Effects of Elicitation Task Variables on Speech Production by Children With Cochlear Implants

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Given the interest in comparing speech production development in children with normal hearing and hearing impairment, it is important to evaluate how variables within speech elicitation tasks can differentially affect the acoustics of speech production for these groups. In a first experiment, children (6–14 years old) with cochlear implants produced a set of monosyllabic words either in isolation or while simultaneously signing the word. Acoustical analyses indicated no change in word duration, voice onset time, intensity, or fundamental frequency between isolated and simultaneous signing conditions. In a second experiment, the same children verbally repeated words that were signed by a video model. The model either signed with inflection or without. Words repeated after inflected models were higher in fundamental frequency and intensity and were more intelligible. In addition, children with poorer speech perception skills sometimes produced the monosyllables as 2 syllables, but this only occurred for words that had multiple sign movements. The results have implications for the comparison of speech development between children with normal hearing and those with hearing impairment.

KEY WORDS: speech production, cochlear implants, acoustics, simultaneous communication

When assessing the speech production of children, researchers or clinicians use a variety of speech elicitation tasks such as asking the child to name a picture or object or to repeat a word in imitation of a tester (Bernthal & Bankson, 2004). For children with severe-to-profound hearing losses who use *simultaneous communication* (SC), the concurrent use of manual sign and speech, these tasks can further involve the imitation of a word signed by a tester. These elicitation tasks provide samples that may be representative of the child's typical speech or representative of his or her best or most intelligible speech efforts with and without simultaneous signing. Children's speech output may be affected by characteristics of the elicitation task, such as the competing task demands when a child must imitate a multimodal model with both auditory and signed components. Children with significant hearing losses may be affected more by these task characteristics because the auditory input that they receive is degraded and auditory feedback is reduced. Further, they must attend to the visual portion of the model as well as the auditory.

Given the multiple sensory inputs (visual and auditory) and motor outputs (manual and vocal articulation) of SC, the elicitation of speech by

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**Dr. Maureen B. Higgins, now deceased, was responsible for the idea and study design for this article.*

children with hearing impairments from total communication backgrounds includes a number of potential sources of variability that are not as evident in speech production requests from normal hearing (NH) children. If one is to make meaningful comparisons on the development of speech communication between these groups, it is essential to understand what differences may result from the conditions of elicitation. There is indirect evidence from several studies that suggest that the added output and input variables of SC can affect speech production. In particular, the demands of simultaneous manual and vocal articulation can lead to changes in temporal properties of speech acoustics, and the visual and dynamic structure of manual signs can be overgeneralized to vocal articulation. The evidence for these output and input effects is reviewed separately below.

Effects of Communication Mode (Output Variables)

While it is probable that signing can complement communication by speech in many settings by adding an additional channel of information, it is possible that the execution of parallel motor plans during SC can perturb the acoustic output when compared with the production of speech alone (SA). In particular, attempts to maintain coincidence of rapid speech articulations and slower sign movements may disrupt the normal temporal patterns of speech (Windsor & Fristoe, 1989, 1990). Given the importance of temporal features in speech communication, these perturbations may have an impact on the acoustic properties of speech and its normalcy or naturalness (Osberger & Levitt, 1979).

SC can alter temporal features of speech acoustics in NH adults. Whitehead and colleagues (Schiavetti, Whitehead, Metz, & Moore, 1999; Schiavetti, Whitehead, Metz, Whitehead, & Mignerey, 1996; Whitehead, Schiavetti, Metz, & Farrell, 1999; Whitehead, Schiavetti, Whitehead, & Metz, 1995) have demonstrated longer sentence, word, interword, vowel, and voice onset time (VOT) durations during SC for both highly trained and relatively inexperienced NH adult signers using manually coded English. However, these authors concluded that despite the effects on speech sound durations induced by SC, there were no alterations of the normal temporal regularities of English that serve as phonetic cues (e.g., vowels were longer before voiced than before voiceless consonants).

One would predict that the SC temporal perturbations noted for NH adults also would be present for children with hearing impairment who use SC. Indeed, there are reasons to expect that children would show even greater SC effects on speech acoustics, especially those children with limited speech production skills. If children have not developed a full appreciation of the normal temporal regularities of speech or if they have degraded auditory input, then their speech output likely will be more influenced by the temporal patterns of the parallel sign movements. In addition, for children who are still learning to sign and to speak, the simultaneous planning and execution demands of SC may require an excessive amount of attention (from the standpoint of a finite pool of mental resources; Kahneman, 1973). To this point, the effects of SC on speech production in children are unknown.

If, in fact, the speech children use is strongly influenced by the temporal characteristics of manual signs produced simultaneously, then one may witness more substantial deviations from normal speech production than mere temporal lengthening. One such example comes from a case study of a child who is a prelingually deafened cochlear implant user at Boys Town National Research Hospital. She sometimes produced monosyllabic words with a CVC structure as two syllables. This incorrect syllabification was only present for words whose manual sign included a multiple movement (in *Signing Exact English [SEE],* a sign system that is a manual code of English). For example, the sign for "goat" involves a hand movement to the chin then to the forehead, whereas the word "coat" has a sign that involves one smooth movement on the chest. Similarly, the sign for "feet" involves brushing one hand against the other two times, whereas the sign for "fat" involves a simultaneous lateral movement with both hands. The child produced 14 double syllables out of 16 elicitations of words with multiple movements and never produced a double syllable for any word with a single movement.

The observations strongly suggest that the child was overgeneralizing the multiple movements of the sign to her speech production. There also was evidence that this syllabification was exacerbated by SC. The only two cases of single-syllable productions for multiple movement words ("feet" both times) were elicited in a condition in which the tester spoke the word only and the child repeated it without signing. When the tester and the child used SC, the child produced multiple-movement words with two syllables every time. In this case, the particular characteristics of the sign movements appear to be generalized to speech production. Whitehead, Schiavetti, Whitehead, and Metz (1997) also found that characteristics of sign movements could affect speech output in adult NH users of SC, with more elaborated movements leading to longer durations for interword pauses and diphthongs.

Effects of Characteristics of Sign Model (Input Variables)

One of the major hurdles for children with hearing impairment is that they are trying to learn the rules and regularities of language with degraded auditory input. As adaptive learners, these children likely are to rely on other sources of information to enhance their understanding of spoken communication, such as the visual information from concurrent signs and lip movements. The lack of robust auditory input may result in generalization from visual movements to speech articulation movements such as in the case of syllabification detailed above. Another possible example of this type of generalization was presented by Higgins, McCleary, and Schulte (2000). They reported on a child with a CI who continued to display *implosives* (negative intraoral air pressure) for the word "pop" long after he remedied its presence for 11 other word tokens. Higgins et al. (2000) speculated that the child had generalized the hand movements for the sign for "pop" to his speech production. The sign involves inserting one hand into the other and slapping the top of a closed fist. If this child generalized the downward movement and the abrupt slap of his hand to his speech production, he may have lowered the larynx and produced a hard glottal attack. Both of these laryngeal behaviors are believed to be involved in implosive production (Higgins, Carney, McCleary, & Rogers, 1996; Monsen, 1983). Higgins et al. (1996) described two other cases of patterns of implosive use that may be generalizations from visual, facial-movement cues.

These cases of overgeneralization are presumed to be examples of learning from the visual input over time in establishing a pattern of production. Of practical importance is whether visual characteristics of a sign model can elicit changes in speech production instantaneously in a child. Any systematic shifts could be useful in intervention settings.

Purpose of the Present Investigation

The studies reviewed above suggest that there are several variables related to SC that may affect speech acoustics in an elicitation task. However, none of these studies directly explored the impact of SC for children. In the present study, we examined the effects of SC on speech production for children with CIs who are educated in a total communication framework. Children who use SC and subsequently receive a CI as their sensory aid present a unique communication situation. To be considered as candidates for cochlear implantation, they were diagnosed with profound hearing losses and received no benefit from conventional amplification. After implantation, auditory input (in the form of direct electrical stimulation) increased, although results of speech perception tests vary greatly across children (Fryauf-Bertschy, Tyler, Kelsay, Gantz, & Woodworth, 1997; Geers, Brenner, & Davidson, 2003; Zwolan et al., 2004). These children with CIs typically continue to receive multimodal communication input at least for some time; they also may continue to speak and sign simultaneously or may use speech more as their primary communication mode (Peng, Spencer, & Tomblin, 2004; Tobey, Geers, Brenner, Altuna, & Gabbert, 2003).

We explored the impact of two variables on the speech acoustics of CI children in a typical speech elicitation task. The first variable is the communication mode of the child during speech production—either speaking without signing (SA) or simultaneously speaking and signing (SC). The second variable is the nature of the signed model provided to the child—specifically, the degree of inflection or intensity of movement used by the signing speaker who elicited the production. The purpose of these experiments is to assess whether these typical variables of an elicitation task can lead to systematic variations in speech acoustics and whether these variations can compromise speech intelligibility. Speech intelligibility was determined using multiple listeners and a write-down procedure.

In the first manipulation, children with CIs who are regular users of SC are asked to produce a set of words in SC and SA modes. The word, vowel, and VOT duration for each word is measured from the acoustic waveform. Given the previous results with NH adults (e.g., Whitehead et al., 1995), we predict that these children would evidence longer durations during SC and that these duration perturbations would be greatest for those children with the poorest speech perception skills (as measured by scores on open-set word recognition tests).

To assess whether more extreme temporal perturbations, such as incorrect syllabification, accompany SC, we have included words that are produced with single- and multiple-movement signs. We predict that these syllabifications also would be more prevalent in children with poorer speech perception skills, because the child who had demonstrated the behavior described above was completely unintelligible and had very limited speech perception skills. In addition, the inclusion of multiple-movement words allows us to examine whether sign characteristics moderate temporal deviations of speech production during SC in children with CIs. The complexity or duration of signs is predictive of the extent of acoustic temporal deviations during SC for NH adults (Whitehead et al., 1997).

One additional question of practical interest in our study is whether these predicted disruptions of speech temporal features and syllable structure during SC affect speech intelligibility. A slower speaking rate is generally associated with better intelligibility (Picheny, Durlach, & Braida, 1985a, 1985b). In fact, Hyde, Power, and Lehigh (1998) reported that the slower speech produced during SC by their group of teachers of the deaf was judged more understandable, if less natural. These results confirmed earlier findings reported by Osberger and Levitt (1979). The relative intelligibility of SC speech has implications for the use of SC by children in social, educational, and clinical settings.

The second task in this study examines a simple case of the effect of sign model on speech production. The same CI children are presented a video of a sign model and asked to speak the signed word. There are two versions of the presentation for each signed word. In one version, the sign movements are inflected by the addition of heavy onset stress and increased facial expression, and in the other version there is little inflection and flat affect. We predicted that children would generalize from the expressiveness of the inflected model to their speech production. In particular, we predicted that children would produce speech with higher fundamental frequencies ($f0$) and greater intensities in response to the more emphatic movements of the inflected model.

The pair of studies presented here will provide some evidence about the variability of speech acoustics contingent on factors of the elicitation task and any consequent effects on intelligibility. The robustness of speech in these tasks has implications for the comparison of speech development in NH and hearing-impaired children.

Method

Speech Production Acoustic Measures

Participant Characteristics

Auditory history. Participants were 14 children who underwent cochlear implant hook-up between 2;2 (years;months) and 13;11 (M = 5;7, SD = 3;0). Eleven participants had become deaf prelingually, whereas 3 participants demonstrated better hearing early in life with progression of their hearing loss and a decrease in speech perception skills. Participants had no history of cognitive, motor, craniofacial, or laryngeal disorders or syndromes associated with such disorders. They all used SC, more specifically, spoken English and SEE. Data from 1 participant was eliminated from the database because she used some ASL signs during the study. This child learned ASL in a true communication situation (e.g., no voice) and, for the study, paired ASL with voicing (which is atypical for ASL). Additionally, some of the signs this participant used varied in terms of complexity of movement or number of movements required to complete the sign. This participant's data was not used in the study due to this discrepancy. Table 1 provides information about each participant's auditory history, CI, and communication characteristics.

Participants were seen for this study between the ages of 6;11 and 14;11 (M = 10;4, SD = 2;4) and had between 0;8 and 8;6 years of cochlear implant experience (M = 4;8, SD = 2;5). We limited our age range to greater than 6;6 to ensure that each participant was old enough to aim for the correct target. Confirmation took place to

Table 1. Auditory history and speech perception scores for participants.

Participant	Age seen	Age at initial activation	Etiology	Internal device	Processing strategy	PBK word score (%)	PBK phoneme score (%)	MPPT (%)	Typical communication mode
F1	10;00	3;06	CMV	Nucleus 22	SPEAK	34	60	83	TC
F2	12;01	3;08	Meningitis	Nucleus 22	SPEAK	58	78	86	TC
F3	12;09	7;11	Unknown	Clar.1.2 EB	SAS	2	14	88	TC
F4	13;03	8;04	Unknown	Clar.1.2 EB	SAS	0	6	54	Sign
F5	14;11	13;11	Connexin 26 mutation	Clar. HF	SAS	0	4	45	Sign
M1	6;11	6;03	EVA/progressive	Clar. HF	SAS	50	74	94	Speech (little sign)
M2	7;08	4;10	genetic/progressive	Clar.1.2 EB	SAS	56	81	81	TC
M3	7;08	6;09	auditory neuropathy/ hyperbilli-rubinemia/ progressive	Clar. HF	SAS	24	49	83	TC
M4	7;09	2;02	meningitis	Clar.1.2 RB	CIS	72	87	86	Speech (little sign)
M5	9;08	4;06	CMV	Clar.1.2 RB	CIS	12	35	91	TC
M6	9;11	4;06	Unknown	Clar.1.2 RB	CIS	6	23	78	TC
M7	10;00	2;11	Unknown	Nucleus 22	SPEAK	34	78	93	TC
M8	10;04	4;01[a]	EVA/progressive	Clar.1.2 EB	MPS	30	63	85	TC
M9	11;04	5;00[a]	Connexin 26 mutation	Clar.1.2 EB	MPS	22	52	89	TC

Note. EVA = enlarged vestibular aqueduct syndrome; CMV = cytomegalovirus; BTE = behind the ear; SAS = simultaneous analog stimulation; CIS = continuous interleaved sampler; MPS = multiple pulsatile sampler; PBK = Phonetically Balanced Kindergarten word list; MPPT = Minimal Pairs Perception Test; TC = Total Communication; EB = enhanced bipolar; HF = high focus; RB = radial bipolar. Scores for the PBK reflect the number of words and phonemes that were identified correctly by the children in an open set speech perception task. Scores for the MPPT reflect the percentage of words that were correctly chosen by the children when given a choice of two words. Chance performance was 50%.

[a] This age indicates original hook-up. These children initially were implanted with Clarion (Clar.)1.2 Radial Bipolar devices. They were replaced later with Clarion 1.2 Enhanced Bipolar devices.

ensure that every participant was familiar with each vocabulary word prior to data collection. The phonemes assessed in this study are well established for children in the age range of our participants. These cautions were in place to ensure that errors associated with the production of the words in the study could be associated with lack of auditory access rather than developmental articulation difficulties. The parents of F4 and F5 indicated that their daughters only wore their external CI equipment during school hours. The remaining children were reported to have worn their external devices full time.

Three of the children were implanted with the Nucleus 22-electrode CI and initially used the Spectra speech processor with the SPEAK processing strategy. Two of these participants had upgraded to the Esprit22-BTE processor. The remaining 11 children used the Clarion cochlear implant. Table 1 contains detailed information about their internal devices, as well as device speech-processing strategies.

Communication history. Two participants (M9 and M8) received their earliest education in an Oral Communication school setting and later transferred to a TC (speech + signing) preschool. M1 and M2's preschool education was in a TC program, but did include a large degree of Oral-only training due to their good auditory skills prior to hearing loss progression. The remaining children were enrolled in TC programs for their preschool education. All of the children in this study used SEE in their school settings and spontaneously produced the SEE signs for all of the words in this study (as opposed to ASL or Pidgin sign).

All of the children, except M4, had sign language interpreters or signing paraprofessionals in elementary, middle, and high school. M4 attended a parochial school and on occasion had a paraprofessional who signed with him. The parents of M1 and M4 reported that speech was their sons' primary mode of communication, although each could communicate fluently in sign. The parents of F4 and F5 indicated that their daughters used sign-only (no voice) for the majority of the day. The remaining children used SC.

Speech perception abilities. The Phonetically Balanced Kindergarten word list (PBK; Haskins, 1949) and the Minimal Pairs Perception Test (MPPT; Robbins, Renshaw, Miyamoto, Osberger, & Pope, 1988) were administered to assess the speech perception ability of the participants in this study. Both tests were administered in a sound-treated booth using CD recordings; the results are shown in Table 1. The PBK test is an open set word recognition test from which word correct and phoneme correct scores can be determined. Stimuli were presented at 70 dB SPL and the participants' results ranged from very poor (0%) to very good (72%). These results fall within the range of published scores for children with CIs (Fryauf-Bertschy et al., 1997; Miyamoto, Osberger, Robbins, Myres, & Kessler, 1993; Osberger, Zimmerman-Phillips, Barker, & Geier, 1999; Tyler et al., 2000). The MPPT is a two-interval forced-choice test that was administered at 60 dB SPL (e.g., beet vs. boot, van vs. fan). Participants were asked to look at two pictures displayed on a computer monitor.[1] Following the presentation of one of the words, the participant was asked to respond using a touch monitor. Participants scored between 45% and 94% (*M* = 81%, *SD* = 14%), where 50% is chance performance.

Elicitation Conditions

SC versus SA. Participants were familiarized with a set of 10 custom-made picture cards illustrating monosyllabic words (*pea, see, pop, stop, goat, coat, feet, fat, head,* and *bed*). The picture stimuli were first introduced in SC by the examiner. Participants then demonstrated their ability to spontaneously name the pictures by naming each one independently using SC. Target words were CV, CVC, or CCVC word structures including phonemes that are established in the repertoires of typically developing age-matched peers with NH and can be pictured easily. To examine the effects of particular sign movement characteristics on speech of children with CIs during SC, we included monosyllablic words that required multiple movements in SEE (*pea, pop, goat, feet,* and *head*) and words that required a single movement (*see, stop, coat, fat,* and *bed*). The participants were monitored in the SA condition by two examiners to ensure that they did not sign. They were given several options for hand placement during the word production. Some participants wore gloves that were attached to a placemat with Velcro; others sat on their hands. Several participants had no difficulty communicating without sign and chose to hold their hands in their lap.

Inflected versus uninflected sign model. A fluent male signer was video recorded producing the stimuli. The video recording was used as a sign model of the stimuli listed above without an audio signal. Each word was presented in two sign conditions: inflected and uninflected. Signs were produced as inflected by modifying the onset plosion of the handshape creating a "heavier," more expressive onset. Additionally, the signer used more pronounced facial expression for the inflected signs. In regard to language, these changes in sign articulation can represent affect and/or result in syntactical differences in the information communicated. Prior to data collection, video sign stimuli were presented in random order to five fluent adult signers. They were asked to indicate whether

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[1] Participant M5 was seen as a pilot subject before the CD recording and touch monitor were available. His score reflects the results of the MPPT administered in a live-voice condition.

the sign was inflected versus uninflected in an effort to confirm that the signs portrayed the intended condition. Agreement was 100%. CI participants were asked to say each word in response to the video model.

Recording Procedure

Data for both studies were collected during a single testing session by a single examiner who was different from the sign model on the videotape. The studies were described for the participants and informed consent was obtained. All testing was completed in a sound-treated booth with a head-mounted microphone (AKG C 567E). These signals were sent to a mixer (Shure M268) and amplified prior to recording with two DAT recorders (Tascam DA-20 and Tascam-320). The DAT recorders were set at two different gains to allow the greatest flexibility in terms of obtaining quality, nonclipped signals to analyze and to avoid loss of data due to equipment malfunction. Data for an individual participant always were obtained from a single tape. When the child and examiner were in position for the study, a calibration signal (500-Hz warble tone) was presented through the speaker at 60 and 70 dB HL. The signal was recorded to a DAT tape via a microphone placed on the participant's head, 4 ft from the speaker. These levels then were measured with a sound level meter and converted to dB SPL.

SC versus SA. Participants were asked to produce a total of 60 productions (10 tokens × 3 repetitions × 2 conditions). The SC and SA sign conditions were kept independent of each other. The examiner elicited initial productions by stating the stimuli number and presenting the picture card. Subsequent productions were elicited by stating "again." Pauses between productions were sufficient to ensure talk-over did not occur. The word order and sign condition were randomized across participants.

Inflected versus uninflected sign model. The participants were instructed to watch a video monitor and to say the word that was signed by the model. Twenty segments were presented to each participant (10 tokens × 2 conditions). The order was randomized across both word and inflection condition.

Data Analysis Procedures

Signals from the DAT recorder were transferred to a computer at a 22050 Hz sampling rate and 16-bit amplitude quantization. Intensity was measured using Cool Edit Pro (Syntrillium Software Corp.). The remaining acoustic measures were performed using Speech Station II (Sensimetrics).

1. Number of syllables. Perceptual judgments of syllable number were supported by first viewing the spectrogram and using the acoustic waveform for additional confirmation. Syllable number was determined for each word in each condition. Pauses or significant decrements in the intensity of F1 and F2 and the acoustic waveform were considered indicators of syllabification. See Figure 1 for an example (this figure was created using the Praat program; Boersma, 2001). This figure displays spectrographic and acoustic waveforms from Participant F4 for the token "head" with two syllables produced and "bed" with one syllable. The few instances in which two syllables were produced were clear cases and were agreed upon by an independent examiner.

2. Temporal measures. Several temporal measures were made: VOT, vowel duration, and word duration. VOT was measured from the acoustic waveform as the time from the burst onset associated with the closure release to the first glottal pulse for the words *pea, pop, stop, goat, coat,* and *bed*. Vowel duration was calculated for all tokens as the duration for which the first two formants were clearly present in the spectrographic signal. Vowel duration was confirmed by examination of the waveform signal. It was calculated as the time from the onset of a rapid increase in periodicity and amplitude of the waveform to the point where significant decrease was observed (Nittrouer, 1993). Word duration was measured from the acoustic waveform as the time from burst or fricative onset to the final trough found in the voicing signal for CVs and CVCs with voiced final consonants. Ending for words with voiceless final consonants was measured at the point where aspiration could not be measured across the majority of frequencies in the spectrogram.

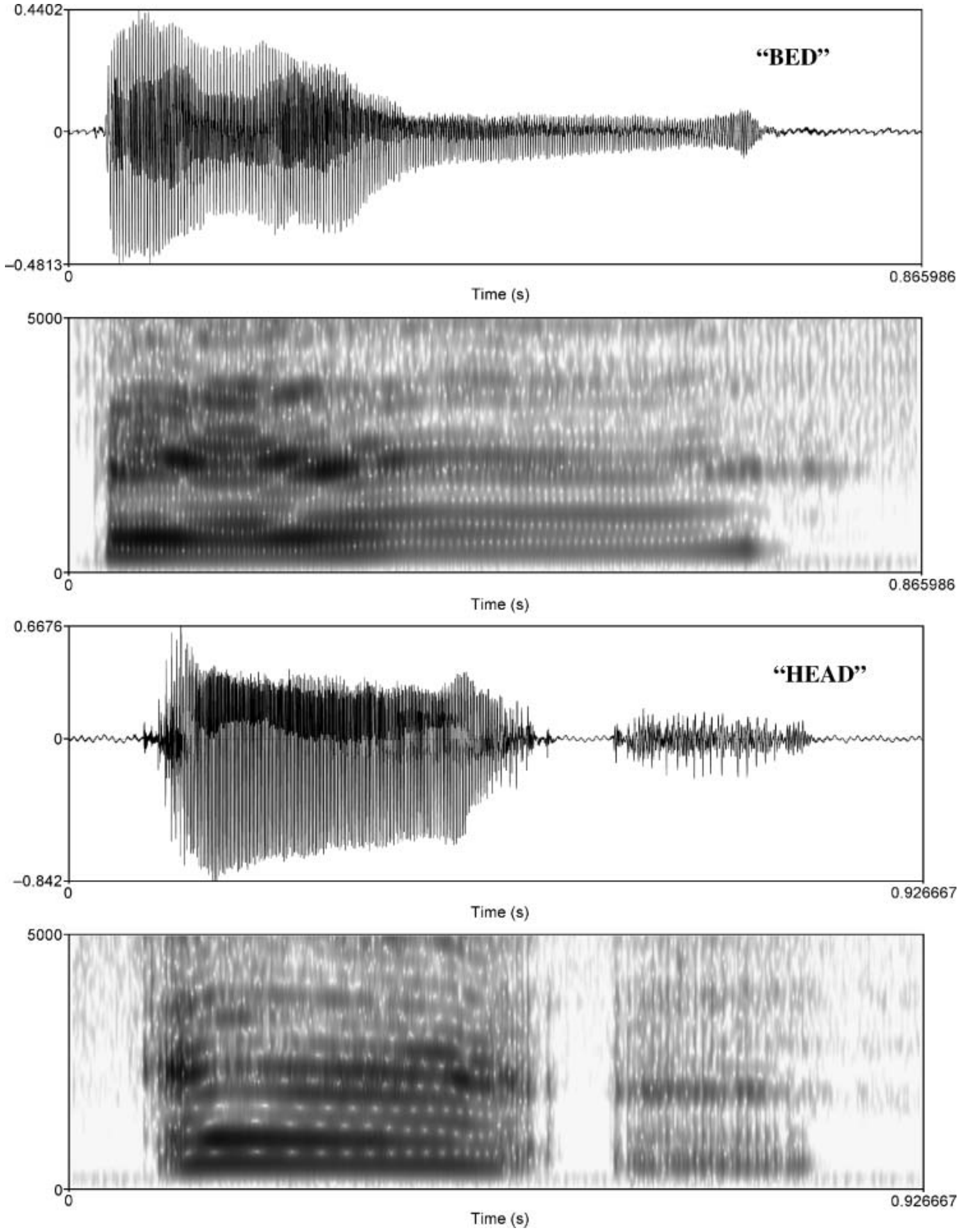
3. Fundamental frequency. $f0$ was measured at vowel midpoint using the pitch track plot in the Speech Station II software. This pitch-tracking algorithm uses center clipping and autocorrelation. If a signal did not demonstrate a stable waveform for a minimum of 50 ms, it was not included in the analyses. Speech Station software was unable to calculate $f0$ appropriately in 3.8% of the words across both studies. This occurred when the production was creaky, noise was present, or when Speech Station overestimated $f0$ because harmonics were evenly spaced. In these cases $f0$ was calculated manually from the average duration of 10 midvowel waveform cycles.

4. Intensity. A 50-ms window around the vowel midpoint of each acoustic waveform was used to calculate the average RMS intensity. This average then was converted to dB SPL using the average RMS intensity of a known intensity warble tone that was recorded onto the DAT tape while the child was in the calibrated position.

Interjudge Reliability

A second researcher reanalyzed all of the data from 2 children to assess interjudge reliability. This represented greater than 10% of the total data set. Interjudge reliability was determined by Pearson product–moment correlations. All correlations were high (r = .972–.998). Mean absolute differences between judges were 2.5 Hz

Figure 1. Acoustic and spectrographic waveforms of the words "bed" and "head" produced by Participant F4. "Bed" was produced with one syllable and its corresponding sign has one movement. "Head" was produced with two syllables and its corresponding sign has two movements.



for $f0$, 0.25 dB for intensity, 2 ms for VOT, 9 ms for vowel duration, and 13 ms for word duration. The judges agreed on syllable number 100% of the time.

Statistical Analysis

Means were computed for each acoustic measure (VOT, $f0$, intensity, vowel, and word duration) collapsing across words and repetitions within the two "number of movement" (single vs. multiple) categories. Missing values were not included in the computation of these means. These dependent variables were subjected to an analysis of variance (ANOVA) with number of movements in the sign as a repeated variable. For the SC versus SA task, an additional repeated-measure variable of communication mode was entered and for the video task, a presentation mode (inflected vs. uninflected) repeated-measure variable was added. A minimum significance value of .05 was used for all tests.

Exclusion of selected measures. Some individual measurements were excluded because the signals were not acceptable for analysis. This included 1.0% of the $f0$ signals that did not demonstrate stability for a minimum of 50 ms. In 1.8% of the productions, ambient noise made it impossible to determine the start or end of a signal. Word duration was not measured when this occurred. VOT could not be measured for 10.3% of words that were supposed to have a word-initial voiceless stop consonant. This was because some participants failed to produce a stop production for appropriate word-initial consonants or noise interfered with the measurement.

A note on production errors. One concern with acoustic measures of child speech and particularly CI child speech is the occurrence of errors in producing the intended segments. This concern is ameliorated somewhat in the present study because the condition comparisons are within-subjects with the exact same word lists. Thus, systematic errors would tend to be present in all conditions. In addition, many of the examined measures are global (e.g., word duration, intensity, $f0$, syllabification) and will tend to be less affected by phonetic-level errors. However, VOT can be influenced by voicing errors. It is difficult to separate those cases in which the child produced a deviant VOT value for a stop and when they made an error at the voicing feature level. It was decided that VOT measures would be made for any production that was an obvious stop consonant.

The number of production errors was determined for each child in each condition by noting examples of deletions, additions, substitutions, cluster reductions, and distortions. The average percentage of errors for all productions of the key words in the SC condition was 19.1% and 17.2% in the SA condition. The error rates in the video conditions were similar (21.9% and 21.7% for the uninflected and inflected conditions, respectively). These error rates are a bit inflated because of the poor speech of participant F4. The number of errors in her speech was clearly greater than any other participant. Without F4, the average percentage of errors was 14.05% and 12.11% for SC and SA conditions, respectively. Despite her poor speech, we retained F4 in the database because the variance in outcomes with CIs is one of the central issues in implant research. The similar number (and type) of errors witnessed in each condition provides some assurance that the results presented below are not due to confounds of differential production errors. The results of the intelligibility measures described below also support this view (at least in the case of SC vs. SA comparisons).

Intelligibility Measures

Participant Characteristics

A total of 168 adult listeners were recruited for the speech intelligibility study. All listeners (139 females and 29 males) were undergraduate and graduate students at the University of Minnesota, with a mean age of 23;0 (*SD* = 0.4 years). Participants passed a hearing screening at 20 dB HL at 500, 1000, 2000, and 4000 Hz bilaterally.

Stimuli

Speech stimuli produced by the 14 child talkers were digitized at 22050 Hz. The corpus of monosyllabic words across the four conditions (SA, SC, inflected, uninflected) was equalized for RMS voltage to reduce differences in intensity across individual words and talkers. Both digitization and equalization were done with Cool Edit Pro software (Syntrillium Software Corp.). Stimuli were presented to listeners with E-Prime software (Psychology Software Tools, Inc.), which controlled stimulus timing and directions on the listener's computer monitor.

Procedures

In one test session, listeners completed the hearing screening, the informed consent procedure, and the listening task. Listeners were paid for their participation.

Participants were tested individually in a sound-treated room. They were seated 2 ft. from a computer monitor in between two matched loudspeakers positioned at 45° angles to the listener. Stimuli were presented in a sound field at 70 dB SPL. Listeners were prompted by directions on the computer monitor. Each listener only heard the speech samples from one individual child in one condition (e.g., SC or SA or inflected or uninflected). The stimuli consisted of the best two repetitions (judged by the experimenter based on noise level and production clarity) of each word. The listening sessions typically lasted 20 min or less. Three different listeners heard the two repetitions of each word produced by each child talker in each condition (14 speakers × 4 conditions × 3 different listeners = 168 total listeners).

Listeners first heard all 10 words in a random order with a 500-ms interstimulus interval without identifying them. Following familiarization, each word was represented one at a time in a different random order. A tester outside the sound room presented each stimulus word with E-Prime at the listener's pace. The listener wrote the word on an answer sheet and repeated the word as well. The tester wrote down the repeated response from the listener and then presented the next stimulus word.

Results

SC Versus SA

Temporal Measures

Table 2 presents the means and standard deviations for all of the temporal measures as a function sign condition. Examination of this table reveals that for all speakers, word durations were similar in SA and SC.

Table 2. Data from communication mode manipulation. Means (and standard deviations) are presented for each temporal measure for words produced in Speech Alone (SA) or Simultaneous Communication (SC) modes.

	Word duration (ms)		Vowel duration (ms)		VOT (ms)	
Participant	SA	SC	SA	SC	SA	SC
F1	551.0 (142.1)	470.7 (91.2)	336.1 (86.6)	319.8 (70.3)	95.0 (45.2)	112.0 (69.3)
F2	452.3 (77.6)	441.8 (101.7)	190.2 (50.4)	178.5 (39.6)	49.5 (30.4)	61.3 (31.7)
F3	499.2 (103.6)	517.8 (167.0)	265.1 (90.9)	272.2 (109.9)	98.7 (18.5)	97.3 (11.4)
F4	671.1 (170.2)	667.6 (138.7)	599.2 (225.3)	581.5 (140.9)	13.5 (3.5)	14.5 (2.1)
F5	584.5 (115.1)	590.1 (121.4)	299.0 (39.3)	297.7 (49.2)	18.0 (11.5)	15.0 (5.0)
M1	518.4 (161.4)	464.6 (168.0)	242.5 (90.3)	247.8 (123.9)	65.0 (42.3)	64.5 (45.2)
M2	474.5 (140.9)	492.0 (192.1)	196.3 (84.4)	179.1 (78.9)	37.5 (13.1)	48.3 (23.6)
M3	478.6 (113.7)	455.3 (56.0)	208.3 (46.5)	197.7 (71.3)	74.0 (48.1)	68.5 (44.3)
M4	451.0 (78.1)	475.7 (108.4)	219.4 (75.8)	179.2 (90.1)	42.0 (33.4)	60.8 (30.6)
M5	495.6 (32.2)	458.2 (92.7)	269.0 (93.5)	262.7 (71.5)	79.8 (77.0)	42.8 (33.4)
M6	552.4 (140.3)	428.7 (118.5)	300.8 (110.0)	274.3 (63.6)	35.0 (96.2)	56.7 (52.5)
M7	399.6 (65.2)	456.6 (183.4)	244.9 (84.1)	311.3 (195.6)	62.5 (33.6)	59.3 (40.6)
M8	523.1 (159.0)	476.3 (167.4)	193.2 (89.7)	204.6 (128.7)	56.8 (26.6)	55.8 (25.6)
M9	421.4 (88.0)	449.1 (179.5)	174.3 (48.8)	184.1 (56.1)	74.0 (30.3)	68.0 (24.8)

Additionally, vowel duration and VOT remained consistent across condition. This was in contrast to the predictions made based on the results of studies with adult signers (Schiavetti et al., 1996; Whitehead et al., 1995). There was no main effect of communication mode on word duration, $F(1, 12) = 1.47, p = .25$; vowel duration, $F(1, 12) = 0.29, p = .60$; or VOT, $F(1, 12) = 0.13, p = .73$. An analysis of VOT for only the voiceless stops also revealed no significant effect of communication mode, $F(1, 11) = 0.01$, $p = .93$.[2] There were no significant interactions between number of movements in the sign and communication mode. That is, multiple-movement signs did not have a greater effect on speech timing during SC.

To examine the prediction that temporal disruptions would be more severe during SC for children with poorer speech perception abilities, we calculated correlations between the phonemes-correct scores from the PBK and the difference between SC and SA conditions for all dependent variables as well as the averages across the speaking conditions. There was a tendency for children with poorer speech perception scores to use an overall slower speaking rate, as indicated by a significant negative correlation between PBK score and average vowel duration ($r = -.596$, $p < .05$) or average word duration ($r = -.613$, $p < .05$). However, there was no evidence that children with poorer speech perception scores were more affected by SC as the correlation coefficients for PBK and (SC − SA) difference scores were nonsignificant for all acoustic variables. In summary, there was no evidence that SC leads to slower articulation of speech during production of words in isolation by children who use CIs.

Intensity and $f0$

Table 3 presents the means and attendant standard deviations for the intensity and $f0$ measures for each speaker in the SC and SA conditions. There was no effect of communication mode on speech intensity, $F(1, 12) = 0.94$, $p = .35$, and PBK scores were not significantly correlated with average intensity or change in intensity across communication modes. However, there was a significant interaction between communication mode and number of movements, $F(1, 12) = 9.08, p < .05$. Post hoc tests revealed that there was no difference in speech intensity between single- and multiple-movement words during SA (73.25 vs. 73.31 dB), but single-movement words were more intense during SC (73.25 v.s 71.59 dB). This unpredicted result indicates that speech intensity may be sensitive to the demands of simultaneous signing. On the other hand, there was no significant main effect of communication mode on $f0$, $F(1, 12) = 0.62, p = .45$, nor any interactions with number of movements. PBK scores were negatively correlated with $f0$ ($r = -.664$, $p < .05$), indicating that poorer speech perception skills were associated with higher $f0$s overall.

Syllabification

Only 1 child (F4) produced any of the monosyllable words as two syllables. Like the case study presented in the introduction, this incorrect syllabification only occurred for multiple-movement words.[3] The child produced "pop" as two syllables three out of six times and "goat" and "head" as two syllables one time each. There was no

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[2] Data from 1 participant (F4) were excluded from analysis because she did not produce a stop for the majority of words with voiceless stops.

[3] This was not the same child as in the case study. That child was not one of the participants.

Table 3. Data from communication mode manipulation. Means (and standard deviations) are presented for fundamental frequency and intensity measures for words produced in SA or SC modes.

	*f*0 (Hz)		SPL (dB)	
Participant	SA	SC	SA	SC
F1	213.6 (8.4)	209.8 (10.1)	72.9 (3.7)	72.5 (4.7)
F2	232.3 (11.7)	232.8 (11.1)	75.3 (2.3)	72.3 (4.8)
F3	268.4 (52.8)	271.1 (52.4)	73.6 (2.0)	75.1 (2.9)
F4	398.7 (50.7)	386.6 (47.3)	69.8 (3.4)	70.2 (4.2)
F5	264.3 (4.1)	267.5 (3.9)	73.0 (1.4)	72.5 (1.3)
M1	229.8 (20.5)	234.2 (17.7)	68.2 (6.0)	72.1 (6.2)
M2	185.5 (21.8)	185.5 (21.4)	68.2 (7.5)	69.2 (6.1)
M3	201.9 (16.7)	236.4 (44.8)	72.6 (4.2)	77.9 (4.3)
M4	274.6 (23.9)	249.9 (32.7)	71.6 (4.8)	64.8 (3.0)
M5	215.1 (29.4)	209.0 (38.6)	78.8 (2.6)	76.1 (4.1)
M6	373.6 (87.5)	336.5 (109.9)	77.5 (3.5)	74.2 (5.5)
M7	249.9 (27.4)	234.4 (24.2)	76.1 (4.1)	70.4 (3.1)
M8	223.1 (12.6)	226.4 (14.9)	73.1 (3.6)	70.7 (4.0)
M9	271.3 (22.8)	271.8 (31.6)	75.3 (2.4)	75.8 (1.6)

evidence that this syllabification was more prevalent during SC. Three of these instances occurred during SA (all "pop" productions) and two during SC. It is notable that this child, like the child described in the introduction, had poor speech recognition skills (scoring 0% on PBK word score; see Table 1).

Intelligibility

The results of intelligibility testing indicated no differences between words produced in SC or SA modes (mean word correct: SC = 48%, SA = 48%; mean phoneme correct: SC = 66%, SA = 69%).

Inflection of Video Sign Model

Intensity and *f*0

Table 4 presents the means and standard deviations for intensity and *f*0 for each individual speaker as a function of whether the sign model was inflected or not. Based on previous examples in which visual characteristics of signs appeared to be generalized to speech production (Higgins et al., 1996, 2000), we predicted that the emphatic movements of the inflected model would result in more forceful speech by the children as indicated by greater intensity and a higher *f*0. These predictions were supported by the data. Productions following an inflected model were more intense than productions following a noninflected model (72.95 vs. 70.45 dB SPL), $F(1, 12) = 11.71$, $p < .01$. Similarly, words produced after an inflected model had a higher *f*0 (247.76 vs. 236.60 Hz), $F(1, 12) = 9.36$, $p < .05$. As in the SC versus SA study, average *f*0 was negatively correlated with PBK scores ($r = -.578$, $p < .05$).

Table 4. Data from signing model manipulation. Means (and standard deviations) are presented for fundamental frequency and intensity measures for words produced in response to a video of a normal or inflected signing model.

	*f*0 (Hz)		SPL (dB)	
Participant	Normal	Inflected	Normal	Inflected
F1	214.3 (11.7)	218.0 (18.4)	68.3 (6.6)	69.9 (6.6)
F2	226.6 (7.1)	234.3 (14.8)	74.2 (4.3)	76.1 (4.2)
F3	273.5 (50.8)	279.7 (52.9)	77.5 (5.1)	77.2 (5.7)
F4	270.6 (57.6)	318.1 (49.9)	65.4 (5.8)	70.4 (4.5)
F5	256.9 (6.5)	256.6 (6.1)	70.6 (1.6)	71.1 (1.3)
M1	255.3 (27.4)	266.5 (33.1)	74.9 (4.4)	75.6 (4.5)
M2	170.4 (25.2)	172.7 (21.4)	62.5 (5.4)	63.4 (3.3)
M3	219.1 (31.5)	215.0 (42.1)	73.4 (2.8)	74.7 (6.1)
M4	269.2 (22.8)	280.6 (23.7)	66.2 (4.5)	67.6 (5.1)
M5	199.6 (22.4)	210.7 (20.0)	73.2 (3.3)	77.3 (3.7)
M6	265.0 (26.2)	298.1 (56.5)	68.4 (4.6)	77.8 (5.6)
M7	246.5 (30.5)	250.0 (18.4)	72.3 (4.6)	77.0 (6.1)
M8	205.2 (19.2)	219.0 (27.2)	65.8 (6.0)	69.8 (8.4)
M9	240.6 (19.2)	249.1 (23.2)	73.6 (2.9)	73.5 (3.7)

Temporal Measures

Table 5 presents the means and standard deviations for all of the temporal measures as a function of whether the sign model used inflection or not. No effects of inflection on temporal measures were predicted and none were found. There were no significant main effects of inflection on word, vowel, or VOT durations (all ps > .05). As in the SC versus SA study, PBK scores were negatively correlated with averages for both vowel duration ($r = -.608$, $p < .05$) and word duration ($r = -.689$, $p < .01$) but were not correlated with the difference scores comparing inflected and uninflected conditions.

Syllabification

Child F4, who had double syllable productions in the SC study, continued to produce incorrect syllabification in this study. Again, she only produced two syllables for multiple-movement words. Of the 10 productions of words with multiple-movement signs (one repetition of each of five words in both inflection conditions), 5 were two syllables. This never occurred for single-movement words. Three of these syllabifications occurred following the low inflection model ("pea," "goat," and "head") and two following the inflected model ("goat" and "head"). Three other children (M5, M6, F1) produced a single instance of incorrect syllabification. These three occurrences also were multiple-movement words (2 productions of "feet" and one of "head"). This pattern of results implicates the multiple movements in the sign as responsible for the syllabification. It also appears that children with poor speech perception skills are more prone to this production deviation.

Table 5. Data from signing model manipulation. Means (and standard deviations) are presented for each temporal measure for words produced in response to a video of a normal or inflected signing model.

	Word duration (ms)		Wowel duration (ms)		VOT (ms)	
Participant	**Normal**	**Inflected**	**Normal**	**Inflected**	**Normal**	**Inflected**
F1	777.1 (260.9)	729.3 (285.4)	472.9 (193.9)	335.6 (196.9)	132.3 (43.1)	113.8 (72.2)
F2	456.2 (59.6)	452.3 (61.4)	185.0 (42.5)	188.5 (48.6)	52.3 (35.6)	53.5 (31.4)
F3	529.1 (111.9)	512.6 (98.7)	267.7 (112.6)	279.3 (123.8)	104.7 (23.9)	92.0 (8.7)
F4	697.4 (290.6)	604.6 (212.7)	476.4 (236.5)	458.3 (178.6)	16.5 (12.0)	12.3 (12.5)
F5	788.1 (145.0)	753.4 (133.1)	375.5 (48.8)	368.4 (57.7)	12.7 (14.8)	13.0 (1.4)
M1	746.1 (135.9)	657.2 (79.3)	343.3 (183.1)	307.8 (123.7)	98.8 (63.0)	85.5 (51.5)
M2	522.2 (209.5)	523.8 (191.5)	192.5 (58.6)	205.9 (85.9)	38.8 (31.6)	42.5 (22.8)
M3	339.5 (189.6)	309.9 (107.5)	156.8 (73.2)	147.5 (76.1)	72.0 (41.8)	52.0 (38.4)
M4	579.8 (141.6)	576.8 (182.2)	241.2 (100.8)	198.1 (93.6)	71.5 (55.1)	66.5 (30.5)
M5	605.9 (134.2)	612.2 (115.3)	288.0 (111.8)	298.5 (97.1)	96.0 (103.2)	120.0 (93.4)
M6	504.1 (192.0)	447.3 (172.1)	335.8 (168.6)	283.4 (104.5)	113.0 (21.2)	52.0 (62.8)
M7	374.8 (160.8)	352.3 (86.3)	193.0 (62.6)	184.8 (59.2)	69.3 (42.1)	63.5 (35.2)
M8	511.6 (203.5)	636.8 (331.4)	191.5 (94.9)	198.0 (115.4)	63.5 (37.2)	69.5 (65.6)
M9	633.8 (193.5)	610.8 (277.0)	237.6 (103.6)	210.3 (71.6)	114.7 (74.6)	91.5 (49.4)

The rare nature of these syllabification errors makes it difficult to generalize the results. However, the fact that these errors occurred only in multiple-movement words is an interesting regularity. If one collapses the data across all four conditions and treats each production as an independent item, then a chi-square analysis reveals that this regularity is unlikely to be a random result, $\chi^2(1) = 12.06, p < .001$.

Intelligibility

Intelligibility was assessed for this set of produced words as it was for the SA versus SC task. There was no significant difference in mean percentage of phonemes correctly identified by listeners (inflection: 69%; no inflection: 65%). However, overall word identification scores were higher in the inflection condition (51%) than in the no-inflection condition (39%). This difference was statistically significant, $F(1, 12) = 5.55, p < .05$, and did not differ depending on the PBK group of the speaker, $F(1, 12) = 0.95$, *ns*. Because the intelligibility score for the inflection condition was similar to that obtained for the SC versus SA tasks, the difference appears to be a decrement in intelligibility resulting from the uninflected model.

Discussion

The goal of the present study was to determine if the acoustics of speech produced by children with CIs could be affected by variation in the elicitation task. Two variables were examined: communication mode and inflection of a sign model. Based on previous findings with NH adults (Schiavetti et al., 1996, 1999; Whitehead et al., 1995, 1999), we predicted that spoken word, vowel, and VOT duration would be lengthened during SC compared with SA and that these perturbations would be greatest for children with limited speech skills. These predictions were not supported by the data. Communication mode did not significantly impact any of these temporal measures and there was no correlation with individual PBK scores. We also proposed that temporal disturbances would be more substantial for signs with multiple movements (Whitehead et al., 1997), but this also was not borne out in the data.

One reason for the discrepancy between our results and previous reports may be differences in methodology. Whitehead and colleagues had their participants sign and speak entire sentences, whereas we asked children with CIs to produce words in isolation. In addition, Whitehead et al. (1995) reported that SC conditions including fingerspelling resulted in the greatest lengthening of temporal measures. We asked our participants to provide the sign for each word without fingerspelling. These methodology choices for our study were made to provide a simple task for young children. We wanted to present each word as a picture because we did not want to limit our population by requiring fluent reading ability. Fingerspelling words correctly also would have been difficult for some of our participants. A possible consequence of our easier elicitation task is that there was less potential for signing to interfere with speaking. When producing sentences in SC mode, the timing of the oral and manual movements are relatively constrained by preceding and following words if one wants to maintain some simultaneity (Windsor & Fristoe, 1989, 1990). In contrast, words produced in isolation are not as constrained and the manual movements are free to end after the acoustic signal for the word, thus causing less disruption of speech timing. Results from Whitehead, Schiavetti, Metz, Gallant, and Whitehead (2000) support this proposition. In a study examining stress and intonation in SC, they report lengthened sentence durations during SC but failed to find significant shifts in vowel duration for key words. Unlike previous studies that had demonstrated longer vowel durations during SC (e.g., Whitehead et al., 1995), these key words occurred at the end of the sentence instead of in the middle of a carrier phrase. Like words produced in isolation, there may have been fewer constraints on simultaneity, leading to less temporal perturbation of speech during SC. We are examining temporal effects of SC for CI children with sentence stimulus sets. In the meantime, the current results demonstrate that, for children with CIs, SC does not result in extensive perturbations of the temporal patterns of speech production for words in isolation. This is a positive outcome for an elicitation task that is common with children in therapy and in research.

Another salient difference between the SC studies cited above and ours is in the participant population. Whereas previous studies had examined signers who probably learned to sign secondary to spoken communication (NH adults, both expert and inexperienced signers), our participants generally learned signed and spoken communication together. As a result, SC is the typical mode of communication for the children in our sample. It is possible that the SC mode did not lead to lengthening of speech articulations because the children have learned to produce simultaneous oral and manual movements with no interference, much like overlearned automatic tasks in the attention literature (e.g., Spelke, Hirst, & Neisser, 1976).

Another possibility is that instead of a lack of perturbation during SC, the reason for the null main effect is the presence of perturbation during SA. That is, because of a strong link between sign and spoken word in the language development of CI children, characteristics of the sign always influence oral production of the word. The spoken and signed versions of a word may not be separable. The result would be that the spoken version of a word would be lengthened regardless of the actual execution of the motor plan for the sign. In a large scale study comparing children with CIs and their NH age mates, Uchanski and Geers (2003) found that one of the most salient differences in speech production acoustics was vowel, word, and sentence duration. Children with CIs usually had longer productions and slower speech rate. If SA and SC are not really different production modes, it could be that hearing-impaired children with CIs (who are signers) always are showing the slower speech associated with SC by Whitehead and colleagues (1995).

Based on previous examples of purported generalizations from visual cues to speech production (Higgins et al., 1996, 2000), we predicted that a highly inflected sign model would lead to greater intensity and a higher $f0$ for speech produced by CI children. Both of these predictions were supported by the data. Highly reliable shifts in $f0$ and intensity were obtained from speech elicited by inflected versus noninflected sign models. The shift may have been a result of the children generalizing from the more dynamic movements of the inflected signer to their control of respiration and vocal fold adjustments. In addition, it is possible that the children were interpreting correctly the inflected signs as emphatic and marked this emphasis in their speech with increased intensity and $f0$. One also cannot rule out the possibility that the viewing of the dynamic movements of inflected signs led to an overall general arousal in the child, which resulted in more forceful speech production.

Regardless of the exact reason, it is clear that characteristics of the sign model can significantly affect speech acoustics in an elicitation task with hearing-impaired children. This occurs even for this special subpopulation of children with hearing losses who receive better auditory input from electrical hearing. This result has implications for comparative studies in which $f0$ and intensity are measured for children with normal and impaired hearing. If signs are used in the elicitation task for hearing-impaired children, the resulting speech may vary as a function of the dynamism of the sign movements. The result could be higher mean $f0$ and intensity measures or greater variance in these measures for children with hearing losses.

The results of these two studies have implications for the comparative study of speech development between NH and hearing-impaired children and the construction of norms for speech production. The differences between NH and hearing-impaired children are not just in the access to the acoustic signal. There are other differences that are chronic or acute that can have an effect in a speech elicitation task. An example of the latter is the effect of sign model inflection on production. Children with hearing losses probably are more affected by the visual variables in an elicitation task than are NH children; this appears to be true even when children receive a CI. Another example of a chronic difference is the presence of a capacity for parallel spoken and manual signing communication. While there were no obvious signs that SC perturbed speech production for words in isolation, it is possible that the dual communication modes interact in any speech elicitation task and this may be one reason for the slower speech reported for CI children (e.g., Uchanski & Geers, 2003). It also should be noted that there was quite a bit of heterogeneity in the demographic information for our participant group. It is possible that there are individual differences in the effects of SC on speech production related to etiology, educational background, age at implant, and so on that are not visible in the average results examined in this article. However, no salient individual difference patterns were recognizable in the current data set.

The variables studied here are only a subset of the potential confounds that may complicate the comparison of speech production skills by NH children and those with hearing loss. The sample that was examined here were children with CIs. Comparisons of speech development of CI versus NH children are essential for documenting the efficacy of implants. However, researchers must continue to take care to appreciate the differences inherent in elicitation tasks that may affect the validity of these comparisons.

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