Published in final edited form as:

Otol Neurotol. 2011 April ; 32(3): 413–418. doi:10.1097/MAO.0b013e31820d9613.

Spoken Word Recognition in Adolescent Cochlear Implant Users During Quiet and Multi-Speaker Babble Conditions

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Abstract

Objective—To assess overall speech intelligibility in adolescent cochlear implanted speakers during quiet and multi-speaker babble conditions.

Study design—A cross sectional assessment of intelligibility incorporating group (auditory-oral versus total communication speakers), sentence context (high versus low contexts) and background conditions (quiet versus multi-speaker babble).

Setting—A camp designed to assess adolescents over a concentrated period of time. Participants: 57 adolescents who participated in an earlier study when they were 8 – 9 years old examining functional outcomes of speech perception, speech production and language were asked to participate in follow-up study.

Methods—Speech intelligibility was assessed by asking the adolescents to repeat sentences. Sentences were digitally edited and played to normal hearing listeners who either provided broad transcriptions of sound accuracy or wrote down the words they understood when the sentences were presented in quiet and in multi-speaker babble.

Main Outcome Variable—The dependent variables were percent correct consonants, vowels and total words identified.

Results—Very few substitutions or omissions occurred,--resulting in high levels of accuracy for consonants and vowels. Speech intelligibility in quiet was significantly greater than in the multi-speaker babble condition. Multi-speaker babble decreased performance uniformly across sentence context for the two groups.

Conclusion—Accurate consonant production based on measures of substitutions and omissions fails to account for distortions and allophonic variations. Reductions in speech intelligibility relative to the phoneme correct productions suggest the allophonic variations related to distortions may influence naïve listener's ability to understand the speech of profoundly deaf individuals.

Introduction

Multichannel cochlear implants (CI) provide an electrical representation of speech that appears useful for obtaining accurate perception and production of messages, particularly in

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Disclosure of Funding: National Institutes of Deafness and Other Communication Disorders

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young children experiencing profound hearing losses. CIs pick up acoustic signals via an externally worn microphone and send the signals to a speech processor that uses signal processing software to extract important aspects of the signal (1;2). These outputs are sent across the skull to an internal receiver that routes the electrical representations to a surgically implanted electrode array in the cochlea (1;2). Speech perception and production continues to improve in accuracy with increased experience with CIs (3–11). Increases in speech production accuracy are evident across consonant and vowel productions (4;5;9;12), suprasegmentals (13;14), words and sentences (9;15–17). Improvement in overall accuracy of listeners' understanding of spoken words (i.e., speech intelligibility) also is noted as children gain more experience with their CIs (8;13;15;18). However, most CI studies are limited to evaluating the speech of children in primary school ages and few studies evaluate the speech of children reaching adolescent ages.

A large proportion of the very first children to receive CIs are now making their way through adolescence into early adulthood. We examined the speech production of a group of adolescents whose speech also was assessed during their elementary school ages. These children represent a small subset of a larger population used to examine speech production, perception, language and reading outcomes at 8 and 9 years of age (6;7;11;19;20) and at their current ages of 15 to 18 years. We focus our attention first on the levels of performance achieved by adolescents with profound hearing losses who received a CI when candidacy guidelines restricted surgery to children 24 months or older and with no-open set recognition. Second, we introduce a new technique for assessing speech samples acquired in older speakers as a means of testing the stability of intelligibility of deaf speakers.

Spoken communication by CI users requires a two-person dyad, the CI speaker and the receiver (typically, an individual with either normal hearing or some degree of hearing loss) (21). Reductions in accuracy of understanding the words in a message may occur when the speaker produces inaccuracies or when the listener perceives inaccuracies. A listener's ability to accurately understand the speech of hearing impaired individuals is impacted by the conditions of the listening environment, including the level and type of background noise (22;23). Several studies indicate normal hearing listeners experience degradation in performance on many language-related tasks when asked to do those tasks in situations with backgrounds containing multiple speech sources (22;23). Speech intelligibility increases in quiet situations with good signal-to-noise (S/N) ratios and declines as the S/N ratios decline, particularly if the noisy background is speech-related (24–26). As CI children near adulthood, they will be required to communicate with listening partners in an increasing number of situations with background noise. In order to examine the intelligibility of the CI adolescents in backgrounds composed of multiple speakers, we examined how normal hearing listeners with limited experience listening to deaf speakers understood the speech of adolescence CI speakers in quiet conditions and in conditions with multiple speakers. We hypothesized that the greatest deterioration in performance during the multi-speaker condition was associated with CI individuals whose speech was less accurately identified in quiet situations.

Methods

All procedures for the study were approved by the Institutional Review Board of the University of Texas at Dallas and all participants signed consent forms. The protocol was submitted by the first author (UTD 08-51).

CI Speaker Participants

Fifty-seven adolescents participated in the study. Mean age of the participants was 16.7 years (standard deviation (SD) 0.6 years) and 28 of the group were female. The average age of implantation was 3.5 years (SD .8 years). All adolescents were unilaterally implanted with Cochlear Corporation devices and used their devices for an average of 13.22 years (SD 1.0 years). Twenty-five of the adolescents reported they used total communication and 32 adolescents reported they used auditory oral modes of communication. Average speech perception performance was 52.0% (SD 25.5%) for the Lexical Neighborhood Test (16) (ranging from 14% to 90%) and 71.2% (SD 32.1) for BKB sentences (ranging from 24% to 100%) presented at 70dB SPL.

Speech Stimuli

All participants were asked to repeat 36 sentences which varied in length across 3-, 5-, and 7-syllables (27). Key words contained in the sentences were either easy to guess (sentences designated as high context) or difficult to guess (sentences designated as low context). Half of the sentences contained high context key words and half of the sentences contained low context sentences. Speech signals were digitally recorded using a microphone placed approximately 12 inches from the participant. Samples were edited to provide individual tokens of each sentence. Each sentence was processed to a -25 root mean square (RMS) power level.

Listener Participants

Adult listeners with limited experience listening to the speech of individuals with hearing losses wrote down the words of the sentence after listening to each sentence once. Each sentence was judged by three different listeners and no listener was allowed to hear a sentence more than once or a speaker more than once. Thus, intelligibility scores consisted of the average of 108 judgments (3 listeners × 36 sentences)/adolescent. Dependent variables were the total number of correctly identified words in the sentences.

Multi-speaker Condition

Multi-speaker babble was produced via two adult speakers, one male and one female, reading passages. The speakers were normal hearing adults between the ages of 20 to 40 years. The duration of the babble varied across sentences based on the target sentence’s duration. Babble was present during the entire sentence with three additional seconds before the onset of the target sentence and two seconds after the offset of the target sentence. Judges were alerted the target sentence was occurring by a .2 sec 1000Hz beep embedded in the babble prior to the sentence.

Measurements

Several measurements were taken from the sentence samples. First, two speech-language pathologists transcribed each of the sentences using the International Phonetic Alphabet with broad transcription techniques modeled after Shriberg and colleagues (28;29). Substitutions and omissions were classified as errors; however, distortions or allophonic variations were classified as correct (28–30). Clinicians were familiar with the sentences; however, they were unfamiliar with the adolescent talkers. Second, intelligibility measures were calculated under the quiet and multi-speaker babble condition by averaging the total correct responses across the listening judges.

Results

Phoneme accuracy for sentences transcribed under quiet conditions is plotted in Figure 1. Average accuracy for consonants and vowels is high for this group of CI adolescents: 92.2% (SD 13.3%) and 97.2% (SD 7.5%), respectively. Comparable high scores and low standard deviations for consonant and vowel productions in sentences also are evident across the auditory oral (98% and 99%, respectively) and total communication (85% and 94%, respectively) modes of communication reported by the teenagers.

Speech intelligibility performance of the CI children when listeners identify the total words in their sentences under quiet and multi-speaker babble conditions is shown in Figure 2. Identification of spoken words produced by CI adolescents is significantly more accurate when listeners are listening in quiet (75.5%, SE 1.6%) than in the multi-speaker babble (56.8%, SE 1.6%) [$F(1,341)=68.37$, $p<.00001$]. No significant advantages in performance are evident for high context sentences relative to low context sentences. During quiet, judges understood 78.4 % (SE 2.7%) for high context sentences and 72.5% (SE 2.78%) for low context sentences. During the multi-speaker babble, judges reported 58.2% (SE 2.8%) accuracy for high context sentences and 55.6% (SE 2.8%) for low context sentences.

Higher levels of speech intelligibility are associated with children using auditory oral modes of communication (76.8%, SE 1.5) than children primarily relying on total communication (55.6%, SE 1.7) [$F(1, 342)= 88.55$, $p<.00000$]. Speech intelligibility in quiet is higher for the teenagers reporting auditory oral methods of communication 86.7% (SE 2.1%) than total communication, 64.2% (SE 2.4%). Higher speech intelligibility during the multi-speaker condition also is noted in the teenagers primarily using auditory-oral modes of communication (66.8%, SE 2.1) than teenagers using total communication (46.9%, SE 2.4). Similar intelligibility scores are observed in high (67.1%, SE 3.6) and low (66.7%, 3.7) context sentences for the auditory oral speaking teenagers during the multi-speaker babble condition. Total communication children are understood 44.5% (SE 4.1) in low and 49.3% (SE 3.6) in high context sentences during the multi-speaker babble. During quiet, auditory oral communicators are understood 83.8% (SE 3.7) and 86.8% (SE 3.6) for low and high context sentences, respectively, while teenagers using total communication are understood 71.3% (SE 4.1) and 67% (SE 4.1), respectively.

Figure 3a and 3b illustrate the relationships between the individual intelligibility values acquired for high and low context sentences for the adolescent CI speakers in the quiet and multi-speaker babble conditions. Strong association between performance on high and low context sentences are evident in the CI teenagers for quiet ($r=.97$, $p<0.0000$) and multi-speaker babble ($r=.89$, $p<.00000$). The strong relationships confirm performance on the low context sentences serve as a reasonable predictor of performance on the high context sentences in both quiet and multi-speaker babble conditions.

Discussion

Data from this study indicate high levels of accuracy for consonant, vowel and speech intelligibility performance in adolescent CI speakers. Consonant and vowel accuracies were based on established procedures classifying omissions and substitutions as errors but classifying distortions as correct phonemes (28–30). Broad transcriptions of consonants and vowels indicate accuracies above 90% for adolescent CI speakers. Children participating in the study averaged 69% correct speech intelligibility at ages 8 – 9 years which tended to be higher than the speech intelligibility scores of children who did not return for testing (55%). The similarity in speech intelligibility levels acquired at ages 8 and 9 years between the children who returned for study as adolescents versus those children who did not suggest the speech intelligibility scores are reflective of adolescents using cochlear implants. These levels are in stark contrast to levels previously reported for slightly younger children (13 – 15 years) who had slightly better residual hearing (98.6dB) and used conventional hearing aids ,whose performance ranged from 47 – 65% phonemes correct (31). Accurate sound productions judged by teams of speech-language pathologists however, do not necessarily translate in to comparable levels of speech intelligibility as judged by less-experienced listeners of deaf speech.

Although speech intelligibility levels are high, they are not as high as the individual phoneme scores. This observation suggests speakers who are unaccustomed to listening to the speech of hearing impaired individuals experience some difficulty in correctly extracting words in connected speech of CI adolescents. Several factors may contribute to the situation. One possible factor contributing to this situation is our use of a percent correct consonant-revised definition which allows allophonic variations or distortions to count as correct responses. Articulatory distortions may contribute to the lower intelligibility scores and suggest the allophonic variations may present special challenges to listeners unaccustomed to the speech of hearing impaired individuals. These allophonic variations may include alterations in resonance (e.g., hypernasality), vocal quality (breathy or harsh qualities), excessive airflow (over exaggerated articulations), and timing issues (elongated segments) (17;32–34). Speech intelligibility scores of adolescent CI speakers also are not influenced by context, where the accuracy of a word's identification may be enhanced by the context surrounding it. Similar levels of performance for sentences with high and low contexts suggests a more global condition, such as allophonic variations, may be the contributor to lower intelligibility. Future studies are needed to explore these possibilities in more depth.

Data from this study indicate the average overall speech intelligibility scores for adolescent CI speakers are remarkably higher than the intelligibility scores (ranges from 18.7% to 42%) previously reported for adolescents slightly younger (13 – 15 years) with profound hearing losses using conventional hearing aids (27;31). Higher speech intelligibility and consonant correct scores are evident in the CI adolescents who use auditory-oral modes exclusively to communicate than in adolescents who use speech as part of their total communication mode. More accurate consonant production may lead to more accurate semantic and syntactic cues underlying speech intelligibility in CI children using listening and speaking as their primary mode of communication. These data support previous reports of higher speech intelligibility in children who rely more heavily on speaking and listening for communication (7;11;18;20;35).

Multi-speaker babble reduces naïve listener's abilities to understand the speech of CI adolescents by nearly 20% relative to listening to the sentences in quiet. It is striking to note that even 20% reductions in overall speech intelligibility still leave these CI teenagers with intelligibility scores higher than those scores obtained under ideal listening conditions reported for children with profound hearing losses who use conventional hearing aids. Listeners do not seem to differentially use sentence context to aid in intelligibility since comparable scores are evident for sentences in low and high contexts. Speech intelligibility in multi-speaker babble does not appear to be differentially influenced by mode of communication since scores for both groups of children decrease by similar amounts; however, these observations will need to be more closely examined in future analyses using larger numbers of participants.

High consonant scores imply the CI adolescent speakers, in general, infrequently omit or substitute consonants. However, this does not appear to necessarily aid naïve listeners in identifying words correctly in the message—particularly, if the message is further compromised by background multi-speaker babble. Multi-speaker babble appears to further accentuate the contributing factors that may be associated with distorted productions and, in turn, further reduce overall speech intelligibility. Reductions in speech intelligibility appear to be comparable for oral and total communicators and for high and low context sentences, suggesting allophonic variations associated with distorted sound production present difficulties for naïve listeners of speech produced by individuals with profound hearing losses, particularly in noisy situations.

Acknowledgments

Portions of this manuscript have been presented at the 10th International Conference on Cochlear Implants and Other Implantable Auditory Technologies in San Diego, California (April 2008), AudiologyNOW in Dallas, Texas (April 2009) and the 11th Symposium on Cochlear Implants in Children in Seattle, Washington (June 2009). Partial funding was provided by NIH Grant Number R01DC008335-03.

Sources of Support: National Institutes of Deafness and Other Communication Disorders

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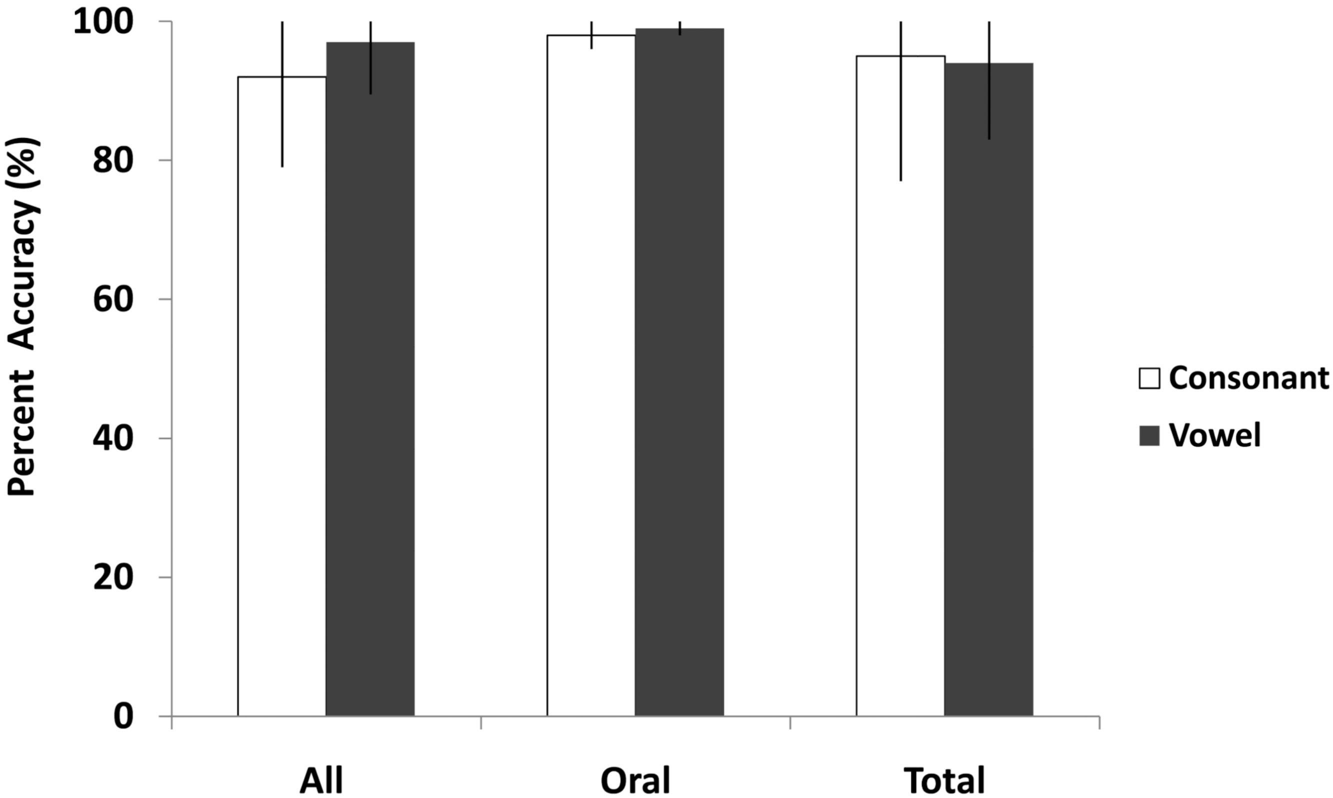


FIGURE 1.
The mean and SDs are shown for accurate production of consonants and vowels for all the participants and for the participants who indicate they use oral communication or total communication.

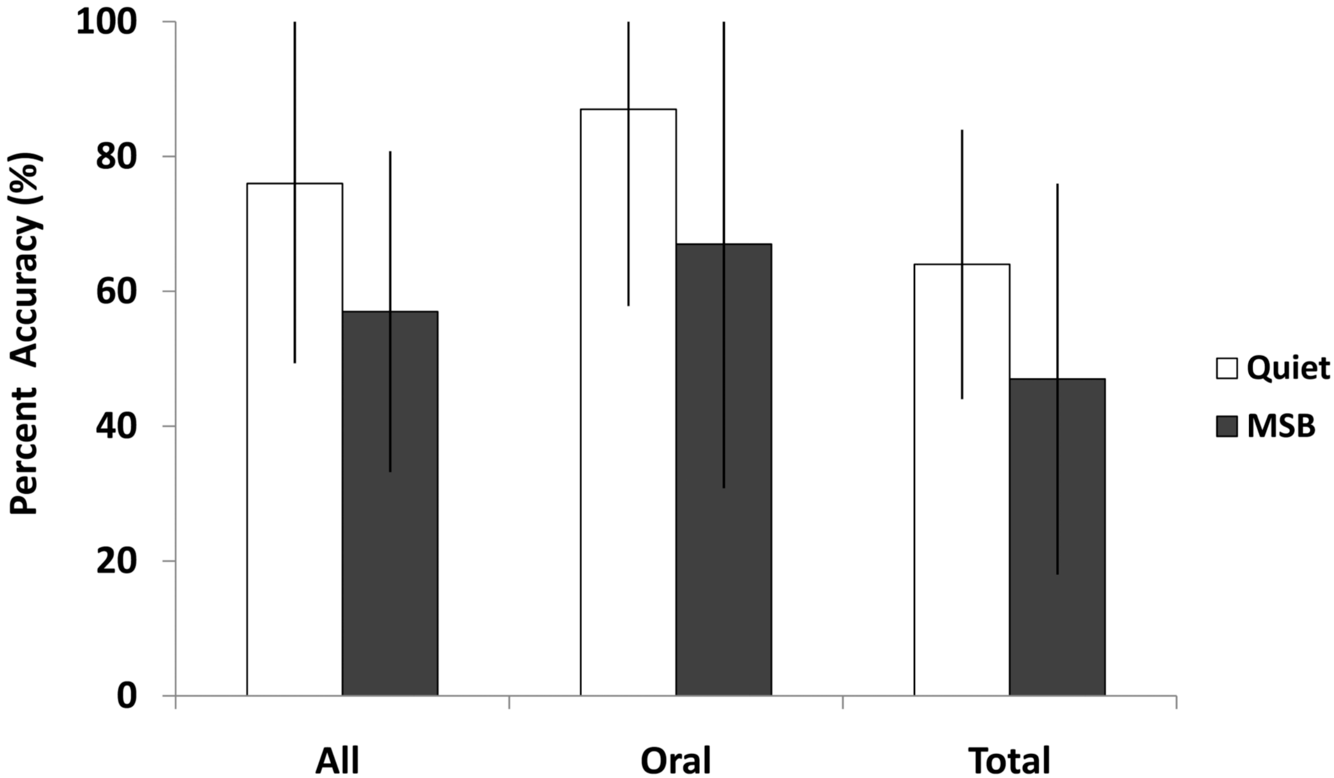
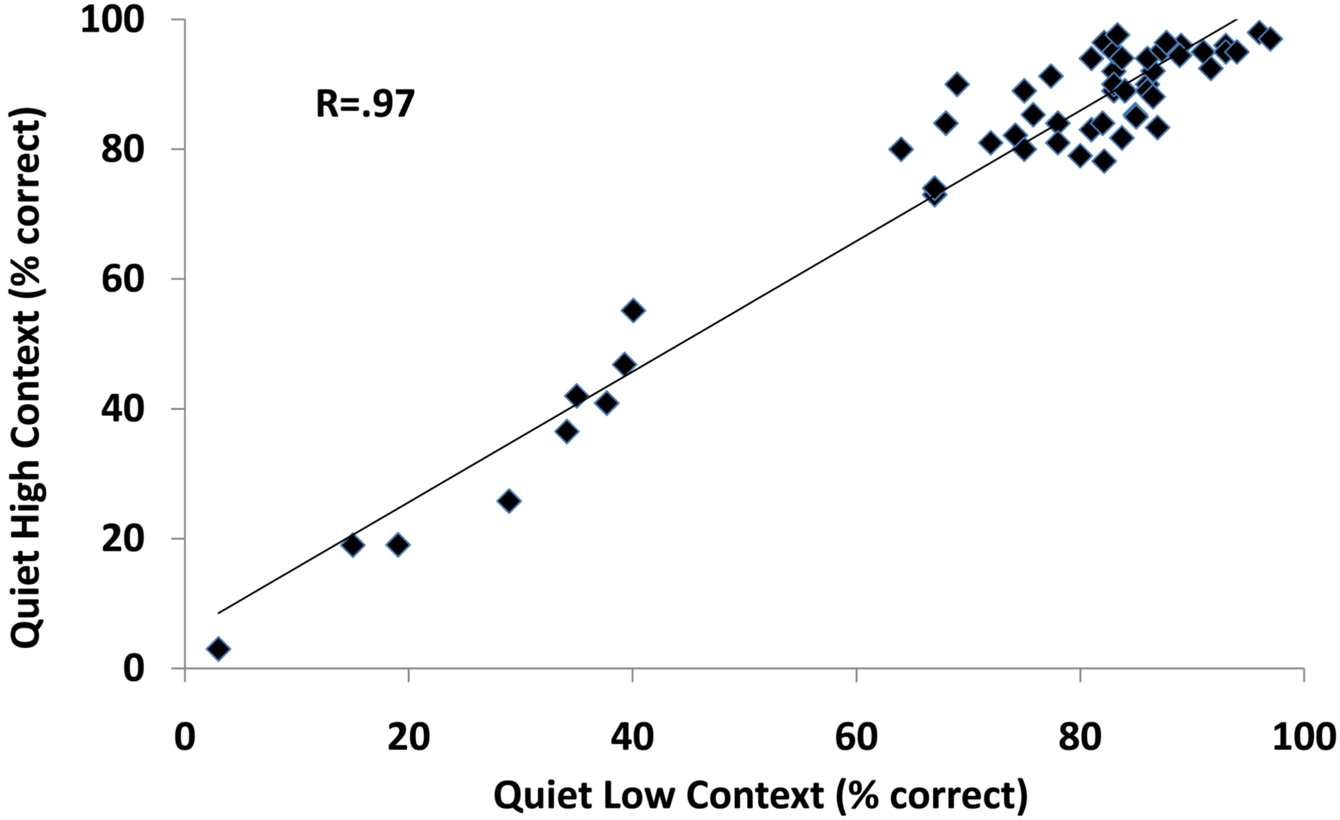


FIGURE 2.
The means and SDs are shown for the total number of words correctly identified by normal-hearing listeners unfamiliar with the speech of hearing-impaired speakers. Data are shown for all the participants and for the participants who indicate they use oral communication or total communication.

3a


R=.97
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100
80
60
40
20
0
0
20
40
60
80
100
Quiet Low Context (% correct)

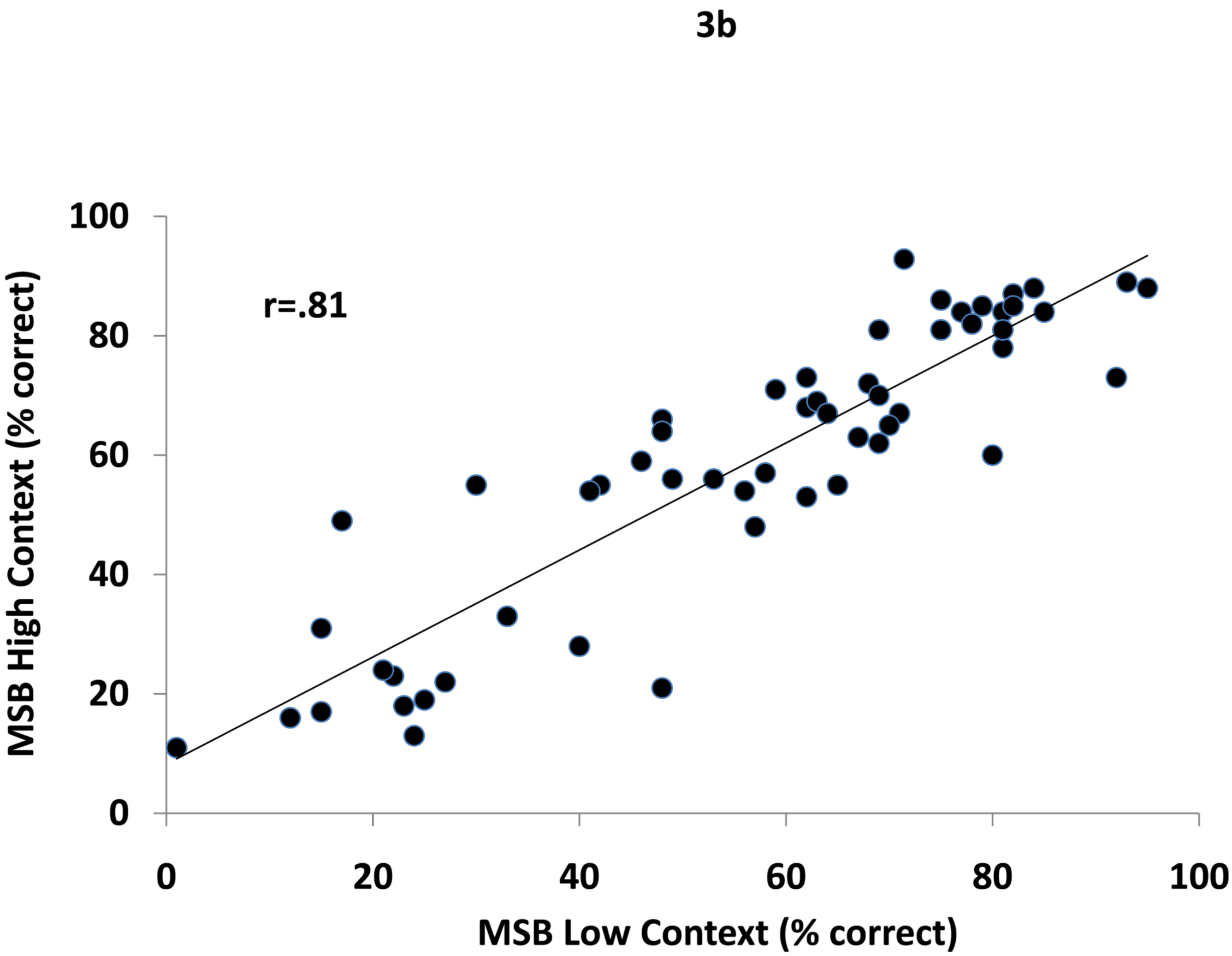

FIGURE 3.

A, The relationship between speech intelligibility scores for high- and low-context sentences presented in quiet to normal-hearing listeners unfamiliar with the speech of hearing-impaired speakers is shown. *B*, The relationship between speech intelligibility scores for high- and low-context sentences presented in multispeaker babble to normal-hearing listeners unfamiliar with the speech of hearing-impaired speakers is shown.

Table 1

Demographic Information of Participants

Gender	Chronological Age	Age at Implantation	Length of implant Use	Communication Mode*
M	17.0	3.9	13.1	OC
F	18.1	3.1	15.0	OC
M	16.2	2.7	13.6	OC
M	16.6	*4.3*	12.3	OC
F	17.1	2.9	14.2	OC
M	16.6	2.9	13.7	OC
M	16.1	3.1	13.0	OC
F	17.0	4.1	12.9	OC
M	18.0	*2.4*	15.6	OC
F	16.6	*2.7*	13.9	OC
F	16.7	2.4	14.3	OC
F	17.5	4.2	13.3	OC
F	16.8	4.4	12.4	OC
F	16.4	5.0	11.4	OC
M	16.8	3.8	13.0	OC
F	16.3	5.2	11.1	OC
F	16.8	4.9	11.9	OC
M	17.4	2.6	14.7	OC
M	16.6	*2.7*	13.9	OC
F	16.2	*2.8*	13.5	OC
M	16.1	*2.3*	13.8	OC
M	18.5	2.5	16.0	OC
M	16.1	*3.1*	13.0	OC
M	16.3	3.3	13.0	OC
F	16.3	*4.0*	12.3	OC
M	16.7	*3.9*	12.8	OC
F	16.3	4.2	12.1	OC
F	16.4	4.2	12.2	OC
M	16.5	3.4	13.1	OC
F	17.2	3.6	13.7	OC
F	16.7	3.7	13.1	OC
M	16.2	3.3	12.9	OC
M	17.0	5.0	12.0	TC
F	17.5	3.0	14.5	TC
M	16.6	*3.4*	13.2	TC
F	16.4	*2.8*	13.6	TC
F	17.9	*4.1*	13.8	TC
M	16.3	3.7	12.6	TC
F	16.7	*3.6*	13.1	TC

Gender	Chronological Age	Age at Implantation	Length of implant Use	Communication Mode*
M	16.5	*3.0*	13.5	TC
F	16.1	*3.3*	12.8	TC
F	16.7	5.2	11.4	TC
M	16.4	3.8	12.5	TC
M	16.9	3.4	13.5	TC
F	16.7	3.8	12.9	TC
M	16.6	3.8	12.8	TC
F	16.8	*2.8*	14.1	TC
F	16.4	*3.8*	12.6	TC
M	16.4	3.1	13.3	TC
M	16.7	*5.0*	11.7	TC
F	16.9	*4.7*	12.2	TC
M	15.0	2.4	12.6	TC
F	16.6	*2.2*	14.5	TC
M	16.1	*2.4*	13.7	TC
M	17.2	*3.5*	13.8	TC
F	16.5	*3.6*	12.8	TC
M	16.2	2.7	13.5	TC