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Effects of Short-Term Auditory Deprivation on the Control of Intraoral Air Pressure in Pediatric Cochlear Implant Users[1]

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Abstract. The purpose of this study was to determine whether two speech measures –peak intraoral air pressure (IOP) and IOP duration – obtained during the production of intervocalic stops would be altered as a function of the presence (or absence) of auditory stimulation provided by a cochlear implant (CI). Five pediatric CI users were required to produce repetitions of the words *puppy* and *baby* with their CIs turned on. The implants were then turned off for 1 hour, at which time the speech sample was repeated with the implant still turned off. Seven normal-hearing (NH) children were used as a comparison group. They were also tested twice with a one-hour interval between sessions. Peak IOP and IOP duration were measured for the medial consonant in both conditions. The results show that auditory condition affected peak IOP more than IOP duration. Peak IOP was greater for /p/ than /b/ with the CI off, but some participants reduced or reversed this pattern when the CI was on. Our findings suggest that different speakers with CIs may employ different articulation strategies as they learn to use the auditory signal in speech production.

Introduction

The primary purpose of providing sound enhancement to an individual with a hearing impairment is to aid in the perception of sound and speech. At the same time, there is evidence to suggest that sensory devices such as hearing aids and CIs also serve to facilitate speech production. Speakers who have been provided with feedback from these devices have been shown to demonstrate shifts in various acoustic and perceptual variables, generally toward the range of normal (Kirk & Hill-Brown, 1985; Leder et al., 1986; Osberger, Maso, & Sam, 1993; Svirsky, Jones, Osberger, & Miyamoto, 1998; Tartter, Chute, & Hellman, 1989; Tobey & Hasenstab, 1991; Tye-Murray, Spencer, & Woodworth, 1995). This suggests that auditory feedback plays a critical role in improving speech intelligibility and maintaining acceptable speech in individuals with hearing impairment. Nonetheless, even in NH individuals, it is not clearly understood how auditory information is used to regulate specific articulatory, physiological, acoustic, or aerodynamic variables so that intelligible speech is developed and maintained.

The ability of adventitiously deafened adults to maintain reasonably intelligible speech has been presented as evidence that on-line auditory feedback is not essential once speech motor patterns have become well established (Borden, 1979; Zimmermann & Rettaliata, 1981). Conversely, the abnormal speech characteristics of children who are deafened early in life highlight the importance of auditory feedback in speech motor learning. A deaf infant or toddler is unable to monitor the acoustic consequences of her phonation. Without access to this source of feedback (Guenther, Hampson, & Johnson, 1998) it is very likely that perceptually critical speech parameters are either not regulated at all or regulated outside the range of activity that is required for perceptually acceptable speech. For a young pediatric CI user, the relationship between auditory feedback and speech motor learning is unique. Such a child is provided with auditory information only after maladaptive speech patterns have developed and needs to learn not only *how* to regulate specific speech parameters, but also *which* parameters to regulate so that perceptually acceptable speech may emerge.

In an effort to determine those speech production parameters that are invariant – and presumably most critical to the control of normal speech production – a number of studies have observed the response of the speech production system to various types of perturbation. Most of these studies have introduced some type of mechanical interference (see Folkins, 1985 for a review). Some studies have involved altering or interrupting feedback mechanisms that are believed to be operative for speech regulation (Kelso & Tuller, 1983; Lane & Tranel, 1971; Prosek & House, 1975; Siegel & Pick, 1974; Siegel, Pick, Olsen, & Sawin, 1976). Several studies have demonstrated changes in the speech production of NH individuals when auditory feedback is manipulated. When amplified speech is fed back to NH individuals, both adults (Siegel & Pick, 1974) and preschool children (Siegel et al., 1976) have been shown to decrease vocal intensity; whereas when auditory feedback is attenuated, vocal intensity is increased (Lane & Tranel, 1971). The immediacy of these responses to auditory feedback manipulations was interpreted as an indication that “an auditory feedback system is available and operative…but that it does not begin to regulate speech except under circumstances in which communication is difficult” (Siegel & Pick, 1974, p. 1624). However, the implications of much of this auditory feedback research tell us little about the role of auditory feedback in motor speech development because the individuals studied were already skilled speakers and the experimental paradigm used in these studies may have forced “attention to auditory feedback which may not necessarily operate under normal circumstances for skilled speakers” (Borden, 1979, p. 309).

“On-Off” Experiments

A more intriguing approach to auditory perturbation comes from a number of studies of induced short-term auditory deprivation in pediatric CI users. The removal of auditory feedback from a pediatric CI user likely reveals different phenomena than auditory perturbation in NH individuals. It may shed light on the manner in which the individual uses auditory feedback for speech production, the motor speech strategies that the individual has learned, and the degree to which the individual relies on online auditory feedback.

Tobey et al. (1991) tested 13 children using the on-off methodology and found that second formant frequencies of vowels were more centralized when the speech processor was turned off while it approached near-normal frequencies with the processor on. Richardson, Busby, Blamey, Dowell, and Clark (1993) studied vowel formant changes in three children and found no consistent changes across participants as a function of auditory feedback. Tye-Murray, Spencer, Bedia, and Woodworth (1996) used phonetic transcriptions and clinician’s ratings to study the speech intelligibility of twenty pre-lingually deafened pediatric CI users in an on-off experiment. In general, the clinicians did not find any differences in intelligibility between the two auditory conditions. In some instances, however, the children exhibited vowel nasalization and inappropriate aspiration of initial consonants when the CI was on. The authors suggested that this reflected an attempt to increase proprioceptive feedback for the purpose of providing heightened awareness of their speaking behavior. Svirsky et al. (1998) used the on-off paradigm to study changes in nasalization in five pediatric CI users. In general, nasalization shifted toward the normal range with the CI turned on.

In two separtate studies of changes in phonation in two pediatric CI users, Higgins, McCleary, and Schulte (1999, 2001) found differences the children’s responses to short-term (one hour) auditory deprivation. One child showed decreases in IOP for both /p/ and /b/, decreases in fundamental frequency and intensity, a decrease in nasal airflow for /m/, and an increased second formant for /a/ after the CI had been turned off. The other child showed no consistent effects for auditory deprivation with the exception of a reduced voice-onset-time for /p/. The authors noted that the child who showed the most consistent changes in the off condition demonstrated better speech production and perception skills, suggesting that this individual may have been using auditory feedback in a regulatory fashion.

Speech Aerodynamics and Auditory Feedback

Many of the articulatory abnormalities observed in the speech of the hearing-impaired have been attributed to aberrant control of speech aerodynamic parameters such as respiratory kinematics (Forner & Hixon, 1977) and oral airflow (Itoh, Horii, Daniloff, & Binnie, 1982; Whitehead & Barefoot, 1983). IOP, particularly in bilabial plosives, has also been a variable of interest in this population (Higgins, Carney, McCleary, & Rogers, 1996; Leeper, Perez, & Mencke, 1980). The production of bilabial plosives involves the rapid increase and release of impounded oral pressure. In normal speakers, the presence or absence of voicing differentiates the magnitude and timing of the IOP that is associated with the production of /b/ or /p/; the voiceless consonant /p/ is produced with higher peak IOP and longer IOP duration than its voiced counterpart /b/ (Arkebauer, Hixon, & Hardy, 1967; Bernthal & Beukelman, 1978; Subtelny, Worth, & Sakuda, 1966). Peak IOPs produced by hearing-impaired speakers have been found to be higher than normal (Martony & Lindqvist, as cited by Leeper et al., 1980), lower than normal (Leeper et al., 1980), or consistently negative (Higgins et al., 1996).

Although the control of speech aerodynamics may be important to developing and maintaining adequate speech, its specific role as a speech motor control variable is not clear. Vocal tract pressure has been proposed as a variable that is monitored and may be employed as part of a feedback system (Malecot, 1970; Prosek & House, 1975). Indeed, normal speakers are able to detect self-generated IOP differences as small as 1.01-1.12 cm H_2O (Williams, Brown, & Turner, 1987) – less than the IOP difference that distinguishes voiced and voiceless consonants. Warren (1986) hypothesized that regulation of vocal tract pressure is principal in speech motor control and that a speaker will maintain vocal tract aerodynamics even at the expense of acoustic accuracy. Moon and Folkins (1991) tested Warren's hypothesis by attempting to force NH speakers into a choice between aerodynamic and acoustic regulation. IOP was measured while the intensity level of frication was attenuated and fed back to the speaker online. Significant changes in IOP, IOP duration, and pressure curve area were observed, but only when the frication level was attenuated by at least 30 dB. In addition, the pressure changes were not as dramatic as the authors had predicted. Moon and Folkins concluded that their results did not support the notion of a regulating system that relies exclusively on speech aerodynamics, nor did it support a regulating system that relies exclusively on auditory feedback (as represented by level of frication).

The presence of a CI generally results in access to feedback not previously available; a deaf child must learn to use sensory input to modulate the speech control parameters that will lead to improved speech intelligibility. This introduction of brief periods of auditory deprivation in pediatric CI users may reveal the extent to which they have learned to modulate and maintain these parameters and the extent to which they may be using online auditory feedback to achieve auditory-perceptual goals. Although the regulation of speech aerodynamics is considered critical to the production of acceptable speech, there is relatively little information regarding the manner in which a child with a CI uses auditory feedback to control speech aerodynamic parameters such as IOP. The purpose of this study was to examine if short-term auditory deprivation alters the control of IOP in pediatric CI users. Specific questions of interest include:

1) When auditory information is provided, do peak IOPs and IOP durations approach the range of normal compared to when auditory information is unavailable?

2) When auditory information is available, are differences in the IOPs associated with the productions of /p/ and /b/ more distinct than when auditory information is unavailable (thus demonstrating the speakers' attempts to use auditory input to mark the /p/-/b/ contrast)?

3) When auditory information is unavailable, are the changes in IOP reflective of an increased reliance on tactile feedback?

Methods

Participants

The participants were five pediatric CI users and seven NH children who served as a comparison group. The CI users were selected for their ability to understand the instructions for this study and their good speech perception and production skills. The motivation for selecting children with superior speech skills (three of the five participants) was to maximize the potential for observing change in their speech when the speech processor was turned on and off. All of the CI user participants used the Nucleus-22 device. Table I shows demographic characteristics of these participants, including age at onset of profound deafness, age at implantation, age at which the speech production tests described here were administered, intelligibility and speech perception scores, and communication mode used by each participant. The participants had used their CIs for 1.5 to 3.7 years at the time of testing.

Table I. *Demographic information regarding the participants with CIs.*

Participant	CI1	CI2	CI3	CI4	CI5
Age at onset of deafness (years)	3.5	0.0	0.0	0.0	0.0
Age at implantation	7.3	8.9	5.5	6.1	5.3
Age at testing	9.9	10.8	9.2	7.6	7.5
Word intelligibility (Monsen Sentence Test)	91%	11%	71%	54%	74%
Speech perception (PBK-phoneme)	76%	74%	66%	84%	83%
Speech perception (LNT-easy words, phoneme)	82%	60%	81%	81%	95%
Communication mode	Oral	TC	TC	Oral	Oral

The seven NH participants all spoke Standard American English. They exhibited normal oropharyngeal anatomy, normal speech articulation, and normal nasal resonance as judged by both investigators. The age range of the normal participants was 8-11 years.

Background Information on the Participants with CIs. The CI users were part of a large group of implanted children whose speech perception and production skills are being followed longitudinally in our laboratory. As part of the longitudinal project, we obtain measures of their speech intelligibility, speech perception, and language development during periodic visits to our lab. The participants selected for this study agreed to undergo additional testing to assess their production of oral pressure during one of their regular sessions. The intelligibility scores and speech perception scores in Table I were obtained using methods described previously (Meyer & Svirsky, 2000; Meyer, Svirsky, Kirk, & Miyamoto, 1998; Svirsky et al., 1998; Svirsky, Sloan, Caldwell, & Miyamoto, 2000). Other studies performed with large, representative samples of pediatric CI users (e.g., Svirsky & Meyer, 1999) indicate that participants inthe present sample were more intelligible and understood speech better than the average pediatric CI user. Because of this, results from the present study may not be generalizable to the entire population of pediatric CI users.

Speech Sample

The speech stimuli included repetitions of the words “puppy” and “baby.” To minimize the articulatory complexity of the speech task for the CI users, a carrier phrase was not used for either group. The rate of repetition was modeled for all participants at approximately 1.5 syllables per second.

Instrumentation

IOP was measured with a rigid polyethylene (PE) tube that was placed between the participants’ lips and positioned in the medial aspect of the oral cavity. The tube was coupled to a pressure transducer (Microswitch 164PC01D37). The pressure signal was amplified and low-pass filtered at 50 Hz using a Biocommunication Electronics 201 amplifier, then digitized at a sampling rate of 2500 Hz. The pressure transducer was calibrated for centimeters of water (cm H_2O) pressure using a Glottal Enterprises MCU-2 manometer. The speech acoustic signal was transduced simultaneously using a Sony ECM-44B microphone and digitized. The acoustic signal was transduced solely for the purpose of token identification.

Procedure

The participants were provided with the speech sample using an oral model provided by the examiner as well as the signs for the target words ("puppy" and "baby"). The participants were instructed to practice the words prior to data collection to demonstrate that their utterances approximated the correct productions of the target words. The examiner did not correct or modify the participants' word productions because each participant was able to produce the target words with sufficient intelligibility.

Each CI user produced repetitions of each word while their CI was turned on (ON condition). The participants produced each word in sets of 5-6 repetitions until at least 25 tokens were obtained. The CI users were then instructed to turn off their speech processors and leave the testing area for one hour. At the end of one hour, the participants returned to the laboratory and the speech sample was repeated with the implant still turned off (OFF condition). The order of the conditions was consistent across participants and conditions, with repetitions of "puppy" being produced prior to repetitions of "baby." The sequence of the auditory feedback condition was always ON followed by OFF.

Tests on the NH participants were performed twice with a one-hour interval in between to simulate the timing of the ON and OFF conditions under which the CI users were tested. For the NH participants, the two conditions will also be referred to as ON and OFF with the understanding that NH participants were not subjected to any auditory deprivation. Normal participants practiced the speech sample prior to data collection in order to provide the "normal" range against which the CI data were compared.

Data Measurement and Analysis

Peak IOP and IOP duration for the medial consonants /p/ and /b/ were measured for each participant. Peak IOP was defined as the point at which the pressure signal achieved its maximum deviation from baseline. IOP duration was defined as the time between the onset and offset of IOP associated with production of the medial consonant. A token was considered to be acceptable if it had a well-defined single peak, and if its onset and offset both occurred relative to baseline. The first token in each set of repetitions was not measured. For each word production obtained under each auditory condition, it was our initial intent to measure twenty acceptable IOP tokens per participant; however, it was not possible to do so in every instance. When a token was determined to be unacceptable, it was due to a pressure offset secondary to saliva in the PE tube or a double-peaked signal, which is attributable to the tongue occluding the opening of the PE tube. We obtained the target number in 38 of 48 total instances in which measurement of 20 IOP tokens was targeted (12 total participants x 2 phonemic targets x 2 auditory conditions). In the remaining instances, the number of tokens measured was as follows: 6 instances of 19 acceptable tokens, 1 instance each of 18, 17, 15, and 14 acceptable tokens. The instances of 17, 15, and 14 measurable tokens occurred with three of the NH participants.

For each participant, mean peak IOPs and IOP durations were determined for both the ON and OFF conditions. General linear mixed models were used to conduct repeated measure analyses of variance with peak IOP and IOP duration as the dependent variables. Hearing status (CI vs. NH), auditory condition (ON-OFF), phonetic context (/p/ vs. /b/), and all interaction terms among the three factors were included as independent variables in the mixed models. A compound symmetry structure was assumed for the correlations for both the peak IOP and IOP duration models, where observations from the same child were treated as correlated and observations from different children were treated as independent. Post-hoc analyses (*t*-tests) were carried out to compare the mean peak IOP and IOP durations between the two auditory conditions and the two phonetic conditions for each participant. Given the total number of post-hoc comparisons made (48), a probability level of .001 was used for each post hoc comparison to control for multiple comparison errors and to achieve an overall significance level of .05 for all post-hoc tests.

Results

Mean IOP Duration

Results of the mixed model analysis for mean IOP duration are provided in Table II. Table III shows the mean IOP durations obtained for the group of CI users in the ON and OFF conditions and for the group of NH speakers in the ON and OFF conditions. A significant three-way interaction between hearing status, condition and phonetic context was obtained. Post-hoc analyses showed that for productions of /p/, the CI group exhibited higher mean IOP durations than the NH group in both the ON and OFF conditions. However, only the OFF condition reaching statistical significance ($t(223)=7.79$, $p=.0001$). Within the CI group, mean IOP duration was longer in the OFF condition than in the ON condition; however, this difference was not statistically significant. For productions of /b/, the mean IOP durations for the CI group were longer than the mean for the NH group in both the ON and OFF conditions; the differences were statistically significant for both auditory conditions ($t(235)=4.47$, $p=.0001$ for ON; $t(236)=6.47$, $p=.0001$ for OFF). Within the CI group, no significant difference in IOP duration was found between the ON and OFF conditions.

Table II. *Results of general linear mixed model analysis.*

Variable: IOP Duration

Effect	Num DF	Den DF	F value	Pr > F
STATUS (CI--NH)	1	10	2.99	0.1143
CONDITION (ON--OFF)	1	10	0.13	0.7227
CONTEXT (/p/--/b/)	1	10	790.69	<.0001
STATUS*CONDITION	1	10	15.76	0.0026
STATUS*CONTEXT	1	10	30.96	0.0002
CONDITION*CONTEXT	1	10	2.39	0.1533
STATUS*CONDITION*CONTEXT	1	10	14.37	0.0035

Variable: Peak IOP

Effect	Num DF	Den DF	F value	Pr > F
STATUS (CI--NH)	1	10	9.62	0.0112
CONDITION (ON--OFF)	1	10	29.32	0.0003
CONTEXT (/p/--/b/)	1	10	258.26	<.0001
STATUS*CONDITION	1	10	2.17	0.1713
STATUS*CONTEXT	1	10	23.48	0.0007
CONDITION*CONTEXT	1	10	10.20	0.0096
STATUS*CONDITION*CONTEXT	1	10	7.70	0.0196

The results of post-hoc testing of the individual effects of auditory condition and phonetic context are presented below.

Auditory Condition: ON versus OFF. The mean IOP durations obtained for each of the NH and CI user participants in the ON and OFF conditions are shown in Table III. During productions of /p/, three participants (CI1, CI4, and CI5) showed no significant difference between the ON and OFF conditions. Two participants (CI2 and CI3) showed a statistically significant difference, with mean IOP duration being longer in the OFF condition for both participants (69.6 ms longer for CI2, 29.15 ms longer for CI3). Two of the NH participants (NH1 and NH3) showed statistically significant ON-OFF differences in mean IOP duration, with IOP duration being longer during ON (47.75 ms difference for NH1, 51.15 ms difference for NH3).

During productions of /b/, four participants (CI1, CI2, CI3 and CI4) showed no significant difference between auditory conditions. One participant (CI5) exhibited significantly longer IOP durations in the OFF condition (23.55 ms difference). Two of the NH participants showed statistically significant ON-OFF differences in mean IOP duration, with participant NH6 showing a longer mean IOP duration during the ON condition (25.6 ms difference), and participant NH2 showing a longer mean IOP duration in the OFF condition (18.05 difference).

Table III. *Individual and Group* mean *IOP durations (in ms) and standard deviations for productions of /p/ and /b/ by NH and CI user participants. Same-letter superscripts represent post hoc comparisons that reached statistical significance. Lowercase superscript: $p \leq .001$; Uppercase superscript: $p \leq .0001$.*

	/p/		/b/	
	ON	OFF	ON	OFF
CI1	192.15 (16.74) ^{A}	184.60 (18.46) ^{B}	129.35 (15.44) ^{A}	127.20 (14.88) ^{B}
CI2	194.05 (42.67) ^{C}	263.65 (35.54) ^{C,D}	157.28 (25.30)	138.45 (11.83) ^{D}
CI3	133.65 (9.22) ^{E}	162.80 (18.78) ^{E,F}	122.75 (17.15)	129.20 (18.66) ^{F}
CI4	323.47 (53.52) ^{G}	337.79 (63.11) ^{H}	167.79 (41.80) ^{G}	137.32 (33.33) ^{H}
CI5	192.25 (28.41) ^{J}	187.65 (21.18) ^{K}	133.45 (14.42) ^{I,J}	157.00 (16.50) ^{I,K}
	ON	OFF	ON	OFF
NH1	177.95 (20.10) ^{L,M}	130.20 (13.56) ^{L,N}	112.35 (14.43) ^{M}	105.25 (8.46) ^{N}
NH2	164.10 (15.32) ^{P}	170.65 (14.89) ^{Q}	118.85 (13.39) ^{o,P}	136.90 (17.74) ^{o,Q}
NH3	208.55 (34.07) ^{R,S}	157.40 (15.44) ^{R,T}	120.95 (17.48) ^{S}	120.30 (14.79) ^{T}
NH4	147.50 (11.28) ^{U}	141.85 (11.58) ^{V}	117.05 (13.93) ^{U}	114.65 (10.47) ^{V}
NH5	175.68 (68.12)	191.23 (57.28) ^{W}	144.10 (22.60)	130.70 (13.12) ^{W}
NH6	230.65 (35.42) ^{Y}	217.64 (57.52) ^{Z}	152.65 (19.53) ^{X,Y}	127.05 (10.88) ^{X,Z}
NH7	173.50 (21.54) ^{AA}	176.40 (20.77) ^{BB}	119.80 (15.76) ^{AA}	116.50 (13.74) ^{BB}
Group Means				
	/p/		/b/	
	ON	OFF	ON	OFF
CI	205.94 (70.41)	226.18 (73.31) ^{CC}	141.55 (29.81) ^{DD}	137.84 (22.54) ^{EE}
NH	182.61 (42.30)	166.24 (40.53) ^{CC}	126.54 (21.93) ^{DD}	121.58 (16.23) ^{EE}

Phonemic target: /p/-/b/ Contrast. In both the ON and OFF conditions, all participants exhibited IOP durations that were longer for /p/ than /b/; the difference was statistically significant for every comparison across all participants except participants N5, CI2, and CI3 in the ON condition. For the CI users, the magnitude of the /p/-/b/ difference within participants was similar across auditory condition for all participants except CI2, where the /p/-/b/ difference was much greater in the OFF condition than it was in the ON condition. In addition, it is evident that participant CI4 exhibited mean IOP durations for /p/ that were dramatically longer than those for /b/ in both auditory conditions.

Mean Peak IOP

Results of the mixed model analysis for peak IOP are provided in Table II. Table IV shows a summary of the mean peak IOPs obtained for the CI and NH groups in the ON and OFF conditions. A significant three-way interaction between hearing status, condition and phonetic context is again shown. For productions of /p/*,* the CI users produced mean peak IOPs that were significantly higher than the mean peak IOPs for the NH group for both the ON and OFF conditions ($t(236)=9.59$, $p=.0001$ for ON; $t(225)=9.37$, $p=.0001$ for OFF). Within the CI group, the mean peak IOP obtained in the OFF condition was higher than the mean peak IOP in the ON condition, but this difference was not statistically significant. For productions of /b/, the mean peak IOPs in both the ON and OFF were higher for the CI group than the NH group. The differences were statistically significant in both auditory conditions ($t(235)=15.38$, $p=.0001$ for ON; $t(234)=73.36$, $p=.0001$ for OFF). No significant difference in mean peak IOP was shown for /b/ within the CI group between the ON and OFF conditions.

Table IV. *Individual and Group mean peak IOPs (in cmH_2O) and standard deviations for productions of /p/ and /b/ by the CI and NH participants. Same-letter superscripts represent post hoc comparisons that reached statistical significance. Lowercase superscript: $p \leq .001$; Uppercase superscript: $p \leq .0001$.*

	/p/		/b/	
	ON	OFF	ON	OFF
CI1	9.70 (1.39) [A,B]	14.08 (2.15) [A]	11.70 (1.48) [B]	12.48 (1.06)
CI2	16.24 (3.43) [c]	20.08 (2.85) [c,D]	18.92 (2.48)	16.22 (2.84) [D]
CI3	8.40 (1.32)	7.33 (1.97)	7.81 (1.17) [E]	5.69 (1.10) [E]
CI4	8.14 (1.64) [f]	9.95 (1.34) [f]	7.52 (1.03)	8.48 (2.02)
CI5	16.31 (4.39) [G]	14.02 (2.04) [H]	9.48 (1.94) [G]	11.08 (1.24) [H]
	ON	OFF	ON	OFF
NH1	7.11 (0.98) [I]	8.50 (0.75) [I,J]	5.96 (1.34)	4.77 (1.66) [J]
NH2	9.32 (1.24) [k,L]	11.49 (1.69) [k,M]	5.40 (1.18) [L]	6.72 (1.83) [M]
NH3	11.08 (0.70) [O]	10.85 (2.21) [P]	4.89 (1.85) [N,O]	7.06 (1.74) [N,P]
NH4	7.02 (0.71) [Q]	6.72 (0.64) [R]	3.58 (1.34) [Q]	4.45 (1.19) [R]
NH5	5.72 (1.72)	6.21 (1.03) [S]	4.02 (1.29)	4.27 (1.08) [S]
NH6	6.30 (1.40) [u]	6.74 (1.07)	4.81 (1.08) [u,T]	6.71 (0.74) [T]
NH7	6.00 (0.70) [V,W]	8.48 (0.85) [V,X]	4.63 (1.04) [W]	5.51 (1.74) [X]

Group Means

	/p/		/b/	
	ON	OFF	ON	OFF
CI	11.79 (4.61) [AA]	13.12 (4.84) [BB]	10.96 (4.43) [CC]	10.82 (4.00) [DD]
NH	7.52 (2.14) [AA]	8.55 (2.34) [BB]	4.76 (1.49) [CC]	5.64 (1.82) [DD]

The results of the post-hoc tests of group differences and the individual effects of auditory condition and phonetic context are presented below.

Auditory Condition: ON versus OFF. In general, the within-target comparisons reveal that some CI users demonstrated higher mean IOPs in the ON condition, while others showed higher IOPs in the OFF condition. For productions of /p/, three of the five CI users (CI1, CI2, and CI4) exhibited mean peak IOPs that were significantly higher in the OFF condition than in the ON condition (by magnitudes ranging from 1.81-4.38 cmH_2O). Participants CI3 and CI5 demonstrated higher mean IOPs in the ON condition, although neither of the comparisons for these participants showed a statistically significant difference. Some of the NH participants exhibited statistically significant ON-OFF differences, with participants NH1, NH2, and NH7 showing higher mean peak IOPs in the OFF condition (by magnitudes ranging from 1.39-2.48 cmH_2O).

For productions of /b/, two CI users (CI2 and CI3) showed higher mean IOPs in the ON condition. Only CI3 showed a statistically significant difference (2.12 cmH_2O difference). Participants CI1, CI4, and CI5 showed higher mean pressures in the OFF condition; none of these differences was statistically significant. For the NH participants, mean peak IOPs were significantly higher in the OFF condition for participants NH3 and NH6 (by magnitudes of 2.17 and 1.90 cmH_2O, respectively).

Phonetic Target: /p/-/b/ Contrast. For the NH participants, mean peak IOPs were higher during productions of /p/ than /b/; the differences were statistically significant in all instances except one (NH6, OFF condition). For the CI users, comparison of mean peak IOPs for /p/ and /b/ within auditory condition are presented in Figure 1. The mean peak IOP was consistently higher for /p/ than for /b/ in all participants in the OFF condition (by magnitudes ranging from 1.47–3.86 cmH_2O); the difference was statistically significant only for participants CI2 and CI5. This effect was not observed in the ON condition, however, where only one participant (CI5) had a mean peak IOP that was significantly higher for /p/ than /b/ (by 6.83 cmH_2O). For participants CI3 and CI4, mean peak IOP for /p/ was slightly higher than it was for /b/ (by 0.59 and 0.62 cmH_2O, respectively), but these differences were reduced compared to the OFF condition, and were not statistically significant. The remaining participants (CI1 and CI2) exhibited mean peak IOPs for /b/ that were higher than those for /p/ (by 2.00 and 2.68 cmH_2O, respectively); this difference was statistically significant for CI1. For these two participants, a reversal in the peak IOP contrast occurred for /p/ and /b/ in the OFF condition.

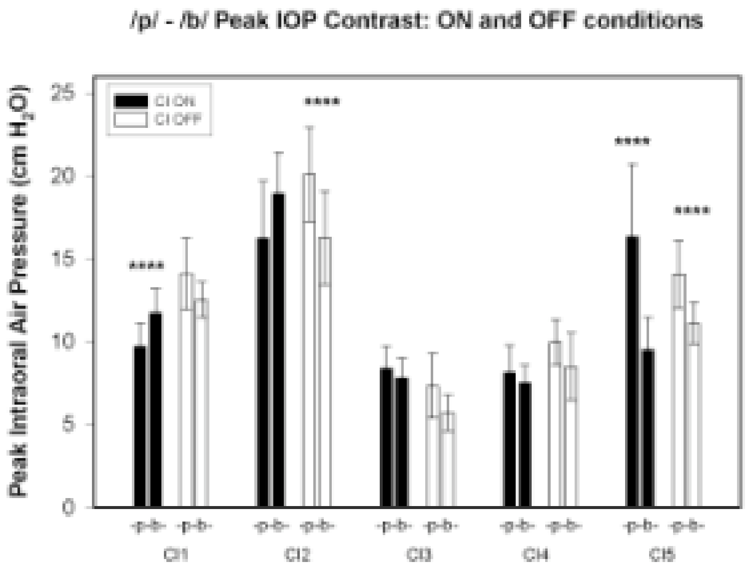

Figure 1. Comparison of mean peak IOPs for /p/ versus /b/ within auditory condition for the CI users. Statistically significant post-hoc comparisons are marked with asterisks. (**** $p \leq .0001$).

Discussion

The purpose of this study was to determine if two specific aerodynamic variables in speech production would be altered by auditory feedback provided by a CI. Given the exploratory nature of this study, explicit hypotheses regarding how the variables of interest might be altered were not proposed. Nonetheless, we anticipated that the variables would shift toward the range of normal when auditory information was available (i.e., when the CI was on). Such a shift did not occur on a consistent basis. In the ON condition, the CI participants exhibited mean peak IOPs for /p/ that were lower and closer to normal than in the OFF condition; however, there was essentially no ON-OFF difference for productions of /b/. All participants (both CI and NH) showed appropriately higher peak IOPs for /p/ than for /b/ in the OFF condition, but this contrast was reduced or reversed in the ON condition for four of the five CI users. This counterintuitive but interesting result has no precedent in the CI literature.

Of the four participants (CI1 thru CI4) who reduced or lost the /p/-/b/ contrast for peak IOP in the ON condition, no two participants exhibited this outcome in the same way. Relative to the OFF condition, these participants showed the following IOP patterns with the CI turned on: participant CI1 maintained a stable IOP for /b/, but decreased IOP for /p/ considerably; participant CI2 decreased the IOP for /p/ considerably while increasing the IOP for /b/ significantly; participant CI3 increased IOP for both /p/ and /b/, but the magnitude of the increase was greater for /b/; and participant CI4 decreased IOP for both /p/ and /b/, but the magnitude of the decrease was greater for /p/. Some of these inter-subject differences may reflect the participants' efforts to shift the magnitude of their peak IOPs to within normal limits, but this is not always an adequate explanation. For instance, Participant CI2's mean IOP shifted in the direction of normal for productions of /p/, but it shifted away from normal for /b/. In addition, the mean peak IOPs for participants CI3 and CI4 were already within the range of normal, so no significant IOP manipulation was required.

IOP duration did not appear to vary as a function of the presence or absence of auditory feedback. While a statistically significant difference was observed between the ON and OFF conditions, the magnitude of the difference was usually not very large (30 ms or less). Further, although the mean IOP duration values were higher in the CI group, the magnitudes of the CI participants' ON-OFF differences were comparable to the ON-OFF differences exhibited by the NH participants. Thus, just as in the NH participants, it is possible that the few ON-OFF differences observed in the CI participants were due to variability that was related to subtle changes in word duration.

The ON-OFF manipulation did not influence the /p/-/b/ contrast for IOP duration in the same way that it did for peak IOP. Mean IOP duration was greater for /p/ than it was for /b/ across both auditory conditions for all participants; this contrast was statistically significant in 13 of the 14 comparisons within the NH group, and in 8 of the 10 comparisons within the CI group. It is possible that the participants may have exploited IOP duration rather than peak IOP in an attempt to mark the voiced-voiceless distinction. The difference in mean peak IOP between /p/ and /b/ has been well established in NH children and adults, and the implication exists that this peak IOP difference is integral to producing and perceiving the voiced-voiceless distinction. However, it has been suggested that both the longer IOP duration and the higher peak IOP that occur during production of the voiceless /p/ help to passively suppress vocal fold vibration for a longer period relative to /b/ (Boucher & Lamontagne, 2001; Stevens, 1991), resulting in a longer voice onset time.

If this is true, then the CI participants who reversed the /p/-/b/ contrast for peak IOP may have employed one of two strategies. It is possible that they may have tried to maintain relatively stable IOP distinctions in duration to influence voice onset time, thereby marking the /p/-/b/ contrast. The results of this study lend tentative support to this notion. A second strategy that participants CI1 and CI2 may have employed to override the higher peak IOPs produced for the voiced consonant /b/ is the implementation of an active laryngeal adjustment to initiate voicing to counter the higher peak IOPs they produced. This type of strategy implies that some children with CIs might modify their speech production by selectively exploiting the acoustic dimensions of the speech signal that are well conveyed by the implant. Participants CI1 and CI2 may have exhibited relatively higher subglottal pressures for the medial /b/ in the word "baby" (where all segments are voiced) secondary to an attempt to increase the intensity of the voicing parameter, which is well perceived by implant users. The auditory information provided from the alternating voiceless-voiced-voiceless-voiced sequence in "puppy" is less consistent; attempts to accentuate the silence associated with the voiceless consonants may have led to a disproportionate decrease in SPL (Svirsky, Lane, Perkell, & Wozniak, 1992), resulting in lower subglottal pressures for /p/ relative to /b/. Thus, the IOP differences observed in the ON condition may be an indirect consequence of the speakers' attempts to manipulate a parameter that is associated with speech aerodynamics, such as SPL (Stathopoulos, 1986), and not the speakers' attempts to actively control an aerodynamic parameter, such as peak IOP.

Interestingly, all participants demonstrated an appropriate /p/-/b/ distinction regarding peak IOPs in the OFF condition. This finding suggests that the participants may have a greater reliance on tactile feedback with the CI off. Given that all of the participants were implanted after the age of 5, this may reflect a control strategy that is more fully developed, allowing for more consistent speech production at this stage in their implant use. Even though these individuals had from 1.5 to 3.7 years of experience with their CIs, it is likely that these participants were still in the process of learning to use the auditory signal to match specific articulatory and aerodynamic processes with a desired acoustic-perceptual signal. In essence, they may be in the process of replacing a well-established speech production model (one without auditory feedback) with a new modified model (one with auditory feedback).

The statistically significant ON-OFF differences that were observed in some of the NH participants were not anticipated. Despite these observed differences, it should be noted that when the mean peak IOPs and IOP durations of the NH group were collapsed across conditions, the mean values fall within the range of mean values reported for normal children (Bernthal & Beukelman, 1978; Leeper et al., 1980; Subtelny et al., 1966). Further, regardless of the ON-OFF differences exhibited by the individuals within this group, appropriate /p/-/b/ contrasts were maintained consistently across conditions. These unexpected within-subject differences could reflect either the fact that NH children tend to demonstrate greater variability in IOP production than do adults (Bernthal & Beukelman, 1978; Subtelny et al., 1966) or a practice effect, as familiarity with the speech task may have resulted in an alteration of speech behaviors. The likelihood of these results occurring in the NH participants may also have been increased by the fact that we did not control for sound pressure level during the speech task, which was motivated by concern that it would lead to speech production patterns by the CI users that would have been uncharacteristic of them in the OFF condition. Although a practice effect may have influenced the results obtained for the CI users, this is less likely since the two conditions were different for this group. Certainly, randomizing the order of the auditory condition across the CI users would have helped to address this issue. However, scheduling of the CI users' regular clinical evaluations on the same day did not permit us to manipulate the auditory condition in this way.

Implications

The small number of participants studied and the relatively inconsistent nature of the results precludes any firm generalizations regarding how pediatric CI users make use of auditory feedback in the regulation of speech production. There appeared to be no relationship between the results reported above and duration of CI use. Participant CI3 had the most experience and exhibited IOP values that were within normal limits, but did not demonstrate the appropriate /p/-/b/ contrast for peak IOP. Of the two individuals who completely reversed the peak IOP contrast with the CI on, one (CI1) had the best word intelligibility and the other (CI2) had the worst word intelligibility among the CI users. The only participant who exhibited the appropriate /p/-/b/ contrast for both IOP measures was CI5; this participant also demonstrated the best speech perception skills in this group. Keeping in mind the somewhat heterogeneous makeup of the CI group studied, the results of this study, as well as others (e.g., Higgins et al., 1999, 2001), are most likely representative of the fact that regardless of age of implantation or experience with the device, children with CIs may be found at different stages of learning what information to extract from the auditory signal for the purpose of developing and regulating speech production.

It is not clear how a developing child uses auditory input to develop perceptually acceptable speech. Guenther et al. (1998) posited that speakers use an auditory perceptual reference frame to plan speech movements for vowels and semivowels. Callan, Kent, Guenther, and Vorperian (2000) suggest that auditory feedback of self-produced speech may be critical to developing speech movements that reproduce auditory targets. Although it is not the intent of this study to validate the auditory perceptual model of speech motor control, this model provides some insight into the speech production of children with CIs. Our assumption is that children with implants develop a model of speech production (i.e., a model of the acoustic and linguistic consequences of their articulatory actions) that is unlike the model developed by NH children. The two models may be similar for some of the acoustic dimensions that are easy to perceive by CI users, such as temporal cues (Van Tasell, Greenfield, Logemann, & Nelson, 1992) and changes in the speech waveform envelope (Van Tasell, Soli, Kirby, & Widin, 1987). However, the models may be different from normal in two possible ways. First, the CI model may not include those acoustic dimensions that are more difficult for CI users to perceive, such as rapidly changing spectral cues (Dorman, Dankowski, McCandless, Parkin, & Smith, 1991). Second, the CI model may include acoustic dimensions that are easily perceived by CI users, but which are overly relied upon for marking articulatory distinctions and which do not necessarily improve speech production (e.g., enhancing the voice-voiceless distinction by increasing the low-amplitude voicing signal for /b/ relative to /p/).

The results of this study are of interest in regard to Warren's (1986) theory that vocal tract pressure serves as the basic parameter of speech motor control. If this were the case, then one would have expected to see no change in peak IOPs as a function of auditory feedback. This pattern would be expected for children with profound hearing loss. These children are considered to rely heavily on tactile feedback during speech development. One might expect that the range of vocal tract pressures that are learned early in the speech development process would become ingrained and resistant to manipulation – even when auditory stimulation is provided. Alternatively, it could be assumed that the CI users in this study had access to an auditory signal for a duration sufficient to learn to regulate peak IOP within a relatively stable range. The fact that the peak IOP was altered as a function of auditory feedback implies that this aerodynamic parameter may not play a primary role in speech motor control, at least in children who were deafened prelingually or at a young age. At the same time, the relative stability of IOP duration that was observed across auditory conditions suggests that temporal aspects of vocal tract pressure may be a more critical control parameter, even if it is not regulated within an operating range that is close to normal (e.g., participant CI4's IOP durations for /p/). It should be noted that Warren, Morr, Rochet, and Dalston (1989) recognized the importance of auditory feedback to the development of speech production and suggested that vocal tract pressure becomes a fundamental control parameter *after* its association with auditory feedback is established during the process of speech development in the presence of normal hearing.

Two methodological issues deserve attention with regard to this study. First, although differences were observed in the aerodynamic variables as a function of the presence or absence of auditory information, there is some question as to whether a longer period of auditory deprivation would have resulted in greater changes in the measures of interest. Continued manipulation of this variable will be a topic of future investigation. Second, we did not attempt to correlate the aerodynamic differences to changes in speech intelligibility. However, as Tye-Murray et al. (1996) discuss, children with prolonged CI use exhibit changes in speech production using the ON-OFF paradigm that are not necessarily detectable to a listener. Our participants had an average of approximately 24 months experience with their CIs, which is not drastically less than the average use of 34 months by the participants in the Tye-Murray et al. study. Although perceptual speech ratings were not obtained as part of this study, changes in speech intelligibility and voicing errors were not noted by the primary investigator (DLJ) in the OFF condition. It is possible that a longer period of auditory deprivation would bring about greater aerodynamic changes with co-occurring changes in speech intelligibility. At the same time, it is acknowledged that parameters other than IOP are involved in the production of an intelligible /p/ or /b/. Further studies will be necessary to address these issues in speech production.

The results of the present study are also relevant to the role of auditory feedback in ongoing speech production. It has been proposed that auditory input is crucial for the development of ongoing speech production during the early stages of learning, but that continuous auditory feedback becomes less important as mature speech motor patterns develop (Guenther, et al., 1998; Tobey, 1993; Zimmermann & Rettaliata, 1981). We hypothesize that speech production in implanted children will be strongly dependent on the auditory information provided by the implant at early stages after implantation. Assuming that a pediatric CI user has the ability to extract acoustic information for the purpose of regulating speech production, this dependence on auditory feedback should decrease over time as users acquire more stable motor patterns for speech production. The ON-OFF experimental paradigm allows a unique opportunity to test this hypothesis. We would expect to see large differences between the ON and

OFF conditions shortly after implantation; these ON-OFF differences should decrease with time as the speech motor patterns become more embedded.

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