjects' overall consonant-recognition performance and the range of their scores across the three vowel contexts.

Comparison with vowel recognition • An interesting question is whether individual subjects' patterns of consonant-recognition scores reflected differences in ability to identify the three vowels /ɑ, i/, and /u/. Figure 5 shows each subject's percent-correct identification scores for these vowels, obtained from the vowel-recognition task. Recall that the stimuli used in this task were vowels presented in /hVd/ context, spoken by six male talkers. Data in Figure 5 are arranged according to subjects' average scores for the three vowels, with poorest performance on the left and increasing performance toward the right. Group mean scores are shown to the far right. The poorer-performing subjects showed large differences in scores across the three vowels. For example, subject P07 (leftmost in the figure) identified /i/ with 70% accuracy and /u/ with 50% accuracy, but identified /ɑ/ with only 7% accuracy, which fell below the chance performance level of 9%. Other poorer-performing subjects showed quite different patterns; for example, subject D03 achieved scores of 90% for /ɑ/, 33% for /i/, and 7% for /u/. The better-performing subjects (toward the right of Fig. 5) showed somewhat more consistent results, with the seven top performers generally showing near-perfect scores for /ɑ/ and /i/ and somewhat lower

Figure 5. Vowel-recognition scores for the three vowels /ɑ, i/, and /u/, taken from the results of an 11-vowel-confusion task. Subjects are ordered from lowest to highest mean scores. Group mean data are shown on the far right. Error bars represent 1 SE of the mean.



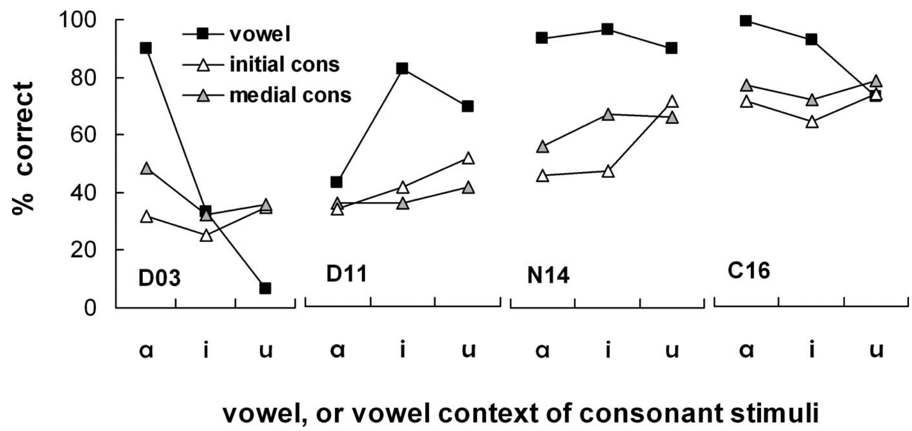


Figure 6. Comparison of vowel-identification scores for the vowels /ɑ, i/, and /u/, with consonant-recognition scores obtained in the /ɑ, i/, and /u/ vowel contexts for initial and medial consonants (male talkers). The data shown are for four representative subjects.

scores for /u/. The group mean scores were 77, 78, and 63%, respectively, for /ɑ, i/, and /u/ and were not statistically different (one-way repeated-measures ANOVA, $F[2,38] = 2.48$, $p > 0.05$).

To evaluate possible relationships between the vowel- and consonant-recognition data, each subject's vowel-recognition scores for the vowels /ɑ, i/, and /u/ were plotted together with their consonant-recognition scores for the initial-male and medial-male consonant conditions. The male–consonant data were selected for comparison because the vowel-recognition scores were obtained with male talkers only. Example plots for four subjects with different levels of overall vowel and consonant recognition are shown in Figure 6. Similar to the impression given by these four plots, visual inspection of the plots for all 20 subjects indicated no systematic relationship between the vowel scores and either set of consonant scores. This suggests that subjects' ability to recognize consonants in a specific vowel context is not directly influenced by their ability to identify the surrounding vowels.

Feature and Phoneme Analyses

Feature analysis • Figure 7 shows mean TI scores for individual consonant features as a function of vowel context. Each row shows the data for a different feature (voicing, manner, or place of articulation), and each column shows the data for a different combination of consonant position and talker gender (initial female, initial male, medial female, and medial male). Horizontal bars indicate pairs of scores that were significantly different from one another ($p < 0.05$) as determined by a one-way (vowel context) repeated-measures ANOVA and post hoc Holm–Sidak tests. To visually emphasize differences that are relatively large, horizontal bars are displayed in a darker color when the mean values differ by 0.1 (10% TI) or more. The lighter horizontal bars represent mean differences less than 0.1. Overall, the voicing and manner features were transmitted considerably better than the place feature. This general result has been observed in previous studies (Fu & Shannon, 1998, 2000a, 2000b; Guerts & Wouters, 1999; McKay & McDermott, 1993; Munson, Donaldson, Allen, et al., 2003; Vandali, 2001; van Wieringen & Wouters, 1999) and reflects the fact that temporal cues, which convey most voicing and manner information, are transmitted more successfully to CI users than spectral cues, which supply information about place of articulation.

For the voicing feature (top row), a strong effect of vowel context is evident for the initial-male condition (top row, second panel). There are also weaker effects of vowel context for the initial-female and medial-female conditions (top row, first and third panels). Note that the effects of context differ across the three conditions that yielded significant differences. The /u/ context produces the best performance for the initial-female and initial-male conditions, whereas the /ɑ/ context produces the best performance for the medial-female condition.

For the manner feature (middle row), weak effects of vowel context are present for two of the four conditions (initial male and medial female). Again, the vowel context producing the best performance varies with condition, with /u/ producing the best performance for the initial-male condition and /ɑ/ producing the best performance for the medial-female condition.

The strongest effects of vowel context are seen for the place-of-articulation feature (bottom row). For this feature, all four stimulus conditions exhibit performance differences greater than 0.1 between the highest and lowest scores. Moreover, unlike the voicing and manner features, the patterns of performance are similar across conditions, with the /ɑ/ and /u/ vowel contexts yielding better performance than the /i/ context. Note that this pattern of results is similar to that observed for overall consonant recog-

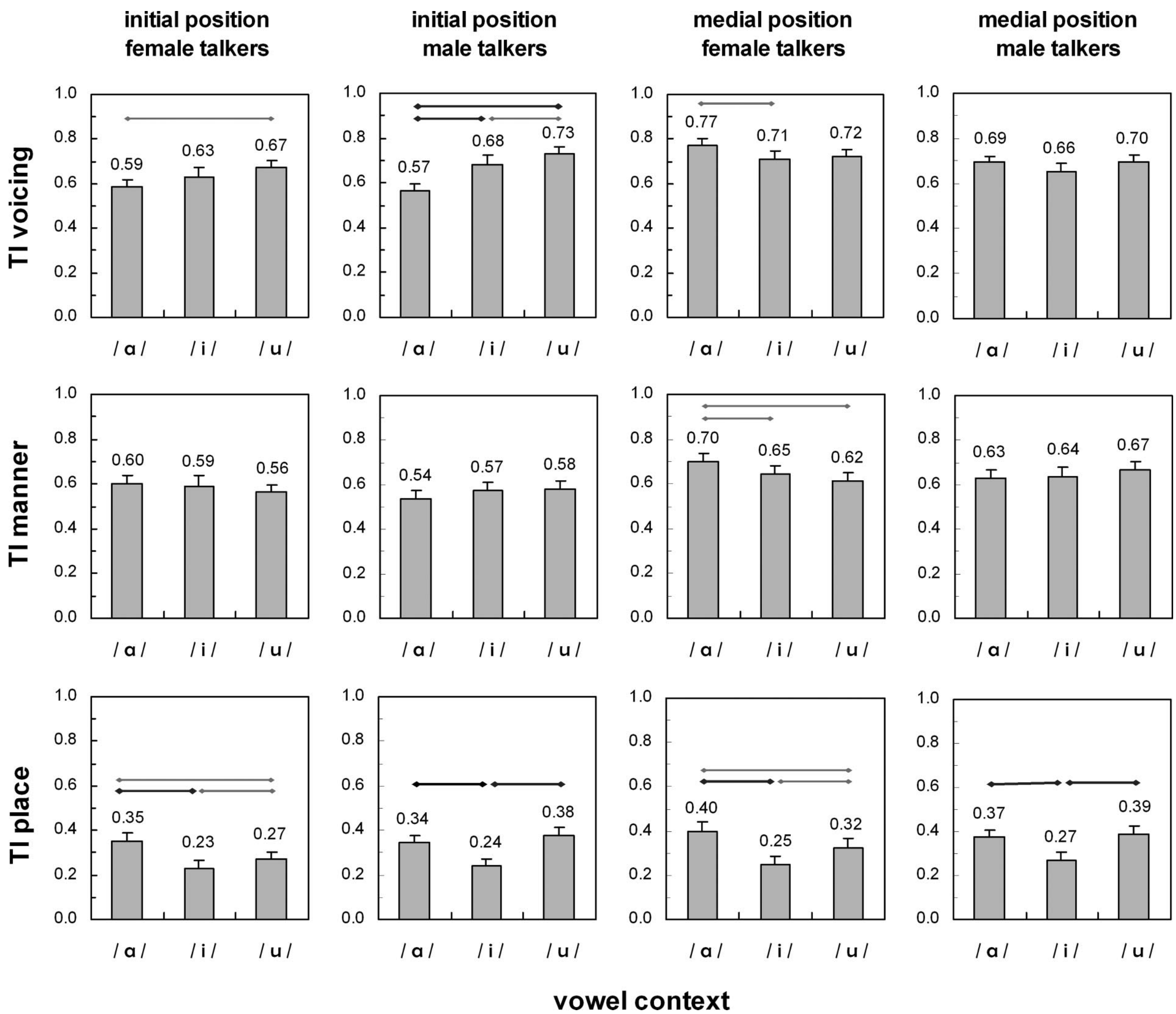


Figure 7. Mean TI scores for the consonant features of voicing, manner, and place of articulation (top, middle, and bottom rows, respectively). Each column shows data for a different stimulus condition. Error bars represent 1 SE of the mean. Horizontal bars indicate pairs of means scores that are significantly different from one another (*p* < 0.05). Darker horizontal bars are shown for mean differences ≥ 0.1; lighter bars are shown for mean differences <0.1.

nition in Figures 1 and 2. This similarity in patterns suggests that context-dependent differences in place-cue perception may be the primary factor underlying the effects of vowel context on overall consonant-recognition performance.

Analysis by individual phoneme • To further investigate the vowel-context effects observed in the group data (Figs. 1 and 2) and feature analyses (Fig. 7), the percent-correct data were analyzed on a phoneme-by-phoneme basis and compared with error patterns in the group confusion matrices. Table 3 summarizes the mean percent-correct scores for all 20 subjects as a function of phoneme. Average percent-correct scores for each phoneme (collapsed across all 12 stimulus conditions) are shown in the leftmost column of the table, with phonemes listed in descending order of these scores. There was a wide range of accuracy in the identification of individual consonants; the affricate consonant /tʃ/ was identified with the highest overall accuracy (83.0% correct), whereas the voiced fricatives /v/ and /ð/ were identified with the lowest accuracy (35.9 and 20.8%, respectively). The remaining columns in Table 3 show mean percent-correct scores for each stimulus condition (initial female, initial male, medial female, or medial male) and mean scores across the four conditions. The rightmost column in each four-column grouping shows the maximum-difference score across contexts, computed in the same way described earlier (Fig. 3). Throughout the table, maximum-difference scores greater than 25% are bolded for visual emphasis.

Inspection of the data in Table 3 reveals that the effects of vowel context are not distributed evenly across consonants. Instead, the largest effects of vowel context occur for a subset of six consonants

Table 3. Percent-correct consonant identification by phoneme and stimulus condition

		Initial position female talkers				Initial position male talkers				Medial position female talkers				Medial position male talkers				Mean (of 4 conditions)			
Cons	Mean % correct	/ɑ/	/i/	/u/	Max diff	/ɑ/	/i/	/u/	Max diff	/ɑ/	/i/	/u/	Max diff	/ɑ/	/i/	/u/	Max diff	/ɑ/	/i/	/u/	Max diff
tʃ	83.0	81.3	72.7	78.0	8.7	83.3	70.0	78.7	13.3	90.7	81.3	89.3	9.3	90.0	90.0	92.0	2.0	86.3	78.5	84.5	8.3
ʃ	81.6	77.3	76.7	72.7	4.7	78.7	78.7	80.0	1.3	94.0	78.0	80.0	16.0	92.7	82.0	91.3	10.7	85.7	78.8	81.0	8.2
t	77.8	80.7	63.3	87.3	24.0	76.0	78.7	87.3	11.3	82.7	62.7	80.0	20.0	83.3	78.0	77.3	6.0	80.7	70.7	83.0	15.3
d	73.9	76.0	64.0	88.7	**24.7**	58.7	62.7	91.3	**32.7**	64.7	68.7	88.7	**24.0**	68.7	68.7	87.3	18.7	67.0	66.0	89.0	**25.0**
j	71.9	73.3	53.3	83.3	**30.0**	80.0	68.7	87.3	18.7	88.7	38.7	82.0	**50.0**	82.7	45.5	82.0	**37.3**	81.2	51.5	83.7	**34.0**
s	70.4	57.3	46.0	82.0	**36.0**	64.0	79.3	90.7	**26.7**	70.0	54.0	72.0	18.0	79.3	70.0	81.3	11.3	67.7	62.3	81.5	23.0
z	67.0	53.0	48.0	68.7	20.7	68.7	74.0	77.3	8.7	60.7	52.0	68.0	16.0	75.3	80.0	79.3	4.7	64.5	63.5	73.3	12.5
n	60.6	68.7	35.3	69.3	**34.0**	58.7	42.0	64.7	22.7	82.0	39.3	78.0	**42.7**	72.0	38.7	80.0	**41.3**	70.3	38.8	73.0	**35.2**
k	60.4	68.0	38.7	70.7	**32.0**	74.7	52.0	76.7	24.7	69.3	31.3	70.7	**39.3**	66.0	43.3	65.3	22.7	69.5	41.3	70.8	**29.7**
g	58.9	62.0	60.0	44.7	17.3	54.0	56.7	60.0	6.0	80.0	50.7	71.3	**29.3**	62.0	43.3	64.0	20.7	64.5	52.7	60.0	18.3
w	58.5	63.3	57.3	49.3	14.0	58.0	67.3	62.7	9.3	56.0	68.7	43.3	**25.3**	52.7	74.0	50.7	23.3	57.5	66.8	51.5	18.0
b	57.2	66.7	59.3	55.3	11.3	58.7	48.7	58.0	10.0	58.7	64.7	37.3	**27.3**	45.3	80.7	55.3	**35.3**	57.3	63.3	51.5	21.0
p	56.4	66.0	50.0	38.7	**27.3**	58.7	54.7	44.0	14.7	72.0	68.7	50.7	21.3	58.0	55.3	62.0	6.7	63.7	57.2	48.8	17.5
r	53.9	41.3	45.3	50.7	9.3	61.3	50.7	64.7	14.0	50.0	53.3	53.3	3.3	69.3	50.7	59.3	18.7	55.5	50.0	57.0	11.3
m	51.1	62.7	46.7	36.7	**26.0**	63.3	37.3	62.0	**26.0**	75.3	47.3	41.3	**34.0**	62.7	34.0	46.0	**28.7**	66.0	41.3	46.5	**28.7**
l	49.3	46.0	54.0	24.0	**30.0**	34.0	60.7	34.7	**26.7**	51.3	76.0	46.7	**29.3**	58.0	64.7	43.3	21.3	47.3	63.8	37.2	**26.8**
f	48.9	49.3	41.3	50.7	9.3	37.3	39.3	56.7	19.3	62.7	46.0	57.3	16.7	56.0	43.3	48.7	12.7	51.3	42.5	53.3	14.5
v	35.9	30.7	38.0	40.0	9.3	30.7	34.0	42.7	12.0	37.3	37.3	32.0	5.3	25.3	42.0	42.7	17.3	31.0	37.8	39.3	11.0
ð	20.8	28.7	12.7	18.0	16.0	16.7	16.7	15.3	1.3	26.7	9.3	34.7	**25.3**	26.0	10.7	35.3	24.7	24.5	12.3	25.8	16.8

The leftmost column shows average percent-correct scores across all conditions. Note that consonants are ordered from best to poorest performance. Data for each stimulus condition are shown in groups of 4 columns in the center of the table. Within each group, percent-correct scores for each vowel context are shown together with the difference between the highest and lowest score ("max diff"). Mean scores across the four stimulus conditions are shown in the rightmost group of columns. Maximum difference scores ≥25% are bolded. Borders surround the data for some consonants demonstrating large effects of vowel context (see text).

whose data are outlined in the table: /d, j, n, k, m/, and /l/. These consonants have mean maximum-difference scores greater than 25% and have consistently large maximum-difference scores across all four stimulus conditions. For /j, n/, and /k/, the effects of vowel context mimic those seen in the group mean data shown in Figures 1 and 2. That is, the percent-correct scores for the /ɑ/ and /u/ vowel contexts are substantially (30 to 35%) higher than scores for the /i/ vowel context, but similar to one another. These three consonants also had the largest maximum-difference scores of the six consonants identified. Uniquely different patterns are seen for each of the remaining consonants, /d, m/, and /l/. In each case, one vowel context produces substantially higher performance than the other two. For /d/, the best performance occurs for /u/, whereas for /m/ it occurs for /ɑ/, and for /l/ it occurs for /i/. Although the effects of vowel context are inconsistent across the six consonants, the /i/ context is advantageous in only one case (/l/), and the overall advantage favors the /ɑ/ and /u/ contexts, which is consistent with the group mean data.

In addition to the six consonants that showed vowel-context effects in all four stimulus conditions, five consonants demonstrated clear effects of vowel context for either initial or medial consonants. Specifically, /s/ showed context effects for consonants in the initial position (initial-female and initial-male conditions), whereas /g, w, b/, and /ð/ showed context effects for consonants in the medial position (medial-female and medial-male conditions). Again, several different patterns were observed. For /s/, scores for the /u/ context were higher than scores for the /i/ and /ɑ/ contexts. For /d/ and /g/, scores for the /ɑ/ and /u/ contexts were higher than scores for /i/ context. Finally, for /b/ and /w/, scores for the /i/ context were higher than scores for the /ɑ/ and /u/ contexts.

It is evident that vowel context influenced the perception of some consonants in nearly every voicing-manner category. Overall, the categories affected most strongly were the voiced stops, nasals, and glide liquids, whereas the voiceless fricatives and voiceless affricatives were affected the least. (Note that no voiced affricates were included in our stimulus set). Because voiced stops, nasals, and glide liquids tend to have robust formant transitions, the strong context effects observed for these phonemes suggest that transition cues are often easier to perceive in one vowel context than another. This makes sense because the extent and direction of formant transitions associated with a particular consonant depend on the formant frequencies of the surrounding vowels.

To evaluate error patterns underlying the strong context effects observed for the six consonants identified, group confusion matrices were compiled for the /ɑ, i/, and /u/ vowel contexts in each of the four stimulus conditions (two consonant positions × two talker genders). The resulting 12 matrices are shown in the Appendix. In addition, summary matrices were created for each of the three vowel contexts by merging the data for each vowel context across the four stimulus conditions. These three summary matrices are shown in Figure 8. Although there are differences in the effects of vowel context on specific error patterns across the four stimulus conditions, the summary matrices capture prominent patterns that underlie vowel-context effects for the six consonants noted above. As indicated in the summary below, these effects primarily reflect place-of-articulation errors, with secondary contributions from manner-of-articulation errors:

1) **/k/.** Percent-correct scores for /k/ are substantially better for the /ɑ/ and /u/ vowel contexts than for the /i/ context. This is primarily attributable to an increase in the number of /t/-for-/k/ (place) errors for the /i/ context compared with the /ɑ/ and /u/ contexts. A secondary factor is an increase in the number of /t/-for-/k/ (manner) errors in the /i/ context.
2) **/d/.** Percent-correct scores for /d/ are substantially higher for the /u/ vowel context than for the /ɑ/ or /i/ contexts. This is attributable to fewer /g/-for-/d/ and /k/-for-/d/ (place) errors when /d/ is presented in the /u/ context.
3) **/m/.** Percent-correct scores for /m/ are highest for the /ɑ/ vowel context, intermediate for the /u/ context, and poorest for the /i/ context. Differences are primarily attributable to the number of /n/-for-/m/ (place) and /l/-for-/m/ (place and manner) errors across the three vowel contexts.
4) **/n/.** Similar to /k/, percent-correct scores for /n/ are substantially higher for the /ɑ/ and /u/ vowel contexts than for the /i/ context. This can be traced primarily to an increase in /m/ (place) errors and secondarily to an increase in /l/-for-/n/ (manner) errors when /n/ is presented in the /i/ context.
5) **/l/.** Percent-correct scores for /l/ show a pattern opposite the most frequently observed pattern of vowel-context effects, with /i/ producing substantially higher scores than /ɑ/ or /u/. This pattern is mainly attributable to a reduction in /n/-for-/l/ (manner) errors for the /i/ context.
6) **/j/.** Similar to /k/ and /n/, /j/ demonstrates clearly higher percent-correct scores for the /ɑ/ and /u/ contexts than for the /i/ context. This stems mainly from an increase in /z/-for-/j/ (place and manner) errors for the /i/ context.

/ɑ/ (all conds)

	p	t	k	b	d	g	tʃ	f	s	ʃ	v	z	ð	m	n	r	l	w	j
p	762	137	113	17	1	10	1	54	8	1	20	2	8	15	10	9	15	14	3
t	72	964	62	1	15	4	28	4	13	5	5	8	9	1	3	3	0	1	2
k	143	176	832	3	1	7	6	6	4	1	0	0	10	2	2	2	5	0	0
b	28	3	1	687	62	13	2	102	10	0	114	7	70	37	9	15	22	16	2
d	1	18	3	26	802	237	0	6	1	1	9	14	22	2	6	5	5	2	40
g	5	6	25	17	245	773	1	6	1	0	19	12	26	1	12	2	6	4	39
tʃ	0	38	4	0	4	6	1036	2	4	83	0	13	4	0	0	0	2	0	4
f	35	4	5	166	11	7	2	614	94	11	46	7	150	27	3	5	1	12	0
s	3	8	0	6	10	4	6	99	810	90	9	86	43	8	5	5	0	1	7
ʃ	0	8	1	0	2	0	67	5	80	1025	0	7	3	0	0	0	0	0	2
v	36	3	5	191	16	25	1	135	12	1	371	45	204	18	17	42	27	40	11
z	1	5	1	3	28	23	1	11	59	11	39	772	93	7	36	12	14	8	76
ð	5	2	5	102	62	40	0	35	13	0	307	77	293	27	69	48	33	47	35
m	19	6	5	28	3	1	0	23	0	1	25	2	5	791	170	18	74	22	7
n	6	6	3	6	13	12	0	5	4	0	5	4	5	124	843	9	60	8	87
r	7	2	1	14	10	13	0	1	2	0	40	9	13	23	56	664	125	151	69
l	2	2	5	2	1	2	0	7	0	1	22	2	7	141	187	109	567	113	30
w	1	0	2	7	1	1	0	1	0	0	64	6	0	16	13	213	174	689	12
j	0	0	1	0	18	19	0	2	1	1	4	47	8	3	53	25	35	12	971

/i/ (all conds)

	p	t	k	b	d	g	tʃ	f	s	ʃ	v	z	ð	m	n	r	l	w	j
p	700	257	97	15	20	40	23	7	5	0	9	2	9	1	3	2	0	1	9
t	40	850	78	1	1	30	159	2	6	8	1	6	10	2	1	2	0	1	2
k	78	427	505	1	1	22	119	6	8	8	2	6	11	0	1	1	2	0	2
b	18	4	5	768	160	26	5	24	7	0	90	9	16	20	8	7	10	7	16
d	2	11	5	114	797	160	3	7	6	2	20	16	9	5	13	2	9	5	14
g	26	56	44	17	281	644	7	6	4	1	13	29	9	1	8	4	3	1	46
tʃ	3	66	7	1	10	54	955	0	13	82	1	3	3	0	0	0	1	0	1
f	21	8	11	76	16	5	10	522	185	27	130	56	94	11	5	8	7	5	3
s	3	5	5	6	2	3	23	182	752	100	17	57	29	5	3	3	3	1	1
ʃ	0	1	0	0	3	4	138	10	74	957	1	3	5	0	0	0	1	1	2
v	14	0	6	125	38	14	3	71	34	8	456	141	155	27	16	30	21	17	24
z	2	0	3	12	9	11	5	19	64	8	109	762	67	17	8	27	28	8	41
ð	21	4	3	169	75	16	2	24	33	5	395	115	151	31	19	47	46	21	23
m	0	0	7	6	1	1	0	4	8	1	16	11	2	498	373	29	167	49	27
n	3	2	3	8	9	5	2	2	13	0	18	13	3	383	471	14	173	43	35
r	3	1	0	7	0	1	1	0	1	1	30	5	4	43	15	609	89	377	13
l	1	1	5	8	3	2	1	1	3	0	41	28	14	97	39	63	775	100	18
w	1	0	1	7	1	0	1	0	1	5	29	3	4	31	17	214	63	812	10
j	3	5	11	10	15	35	9	3	16	4	45	208	23	21	59	28	46	27	632

/u/ (all conds)

	p	t	k	b	d	g	tʃ	f	s	ʃ	v	z	ð	m	n	r	l	w	j
p	585	159	293	6	6	29	0	45	1	1	11	1	9	3	4	5	10	23	9
t	3	994	6	0	8	13	142	0	9	10	1	4	8	0	0	0	1	0	1
k	175	129	848	0	3	10	5	6	2	3	2	2	8	0	0	1	2	3	1
b	8	4	5	616	156	81	5	42	2	0	125	6	63	6	13	20	15	23	10
d	1	26	1	6	1067	45	2	1	0	0	3	7	8	0	2	2	3	1	25
g	19	13	41	48	254	719	0	11	0	0	37	4	23	5	5	3	5	2	11
tʃ	0	61	4	1	6	2	1011	1	10	91	0	8	2	1	0	0	0	0	2
f	6	9	5	68	22	5	3	637	88	10	102	25	170	14	5	10	9	7	5
s	0	6	4	2	0	2	7	24	976	104	2	49	13	1	0	7	1	1	1
ʃ	0	4	2	0	0	0	135	1	72	971	0	10	0	0	0	1	0	0	4
v	11	2	8	62	43	17	3	38	9	0	470	104	142	26	21	99	60	65	20
z	0	4	1	0	7	1	4	6	74	14	37	879	21	6	11	8	8	2	117
ð	6	2	2	79	141	37	0	37	13	0	273	89	308	12	44	29	40	15	73
m	4	4	6	13	6	4	0	6	0	1	27	4	4	556	263	70	132	62	38
n	5	1	3	5	11	2	1	1	0	2	22	5	3	107	873	12	73	13	61
r	1	0	0	11	0	3	0	4	3	0	70	10	13	32	49	680	107	194	23
l	2	1	4	18	10	2	0	3	2	1	86	20	29	142	286	45	443	45	61
w	1	0	0	5	0	4	0	4	3	0	50	6	9	31	11	341	103	616	16
j	1	1	5	0	15	1	0	1	0	8	27	43	3	5	46	26	10	7	1001

Figure 8. Summary confusion matrices for consonants presented in the /ɑ, i/, and /u/ vowel contexts. Each matrix represents the group data for 20 subjects collapsed across the four stimulus conditions tested (initial female, initial male, medial female, and medial male).

A comprehensive analysis of acoustic cues that may underlie the consonant-identification errors described above is beyond the scope of this manuscript. However, for illustrative purposes, we will briefly discuss acoustic features that could account for two of the more prominent vowel-dependent errors: /t/-for-/k/ responses and /m/–/n/ confusions (combined /n/-for-/m/ and /m/-for-/n/ errors). Both types of errors occurred more frequently in the /ɑ/ vowel context than in the /ɑ/ or /u/ contexts.

/t/-for-/k/ errors • These errors reflect an inability to distinguish place-of-articulation cues for /k/ and /t/. The key acoustic cues that encode place of articulation for the stop consonants are the spectrum of the release burst and the patterns of F2 and F3 formant transitions. With respect to the burst spectra, the burst for /t/ has a broad spectrum, with the most intense energy above 3 kHz, whereas the burst for /k/ has a narrower spectrum, with the peak frequency depending on vowel context. For front vowels such as /i/, peak energy in the /k/ burst occurs near 2500 Hz. For back vowels such as /ɑ/ and /u/, which have lower F2 frequencies, peak energy occurs at a lower frequency because of anticipatory coarticulation. It is likely that this lowering of the peak burst frequency for /k/ in the /ɑ/ and /u/ contexts increases the spectral contrast between the /k/ and /t/ bursts, thereby reducing the number of /t/-for-/k/ confusions. Regarding formant transition cues, /t/ and /k/ have similar F2 transitions, which move upward in frequency during the vowel–consonant transition and downward in frequency during the consonant–vowel transition. However, they are distinguished by the F3 transition, which moves parallel to F2 for /t/ but converges on F2 during the closure for /k/. The difference in F3 transitions for /t/ versus /k/ is more obvious for the back vowels /ɑ/ and /u/ than for the front vowel /i/ because F2 is lower and there is a larger frequency separation between F2 and F3.

Overall, the context effects reflected in /t/-for-/k/ errors may be explained by the reduced spectral resolution in CI users. Whereas normal-hearing listeners can distinguish burst spectra and F3 transitions for /k/ and /t/ in both front- and back-vowel contexts, it is likely that CI users have more difficulty distinguishing these features in the front-vowel (/i/) context, resulting in an increased number of /t/-for-/k/ confusions.

/m/–/n/ confusions • Similar to /k/-/t/ errors, confusions between the nasal consonants /m/ and /n/ signify an inability to perceive relevant place-of-articulation cues. Such cues are present in the spectrum of the nasal murmur, the spectral change at consonant release, and the vowel formant transitions (Kurowski & Blumstein, 1984; Repp, 1986). However, they are weakened by variable antiresonances associated with nasalization of the consonant and surrounding vowels (Pickett, 1999). Our finding that /m/–/n/ confusions occur most frequently for the /i/ vowel context is consistent with perceptual data reported by Repp (1986) in normal-hearing listeners. Repp (1986) showed that spectral cues distinguishing /m/ and /n/ vary with vowel context and are weaker for /i/ than for /ɑ/ and /u/. In the /ɑ/ and /u/ contexts, /m/–/n/ distinctions can be achieved by using spectral information from any brief portion of the nasal murmur or vowel transition. In the /i/ context, /m/–/n/ distinctions seem to require the combined information from both sources. Given the reduced redundancy of spectral place-of-articulation cues for the /i/ context, it is not surprising that this context produces the greatest number of /m/–/n/ confusions for CI listeners.

DISCUSSION

A general result of this study is that the "average" CI user achieves higher consonant-recognition scores when consonants are presented in an /ɑ/ or /u/ vowel context than when consonants are presented in an /i/ vowel context. This basic finding was observed for consonants presented in both initial and medial positions and was generally true for both male and female talkers. However, the decrement in performance for the /i/ vowel context was relatively small. If the group data shown in Figures 1 and 2 are combined across consonant position (initial, medial) and talker gender (male, female), the resulting mean scores are 62.6% for the /ɑ/ vowel context, 56.0% for the /i/ vowel context, and 62.5% for the /u/ vowel context. This corresponds to an average performance difference of approximately 6.5% between the /ɑ/ or /u/ contexts, which produce higher scores, and the /i/ context, which produces lower scores.

In contrast to the mean data, some individual subjects showed large differences in consonant-recognition scores across different vowel contexts (Fig. 3). Differences generally reflected better performance with the /ɑ/ and /u/ vowel contexts than with the /i/ context, as expected from the group data. Even so, differences were not systematic or predictable. For a given subject, the magnitude of vowel-context differences varied across the four combinations of consonant position (initial, medial) and talker gender (male, female). Moreover, the magnitude of vowel-context effects was unrelated to subjects' overall performance.

From a clinical perspective, testing consonant recognition in a single vowel context could provide misleading results. A more meaningful estimate could be obtained by testing each individual with a variety of vowel contexts; however, as stated earlier, this process would be time consuming and, thus, impractical for many clinical and research applications. Our findings suggest that a reasonable compromise might involve testing with two vowel contexts: /ɑ/ and /i/. The /ɑ/ context has been used predominantly in the past and, therefore, allows for comparison of past performance with current and future performance, both within subjects and between groups of subjects using earlier- and later-generation CIs. The /ɑ/ vowel context also seems to provide an estimate of "better" consonant recognition in most subjects. Inclusion of the /i/ context would provide a second estimate of performance for a more difficult stimulus condition. By combining the estimates of consonant recognition obtained using the /ɑ/ and /i/ contexts, a more accurate estimate of overall performance would be obtained. Additional data concerning the effects of vowel context on consonant recognition for vowels other than /ɑ, i/, and /u/ could lead to further refinement of this testing strategy. It is possible that other vowel contexts produce consistently higher or lower performance than the three that were evaluated in the present study. If so, then a different combination of vowel contexts may be required to obtain a "fair" estimate of CI users' consonant-recognition abilities.

It should be noted that several factors other than vowel context are likely to affect CI users' consonant recognition for isolated phonemes in quiet. In particular, stimulus level can have dramatic effects on consonant recognition (Donaldson & Allen, 2003; Skinner, Holden, Holden, et al., 1997) primarily because of changes in the audibility of low-level cues such as those related to place of articulation (Donaldson & Allen, 2003). Stimuli in the present study were presented at a stimulus level of 60 dBA, which corresponds to normally-loud speech (Pearsons, Bennet & Fidel, 1976) and is typical of stimulus levels used for clinical testing. The use of higher or lower stimulus levels could potentially alter relative performance across different vowel contexts for some consonants, but we would not expect it to alter the main outcomes of this study.

The present data reinforce the well-established notion that spectral cues are a key factor limiting speech recognition in many CI users. Spectral (place of articulation) cues were seen to be the most poorly transmitted cues in the feature analysis performed on the group data (Fig. 7) and were also the primary source of vowel-context effects for six key consonants. In contrast, voicing and manner cues, which are coded primarily by temporal aspects of the speech signal, were transmitted with greater accuracy. It is not clear how CI users' limited perception of consonant place cues is affected by the brief duration, dynamic nature, and (sometimes) low amplitudes of these cues. Several studies have related spectral speech-cue transmission to psychophysical tasks of spectral resolution (Donaldson & Nelson, 2000; Henry & Turner, 2003; Nelson, Van Tasell, Schroder, et al., 1995), but these studies have used long-duration psychophysical stimuli. To date, there has been little focus on spectral resolution for brief stimuli that would be comparable in duration with consonant place cues such as formant transitions and stop-consonant bursts. A potentially relevant observation from the present study is that two subjects (D01, N14) achieved very high scores (90% correct) on the vowel-recognition task but much lower consonant-recognition scores (56 to 57%) (Table 1). Feature analyses of their individual consonant-confusion data (not shown) indicate that the latter scores were limited primarily by place-of-articulation errors. Thus, it appears that these subjects were able to make use of long-duration spectral cues necessary for vowel identification but were unable to make use of brief-duration spectral cues to distinguish consonant place of articulation. Additional research is needed to elucidate the nature of spectral cue limitations in both better- and poorer-performing CI users. There is likely a hierarchy of processing for spectral cues in which long-duration, static spectral cues are easiest for CI users to perceive, and short-duration, transient spectral cues are more difficult. This possibility could be evaluated in psychophysical experiments that explore the effects of stimulus characteristics (e.g., duration and complexity) on spectral discrimination or through detailed analyses of speech-error patterns. With respect to error analyses, the group confusion matrices provided in the Appendix may provide useful data. These matrices contain substantial information beyond that explored in the present study and could be used to address a number of more detailed questions concerning consonant perception in CI users.‡

Loizou et al. (2000) have suggested that consonants presented in the /ɑCɑ/ format are less sensitive to performance changes with stimulation rate than consonants presented in the /iCi/ or /uCu/ contexts. We did not address this possibility directly in the present study, but we did look for differences in vowel-context effects across groups of subjects using different stimulation rates in their clinical speech processors. Although we failed to observe any systematic differences of this type, our finding does not rule out the possibility that changes in stimulation rate produce greater improvements for consonants presented in one vowel context versus another. It should be noted that Loizou et al. (2000) used small numbers of stimuli in their study, so it is not clear whether the differences they observed were statistically significant. Thus, a replication of their findings may be warranted. Because consonant recognition is frequently used to assess the perceptual effects of changes to a CI user's speech-processor

‡On request, confusion matrices are available in Microsoft Excel format to interested investigators.

map, the general issue of which stimuli are best for evaluating such changes should be addressed explicitly in future research.

SUMMARY AND CONCLUSIONS

1) The average consonant-recognition scores of CI users are slightly (6.5%) but significantly higher for consonants presented in an /ɑ/ or /u/ context than for consonants presented in an /i/ context. These effects of vowel context occur for both initial and medial consonants and appear to be independent of the overall level of a subject's consonant-recognition performance, his or her ability to identify the surrounding vowels, and the stimulation rates used in his or her speech processor. These effects are also largely independent of talker gender.

2) In contrast to the group mean data, some individual subjects show large (>15%) differences in percent-correct consonant recognition across different vowel contexts. These individual differences almost always reflect the same patterns observed in the average data; namely, performance for the /ɑ/ and /u/ vowel contexts is higher than performance for the /i/ context.

3) Further research is needed to explore the effects of vowel context on consonant recognition for vowels other than those assessed in the present study and to determine which vowel contexts are most sensitive to parametric changes in CI speech-processor maps. Until such data are obtained, it is recommended that consonant recognition be tested in two vowel contexts, /ɑ/ and /i/, which represent an easier and a more difficult condition for the typical CI user.

4) Vowel context primarily affects subjects' perceptions of the place-of-articulation feature, with secondary effects on manner of articulation. Context effects are not distributed equally across consonants but are concentrated on a subset of six consonants (/d, j, n, k, m/, and /l/) that show effects of 25 to 35%. Three of these consonants (/j, n/, and /k/) show performance patterns similar to the group mean pattern (/ɑ/ and /u/ yield higher scores than /i/), whereas each of the others shows a different pattern. Several other consonants show strong context effects in either the consonant-initial or consonant-medial positions. In general, vowel-context effects tend to be strongest for the voiced stops, nasals, and glide liquids and weakest for the unvoiced fricatives and unvoiced affricates.

5) CI users demonstrate poor perception of consonant place-of-articulation cues. Additional research is needed to identify factors that limit or enhance listeners' perceptions of these brief spectral cues.

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APPENDIX

Confusion matrices showing the combined stimulus-response data for all 20 subjects for each of the 12 stimulus sets tested in the present study. Labels along the left side of each matrix indicate the stimulus presented; labels across the top indicate the subject's response.

/Cɑ/ female

	p	t	k	b	d	g	tʃ	f	s	ʃ	v	z	ð	m	n	r	l	w	j
p	197	25	24	1	0	4	1	3	1	0	4	1	1	4	5	6	10	10	3
t	23	241	9	1	4	1	10	1	2	2	2	0	1	0	1	1	0	0	1
k	52	32	203	1	0	4	0	0	0	0	0	0	2	2	0	0	4	0	0
b	4	0	1	200	17	5	1	29	1	0	14	0	7	6	1	4	4	5	1
d	0	0	0	0	228	48	0	2	0	0	1	2	1	0	2	0	0	1	15
g	0	1	3	4	80	186	1	2	1	0	3	1	5	0	0	1	1	1	10
tʃ	0	7	2	0	1	4	244	0	3	31	0	4	0	0	0	0	0	0	4
f	15	1	1	72	0	4	0	147	13	5	14	0	24	2	0	2	0	0	0
s	2	2	0	3	6	4	1	47	171	13	3	11	24	4	0	2	0	1	6
ʃ	0	3	0	0	2	0	21	1	35	231	0	3	2	0	0	0	0	0	2
v	9	0	1	65	4	4	0	55	0	0	91	3	43	4	4	4	3	6	4
z	1	2	0	0	7	6	0	9	23	6	13	159	33	2	5	2	7	3	22
ð	2	0	2	26	22	5	0	16	3	0	64	9	86	3	17	10	10	10	15
m	7	0	1	6	0	1	0	3	0	1	5	0	1	188	54	5	16	7	5
n	0	0	0	1	0	2	0	2	1	0	2	1	4	25	206	0	17	1	38
r	4	1	0	4	1	2	0	1	1	0	9	2	5	10	23	123	27	51	36
l	1	0	1	0	0	0	0	3	0	0	5	0	3	39	59	11	138	21	19
w	0	0	0	1	0	1	0	0	0	0	18	1	0	4	1	54	30	189	1
j	0	0	1	0	4	0	0	1	0	1	2	18	4	1	25	13	5	5	220

/Ci/ female

	p	t	k	b	d	g	tʃ	f	s	ʃ	v	z	ð	m	n	r	l	w	j
p	164	59	44	2	2	4	15	1	4	0	1	2	0	0	0	0	0	0	2
t	8	195	22	1	1	5	50	1	4	3	0	3	1	2	1	1	0	0	2
k	22	107	127	0	1	4	22	1	2	3	0	3	4	0	1	0	1	0	2
b	4	3	0	188	40	6	1	10	2	0	23	4	8	1	0	2	1	4	3
d	0	1	1	41	198	36	0	2	0	1	6	0	0	1	4	0	4	1	4
g	5	8	10	4	38	195	4	0	2	0	5	12	1	1	1	1	0	0	13
tʃ	1	16	2	1	6	8	232	0	12	18	0	1	2	0	0	0	1	0	0
f	6	2	1	31	9	2	1	138	36	2	33	9	20	1	1	1	4	3	0
s	3	5	4	6	1	2	6	79	142	26	8	8	5	1	1	1	1	1	0
ʃ	0	1	0	0	1	1	19	1	22	244	1	3	3	0	0	0	1	1	2
v	5	0	2	15	12	6	2	20	14	3	117	32	39	3	1	6	6	8	9
z	0	0	3	8	5	5	2	11	24	2	35	145	22	5	0	4	8	5	16
ð	4	1	2	45	17	7	2	13	5	3	94	29	43	4	4	4	9	4	10
m	0	0	0	1	0	0	0	0	0	0	4	1	0	145	81	11	28	23	6
n	2	0	0	3	3	0	0	0	0	0	5	2	1	113	112	3	35	13	8
r	0	1	0	2	0	0	1	0	1	1	5	2	0	24	5	147	30	76	5
l	0	0	0	7	1	1	0	1	0	0	16	7	3	27	10	13	173	30	11
w	1	0	1	4	0	0	1	0	0	2	3	1	1	9	6	59	30	182	0
j	2	2	4	1	2	8	5	2	1	2	7	29	4	8	25	5	11	7	175

/Cu/ female

	p	t	k	b	d	g	tʃ	f	s	ʃ	v	z	ð	m	n	r	l	w	j
p	116	55	84	0	1	6	0	9	1	1	5	1	3	0	3	0	5	5	5
t	0	262	1	0	0	0	31	0	1	4	0	1	0	0	0	0	0	0	0
k	34	37	211	0	1	4	1	2	2	0	0	1	4	0	0	0	0	3	0
b	1	3	2	165	37	9	1	13	1	0	30	0	19	2	3	5	0	5	4
d	0	7	0	1	265	17	0	0	0	0	1	1	0	0	0	0	0	0	8
g	1	8	2	16	118	134	0	4	0	0	6	1	1	1	0	1	2	0	5
tʃ	0	23	1	0	2	0	233	0	1	32	0	7	0	0	0	0	0	0	1
f	1	1	2	28	10	1	0	151	16	4	24	8	41	4	2	0	1	4	2
s	0	2	4	2	0	0	1	16	246	13	1	6	5	0	0	4	0	0	0
ʃ	0	0	1	0	0	0	53	0	27	218	0	1	0	0	0	0	0	0	0
v	4	1	2	11	9	5	1	19	2	0	119	26	23	4	2	30	18	18	6
z	0	1	1	0	2	0	1	2	19	3	21	206	5	1	2	2	1	1	32
ð	3	1	0	27	12	1	0	25	9	0	81	30	53	5	11	6	15	8	13
m	1	0	0	9	1	3	0	3	0	0	9	0	0	110	62	20	54	20	8
n	0	0	1	1	4	1	0	0	0	0	9	3	1	26	207	4	25	2	16
r	0	0	0	2	0	1	0	2	1	0	43	6	3	12	13	151	25	36	5
l	1	1	2	14	1	0	0	3	0	0	38	4	9	44	73	16	71	9	14
w	1	0	0	0	0	1	0	0	1	0	15	0	2	7	3	98	20	148	4
j	1	0	0	0	4	0	0	0	0	0	7	10	0	3	22	1	1	1	250

/Cɑ/ male

	p	t	k	b	d	g	tʃ	f	s	ʃ	v	z	ð	m	n	r	l	w	j
p	176	25	30	6	1	4	0	26	1	1	10	0	3	7	2	2	2	4	0
t	24	227	21	0	6	1	4	2	5	1	0	1	3	1	1	1	0	1	1
k	25	41	224	1	0	1	2	1	0	1	0	0	1	0	0	2	1	0	0
b	9	2	0	175	5	3	0	34	1	0	19	0	12	7	6	6	12	8	1
d	1	1	0	17	175	52	0	3	1	1	8	2	9	2	4	2	4	0	18
g	4	2	15	8	59	161	0	3	0	0	7	1	15	1	1	0	3	2	18
tʃ	0	4	0	0	0	1	250	1	1	38	0	2	3	0	0	0	0	0	0
f	10	0	2	75	9	1	0	112	12	2	24	0	34	8	0	3	1	7	0
s	0	0	0	3	3	0	1	11	192	15	1	57	12	0	2	2	0	0	1
ʃ	0	1	1	0	0	0	32	2	24	236	0	3	1	0	0	0	0	0	0
v	5	1	1	65	4	2	0	26	3	1	92	5	42	8	3	10	13	18	1
z	0	1	0	0	4	12	1	1	3	1	4	205	18	0	8	3	4	2	33
ð	3	1	3	44	15	14	0	17	3	0	51	9	49	13	11	23	8	20	16
m	8	4	2	9	1	0	0	11	0	0	10	1	1	190	23	6	30	4	0
n	2	4	2	0	4	6	0	2	1	0	2	2	1	45	176	4	24	3	22
r	2	1	1	0	0	2	0	0	1	0	9	0	6	5	12	183	26	44	8
l	1	1	1	1	0	2	0	1	0	0	8	2	4	39	42	37	102	59	0
w	1	0	0	1	0	0	0	0	0	0	15	1	0	9	3	56	36	174	4
j	0	0	0	0	4	12	0	1	1	0	2	8	0	1	10	3	14	5	239

/Ci/ male

	p	t	k	b	d	g	tʃ	f	s	ʃ	v	z	ð	m	n	r	l	w	j
p	164	51	30	4	11	25	1	1	0	0	3	0	0	0	3	0	0	1	6
t	3	235	24	0	0	1	24	1	1	3	1	2	4	0	0	0	0	1	0
k	12	77	156	1	0	3	37	3	3	5	1	1	1	0	0	0	0	0	0
b	1	0	5	145	52	16	1	13	2	0	17	0	6	16	5	1	7	1	12
d	1	3	4	28	188	41	2	4	1	1	6	0	2	3	4	0	3	1	8
g	1	3	14	4	59	169	1	0	0	0	4	3	3	0	6	2	3	1	27
tʃ	0	9	5	0	0	24	210	0	1	46	1	2	1	0	0	0	0	0	1
f	0	1	9	21	4	2	5	118	45	20	36	9	22	4	1	0	1	0	2
s	0	0	1	0	0	0	8	16	238	11	5	12	7	0	0	1	1	0	0
ʃ	0	0	0	0	0	3	60	0	1	235	0	0	1	0	0	0	0	0	0
v	0	0	3	30	15	5	1	5	3	1	102	24	56	10	10	10	8	6	11
z	0	0	0	0	1	4	3	3	8	2	14	222	17	2	1	8	2	2	11
ð	0	3	1	43	14	5	0	6	3	1	82	28	50	8	11	15	10	11	9
m	0	0	5	2	1	1	0	1	1	1	10	0	2	111	111	7	25	14	8
n	0	2	3	1	2	1	0	2	1	0	11	0	2	85	125	4	21	20	20
r	2	0	0	2	0	1	0	0	0	0	9	1	3	9	5	151	20	90	7
l	1	0	5	0	1	0	0	0	0	0	14	2	11	22	12	16	181	33	2
w	0	0	0	0	0	0	0	0	0	3	9	0	2	9	9	43	15	202	8
j	1	2	6	4	3	12	2	0	1	1	9	20	4	5	14	4	4	3	205

/Cu/ male

	p	t	k	b	d	g	tʃ	f	s	ʃ	v	z	ð	m	n	r	l	w	j
p	132	17	74	2	0	8	0	31	0	0	6	0	3	3	0	2	1	18	3
t	1	261	2	0	1	1	25	0	4	3	0	0	2	0	0	0	0	0	0
k	43	17	230	0	1	2	1	0	0	0	2	0	1	0	0	1	1	0	1
b	2	0	1	174	28	6	1	12	1	0	38	0	7	2	2	4	5	11	6
d	0	1	0	4	274	8	0	0	0	0	0	4	0	0	2	0	0	0	7
g	6	1	10	15	56	179	0	1	0	0	14	1	4	2	3	0	2	1	5
tʃ	0	10	2	0	2	0	235	0	4	46	0	1	0	0	0	0	0	0	0
f	1	4	1	31	3	0	1	169	25	4	40	0	13	1	0	2	1	2	2
s	0	1	0	0	0	1	0	1	271	9	0	14	1	1	0	1	0	0	0
ʃ	0	1	1	0	0	0	52	0	5	239	0	1	0	0	0	0	0	0	1
v	2	0	5	21	15	6	0	5	2	0	127	10	17	11	3	18	24	29	5
z	0	0	0	0	1	0	3	1	8	3	11	231	5	3	4	3	2	0	25
ð	1	0	0	34	28	17	0	5	1	0	105	7	46	5	10	3	5	4	29
m	1	0	6	2	0	0	0	2	0	0	11	0	3	185	32	5	25	14	14
n	1	0	2	0	0	0	0	1	0	2	10	2	2	37	193	2	19	2	27
r	0	0	0	8	0	0	0	1	1	0	5	1	0	3	3	193	3	77	5
l	1	0	2	2	2	1	0	0	0	0	22	6	1	41	68	7	104	23	20
w	0	0	0	4	0	0	0	4	0	0	17	0	0	8	0	64	14	188	1
j	0	1	3	0	3	0	0	0	0	0	6	8	0	0	14	1	2	1	261

/ɑCɑ/ female

	p	t	k	b	d	g	tʃ	f	s	ʃ	v	z	ð	m	n	r	l	w	j
p	215	45	21	5	0	0	0	3	2	0	3	1	2	1	0	1	1	0	0
t	21	247	19	0	0	0	6	0	3	0	0	0	2	0	1	1	0	0	0
k	36	42	207	0	1	0	2	3	4	0	0	0	4	0	1	0	0	0	0
b	8	0	0	176	18	4	1	5	4	0	37	2	19	13	2	2	6	3	0
d	0	4	0	1	193	90	0	1	0	0	0	2	4	0	0	1	1	1	2
g	1	2	4	1	48	240	0	1	0	0	0	1	0	0	1	0	1	0	0
tʃ	0	12	0	0	3	0	272	0	0	7	0	5	0	0	0	0	1	0	0
f	4	2	1	1	0	0	1	187	45	3	3	5	34	10	0	0	0	4	0
s	0	3	0	0	1	0	1	23	210	40	3	9	3	4	3	0	0	0	0
ʃ	0	3	0	0	0	0	4	1	10	281	0	1	0	0	0	0	0	0	0
v	17	2	3	36	1	3	0	26	7	0	112	12	52	3	2	8	3	10	3
z	0	2	1	2	11	3	0	1	22	1	13	182	30	4	14	4	1	0	9
ð	0	1	0	24	16	7	0	1	3	0	106	22	80	5	15	7	5	8	0
m	0	0	0	5	0	0	0	0	0	0	4	0	0	226	37	4	15	8	1
n	2	1	0	0	3	0	0	0	0	0	1	0	0	16	246	2	8	1	20
r	0	0	0	9	9	9	0	0	0	0	13	6	2	4	6	150	32	41	19
l	0	0	0	0	0	0	0	0	0	1	1	0	0	26	58	33	154	19	8
w	0	0	1	1	0	0	0	0	0	0	14	2	0	2	5	54	48	168	5
j	0	0	0	0	5	1	0	0	0	0	0	8	3	1	8	3	4	2	265

/iCi/ female

	p	t	k	b	d	g	tʃ	f	s	ʃ	v	z	ð	m	n	r	l	w	j
p	206	64	10	0	4	7	6	0	0	0	0	0	1	0	0	1	0	0	1
t	17	187	16	0	0	8	64	0	0	2	0	1	4	0	0	1	0	0	0
k	34	129	93	0	0	7	26	2	3	0	0	2	4	0	0	0	0	0	0
b	1	0	0	194	57	0	1	0	1	0	34	3	2	0	1	3	2	1	0
d	0	6	0	21	206	49	1	1	4	0	0	7	2	0	0	1	1	1	0
g	17	7	7	6	101	151	0	0	0	1	0	8	1	0	0	0	0	0	1
tʃ	1	35	0	0	3	11	243	0	0	7	0	0	0	0	0	0	0	0	0
f	7	2	1	11	2	0	0	137	54	2	27	25	21	4	1	3	1	1	1
s	0	0	0	0	0	1	4	53	162	51	3	14	7	2	1	1	1	0	0
ʃ	0	0	0	0	1	0	37	5	24	233	0	0	0	0	0	0	0	0	0
v	3	0	0	23	6	3	0	24	8	2	111	65	26	9	3	8	5	2	2
z	0	0	0	3	1	0	0	5	20	2	44	156	20	8	4	11	15	0	11
ð	3	0	0	44	20	2	0	3	19	1	114	41	27	5	1	9	5	2	4
m	0	0	0	0	0	0	0	0	4	0	0	4	0	141	72	7	58	7	7
n	1	0	0	0	2	3	2	0	9	0	1	4	0	91	118	1	62	3	3
r	1	0	0	1	0	0	0	0	0	0	8	1	1	3	2	160	27	95	1
l	0	1	0	0	1	1	1	0	2	0	1	11	0	25	9	9	228	7	4
w	0	0	0	1	1	0	0	0	0	0	5	0	1	5	2	63	16	206	0
j	0	1	0	3	6	3	2	0	11	0	14	75	6	6	13	8	28	8	116

/uCu/ female

	p	t	k	b	d	g	tʃ	f	s	ʃ	v	z	ð	m	n	r	l	w	j
p	152	49	73	1	2	13	0	4	0	0	0	0	1	0	0	2	2	0	1
t	2	240	0	0	2	1	48	0	2	3	1	0	0	0	0	0	0	0	1
k	39	37	212	0	1	3	2	2	0	2	0	0	1	0	0	0	1	0	0
b	2	0	2	112	42	48	2	2	0	0	40	2	19	2	5	10	6	6	0
d	0	1	0	1	266	11	0	0	0	0	2	2	3	0	0	2	3	1	8
g	3	1	9	8	47	214	0	0	0	0	9	0	5	0	1	2	1	0	0
tʃ	0	13	1	1	2	2	268	0	3	6	0	0	2	1	0	0	0	0	1
f	1	1	2	2	4	2	1	172	10	0	27	9	53	1	2	7	5	0	1
s	0	2	0	0	0	1	3	6	215	54	0	14	3	0	0	1	0	1	0
ʃ	0	3	0	0	0	0	20	0	26	240	0	8	0	0	0	0	0	0	3
v	3	0	1	10	3	1	0	4	2	0	96	38	51	6	14	42	12	9	8
z	0	2	0	0	2	0	0	3	26	5	5	204	5	0	0	3	4	1	40
ð	2	1	2	11	41	6	0	5	1	0	45	21	104	1	16	12	10	1	21
m	1	2	0	0	0	0	0	0	0	0	3	0	0	123	76	34	36	20	5
n	2	1	0	0	3	0	1	0	0	0	1	0	0	23	234	3	21	6	5
r	1	0	0	1	0	2	0	1	1	0	19	1	8	9	17	159	37	36	8
l	0	0	0	1	5	0	0	0	1	0	19	3	12	30	57	10	139	8	15
w	0	0	0	1	0	0	0	0	1	0	7	1	3	7	5	101	41	129	4
j	0	0	0	0	6	0	0	1	0	4	10	12	1	0	1	15	4	1	245

/ɑCɑ/ male

	p	t	k	b	d	g	tʃ	f	s	ʃ	v	z	ð	m	n	r	l	w	j
p	174	42	38	5	0	2	0	22	4	0	3	0	2	3	3	0	2	0	0
t	4	249	13	0	5	2	8	1	3	2	3	7	3	0	0	0	0	0	0
k	30	61	198	1	0	2	2	2	0	0	0	0	3	0	1	0	0	0	0
b	7	1	0	136	22	1	0	34	4	0	44	5	32	11	0	3	0	0	0
d	0	13	3	8	206	47	0	0	0	0	0	8	8	0	0	2	0	0	5
g	0	1	3	4	58	186	0	0	0	0	9	9	6	0	10	1	1	1	11
tʃ	0	15	2	0	0	1	270	1	0	7	0	2	1	0	0	0	1	0	0
f	6	1	1	18	2	2	1	168	24	1	5	2	58	7	3	0	0	1	0
s	1	3	0	0	0	0	3	18	237	22	2	9	4	0	0	1	0	0	0
ʃ	0	1	0	0	0	0	10	1	11	277	0	0	0	0	0	0	0	0	0
v	5	0	0	25	7	16	1	28	2	0	76	25	67	3	8	20	8	6	3
z	0	0	0	1	6	2	0	0	11	3	9	226	12	1	9	3	2	3	12
ð	0	0	0	8	9	14	0	1	4	0	86	37	78	6	26	8	10	9	4
m	4	2	2	8	2	0	0	9	0	0	6	1	3	187	56	3	13	3	1
n	2	1	1	5	6	4	0	1	2	0	0	1	0	38	215	3	11	3	7
r	1	0	0	1	0	0	0	0	0	0	9	1	0	4	15	208	40	15	6
l	0	1	3	1	1	0	0	3	0	0	8	0	0	37	28	28	173	14	3
w	0	0	1	4	1	0	0	1	0	0	17	2	0	1	4	49	60	158	2
j	0	0	0	0	5	6	0	0	0	0	0	13	1	0	10	6	12	0	247

/iCi/ male

	p	t	k	b	d	g	tʃ	f	s	ʃ	v	z	ð	m	n	r	l	w	j
p	166	83	13	9	3	4	1	5	1	0	5	0	8	1	0	1	0	0	0
t	12	233	16	0	0	16	21	0	1	0	0	0	1	0	0	0	0	0	0
k	10	114	129	0	0	8	34	0	0	0	1	0	2	0	0	1	1	0	0
b	12	1	0	241	11	4	2	1	2	0	16	2	0	3	2	1	0	1	1
d	1	1	0	24	205	34	0	0	1	0	8	9	5	1	5	1	1	2	2
g	3	38	13	3	83	129	2	6	2	0	4	6	4	0	1	1	0	0	5
tʃ	1	6	0	0	1	11	270	0	0	11	0	0	0	0	0	0	0	0	0
f	8	3	0	13	1	1	4	129	50	3	34	13	31	2	2	4	1	1	0
s	0	0	0	0	1	0	5	34	210	12	1	23	10	2	1	0	0	0	1
ʃ	0	0	0	0	1	0	22	4	27	245	0	0	1	0	0	0	0	0	0
v	6	0	1	57	5	0	0	22	9	2	126	20	34	5	2	6	2	1	2
z	2	0	0	1	2	2	0	0	12	2	16	239	8	2	3	4	3	1	3
ð	14	0	0	37	24	2	0	2	6	0	105	17	31	14	3	19	22	4	0
m	0	0	2	3	0	0	0	3	3	0	2	6	0	101	109	4	56	5	6
n	0	0	0	4	2	1	0	0	3	0	1	7	0	94	116	6	55	7	4
r	0	0	0	2	0	0	0	0	0	0	8	1	0	7	3	151	12	116	0
l	0	0	0	1	0	0	0	0	1	0	10	8	0	23	8	25	193	30	1
w	0	0	0	2	0	0	0	0	1	0	12	2	0	8	0	49	2	222	2
j	0	0	1	2	4	12	0	1	3	1	15	84	9	2	7	11	3	9	136

/uCu/ male

	p	t	k	b	d	g	tʃ	f	s	ʃ	v	z	ð	m	n	r	l	w	j
p	185	38	62	3	3	2	0	1	0	0	0	0	2	0	1	1	2	0	0
t	0	231	3	0	5	11	38	0	2	0	0	3	6	0	0	0	1	0	0
k	59	38	195	0	0	1	1	2	0	1	0	1	2	0	0	0	0	0	0
b	3	1	0	165	49	18	1	15	0	0	17	4	18	0	3	1	4	1	0
d	1	17	1	0	262	9	2	1	0	0	0	0	5	0	0	0	0	0	2
g	9	3	20	9	33	192	0	6	0	0	8	2	13	2	1	0	0	1	1
tʃ	0	15	0	0	0	0	275	1	2	7	0	0	0	0	0	0	0	0	0
f	3	3	0	7	5	2	1	145	37	2	11	8	63	8	1	1	2	1	0
s	0	1	0	0	0	0	3	1	244	28	1	15	4	0	0	1	1	0	1
ʃ	0	0	0	0	0	0	10	1	14	274	0	0	0	0	0	1	0	0	0
v	2	1	0	20	16	5	2	10	3	0	128	30	51	5	2	9	6	9	1
z	0	1	0	0	2	1	0	0	21	3	0	238	6	2	5	0	1	0	20
ð	0	0	0	7	60	13	0	2	2	0	42	31	105	1	7	8	10	2	10
m	1	2	0	2	5	1	0	1	0	1	4	4	1	138	93	11	17	8	11
n	2	0	0	4	4	1	0	0	0	0	2	0	0	21	239	3	8	3	13
r	0	0	0	0	0	0	0	0	0	0	3	2	2	8	16	177	42	45	5
l	0	0	0	1	2	1	0	0	1	1	7	7	7	27	88	12	129	5	12
w	0	0	0	0	0	3	0	0	1	0	11	5	4	9	3	78	28	151	7
j	0	0	2	0	2	1	0	0	0	4	4	13	2	2	9	9	3	4	245

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