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Sneha V. Bharadwaj, Amanda G. Graves, Delia D. Bauer, and Peter F. Assmann

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Effects of auditory feedback deprivation length on the vowel /ε/ produced by pediatric cochlear-implant users

Sneha V. Bharadwaj, Amanda G. Graves, Delia D. Bauer, and Peter F. Assmann
School of Behavioral and Brain Sciences, Callier Center for Communication Disorders,
University of Texas at Dallas, 811 Synergy Park Blvd, Richardson, Texas 75080
snehab@utdallas.edu, agg043000@utdallas.edu, dda051000@utdallas.edu, assmann@utdallas.edu

Abstract: Effects of auditory deprivation on speech production by ten cochlear-implanted children were investigated by turning off the implant for durations ranging from 0.3 to 5.0 s and measuring the formant frequencies ($F1$ and $F2$) of the vowel /ε/. In five of the ten talkers, $F1$ and/or $F2$ shifted when auditory feedback was eliminated. Without feedback, $F2$ frequency lowered consistently, suggesting vowel centralization. Phonetic transcription indicated that some of these acoustic changes led to perceptible shifts in phonetic quality. The results provide evidence that brief periods of auditory deprivation can produce perceptible changes in vowels produced by some cochlear-implanted children.

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1. Introduction

Auditory feedback is considered important for speech development and maintenance (e.g., Borden, 1979; Perkell *et al.*, 1992). While several studies of deaf and normal-hearing individuals have attributed a calibrational role for auditory feedback in speech production within the short term (e.g., Zimmermann and Rettaliata, 1981), the exact nature of its role continues to be a topic of investigation. Studies of deaf individuals have employed the processor-on versus -off paradigm (e.g., Svirsky and Tobey, 1991; Svirsky *et al.*, 1992) as it allows an investigator to examine various aspects of speech produced in the presence and the complete absence of auditory feedback. This approach also permits the researcher to control the length of time for which auditory feedback is present or absent. Changes in both suprasegmental and segmental aspects of speech have been documented when auditory deprivation varied from 20 s–24 h (e.g., Svirsky and Tobey, 1991; Matthies *et al.*, 1996). Moreover, a few studies have demonstrated that auditory feedback-related changes in speech (e.g., fricative consonants, voice quality) produced by some talkers are perceptible to normal-hearing listeners (Tartter *et al.*, 1989; Bharadwaj *et al.*, 2006). While studies of acquired hearing impairments have shown gradual deterioration in speech quality consequent to hearing loss, studies using on-off paradigms or off-on-off paradigms have noted rapid changes in speech following auditory deprivation and restoration (see Svirsky *et al.*, 1992). These rapid changes suggest that the speech production mechanism needs to be updated with feedback information in order to fine-tune its settings and that the absence of feedback leads to drifting in speech parameters (e.g., Matthies *et al.*, 1996). In addition, these rapid changes in speech may represent either a deliberate strategy used by talkers who attempt to produce clear speech in the absence of auditory feedback or a switch from the use of the current internal model to the one acquired before cochlear implantation (see Bharadwaj *et al.*, 2006, for a summary).

Another approach to investigating the short-term effects of auditory feedback is to examine the time window involved in adjusting/correcting parameters of speech in response to altered auditory feedback in listeners with normal hearing (e.g., Kawahara and Williams, 1996;

Houde and Jordan, 1998; Jones and Munhall, 2000; Xu *et al.*, 2004; Purcell and Munhall, 2006b). Studies of normal-hearing individuals have shown adjustments in fundamental frequency ($F0$) over the length of a vowel or syllable, approximately 150 ms following manipulations to auditory feedback. While some investigators suggest that the time window of 150 ms would be too brief to assist in the online control of $F0$ (e.g., Donath *et al.*, 2002), other researchers propose that auditory feedback is used to regulate $F0$ across the length of a syllable (e.g., Xu *et al.*, 2004). In most of the auditory feedback perturbation studies, manipulation to auditory feedback has primarily involved upward or downward shifts in $F0$ only. There are a limited number of studies investigating the effects of online perturbation of auditory feedback on other speech attributes such as the formant frequencies, $F1$ and $F2$. An exception is Purcell and Munhall (2006a) who showed compensations in the production of the vowel /ɛ/ by normal-hearing adults in response to an unexpected increase or decrease in $F1$. The compensation was estimated to begin less than 460 ms following manipulation to auditory feedback, suggesting that the time involved in implementing auditory feedback-based corrective changes to $F1$ is longer than for $F0$. These findings raise important questions about the minimal time needed to make auditory feedback-based corrective changes in various types of speech parameters. Such data from children are quite limited and might make a valuable contribution to our understanding of the role of auditory feedback in the development of internal models for speech (see Perkell *et al.*, 2000; Guenther, 2006).

The present study examined whether brief deprivation of auditory feedback ranging from 0.3–5.0 s leads to significant shifts in $F1$ and $F2$ of the vowel /ɛ/ produced by children who were fitted with cochlear implants. An additional objective of this study was to investigate whether the acoustic effects that occur in vowels in the absence of auditory feedback are perceptible to trained listeners.

2. Acoustic analyses and phonetic transcription

2.1 Methods

2.1.1 Participants

Participants were ten prelingually deafened children who were fitted with multichannel cochlear implants. Information concerning age, gender, age of implantation, length of implant use, type of implant, implanted ear, and speech intelligibility is reported in Table 1. All participants had severe-profound hearing loss in the unimplanted ear. Participants were monolingual speakers of American English and used the oral-aural mode of communication. Participants were paid for their participation. The range of speech intelligibility scores (production) for each talker is reported in Table 1 and was assessed using the procedure described in Tobey *et al.* (2003). In this procedure, a set of three different listeners heard 36 sentences spoken by each talker and wrote down what they heard, guessing if necessary. The scoring was based on the total number of words in a sentence understood correctly by listeners.

2.1.2 Speech materials and procedures

The speech materials for this experiment included three sentences each with increasing phonetic material preceding the target vowel: (1) "a **head** again," (2) "This is a nose and a **head** again," and (3) "Hey look here, this is a nose and a **head** again." The target vowel was /ɛ/ in the word "head." This vowel was selected because several studies have shown significant formant frequency shifts when it is produced in the absence of auditory feedback (e.g., Svirsky and Tobey, 1991). Across the three sentence types, vowel /ɛ/ is increasingly distant (approximately 0.3–5.0 s) from the sentence onset.

Participants read a randomized list of 12 repetitions of each sentence in two conditions: cochlear implant processor-on (auditory feedback present) and processor-off (auditory feedback absent). The processor was turned on or off manually by the experimenter at the beginning of each sentence in a predetermined random order. Participants did not speak anything other than the target sentences. The sentences were audio recorded in a sound-treated room

Table 1. Demographic information for early-implanted and late-implanted participants.

Talker	Age (yrs)	Sex	Implanted age (yrs)	Length of CI use (yrs)	CI type and/ implanted ear	Range of speech intelligibility score (%)	Speech perception score (H.I.N.T.)
T1	7:2	F	2:1	5:1	Advanced bionics/L	95–96	89
T2	10:0	F	2:1	7:11	Nucleus 24/ L,R	99–100	86
T3	15:3	M	3:7	11:5	Nucleus 22/L	89–91	68[a]
T4	7:9	F	3:9	4:0	Advanced bionics/R	90–94	97
T5	10:4	M	2:7	7:9	Advanced bionics/R	81–91	56
T6	12:0	F	5:11	6:1	Nucleus 24/ L	95–98	98
T7	13:10	F	5:0	8:10	Nucleus 22/L	83–96	94
T8	10:6	F	5:1	5:5	Med-El C40+/L	94–96	88
T9	12:4	M	9:9	2:6	Nucleus 24/R	56–72	74
T10	9:7	M	5:4	4:3	Nucleus 22/L	83–96	88[b]

[a] PBK-50.

[b] Lexical Neighborhood Test.

using Sony PCM-M1 Digital Audio Recorder and a Sony ECM-719 condenser microphone placed approximately 10 in. from each participant's mouth. The recordings were conducted in one session lasting approximately 45 min.

Digital audio recordings were transferred to computer hard disk at a sampling rate of 22 kHz and 16-bit quantization. $F1$ and $F2$ of the vowel /ɛ/ were estimated for a total of 720 productions [10 talkers × 3 sentences × 12 repetitions × 2 conditions] at the midpoint of the steady-state portions of the vowel using Linear Predictive Coding (LPC) spectra combined with a peak-picking algorithm (Mertus, 2002). For each talker, there were a few cases where formant frequency estimation was difficult. For these cases, several steps were taken to ensure that formant frequency estimation was as accurate as possible including (a) centering a 20-ms hamming window at 20 and 40 ms to the left or right of the vowel midpoint and (b) identifying merged or missing formants through visual inspection of LPC spectra overlaid with discrete Fourier transform spectra. For each talker, the length of auditory deprivation was measured as the duration from the sentence onset to the midpoint of target vowel for all three sentence types produced in the processor-off condition (see bottom arrow in Fig. 1). This represents the average time for which auditory feedback was absent prior to vowel midpoint.

Two graduate students carried out narrow phonetic transcriptions of the target word "head" produced in both processor-on and -off conditions. Transcribers heard the target word in the original sentence contexts via headphones. Transcribers were trained in phonetic transcription. They were monolingual, native speakers of American English and were blind to the results of the acoustic analyses. In cases of disagreement between the two transcribers, a third transcriber was enlisted to serve as a tie-breaker.

2.2 Results

In an effort to compensate for differences in vocal tract size, formant frequency data were normalized using Nearey's log mean normalization procedure (Nearey, 1989). A two-way analysis of variance was conducted (with processor conditions and sentence type as factors) using log-normalized formant frequency values. In addition, three planned comparisons (with *Bonferroni* corrections and family-wise p value set at $p < 0.0167$) were performed for each talker to determine whether there were any significant processor-on versus -off differences, across the three

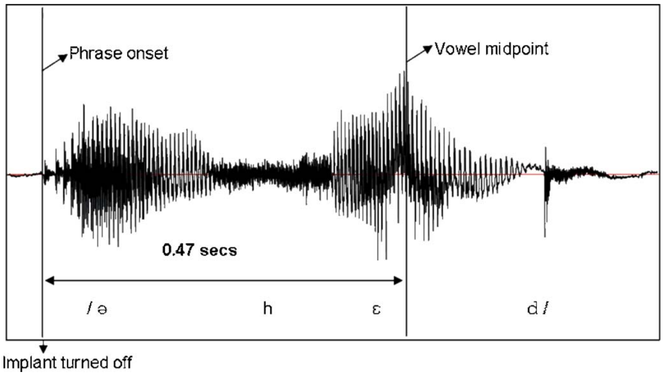

Fig. 1. (Color online) Waveform of the sentence "*a head*". The arrow at the bottom shows that auditory feedback is absent for approximately 0.47 s by the time the speaker has reached the midpoint of the target vowel /ɛ/.

sentence types. The F-ratios and Cohen's d values (Cohen, 1988) for each of the significant comparisons are reported in Table 2.

Figure 2 shows $F1$ and $F2$ values in kHz for the vowel /ɛ/ produced by ten talkers in three sentence contexts in both processor-on and -off conditions. The duration of auditory feedback deprivation associated with each sentence and each talker is listed above the subplots in Fig. 2. Figure 3 shows that there was no overlap in the length of auditory feedback deprivation across the three sentence types for any given talker. For sentence 1, with an average (across 12 repetitions) of 0.3–0.7 s of auditory deprivation, one talker (T1) showed a statistically significant $F1$ decrease and two talkers (T6 and T8) showed significant $F2$ decrease. For sentence 2, with an average of 1.5–3.0 s of auditory deprivation, three talkers (T6, T7, and T8) showed a statistically significant $F2$ decrease. None of the ten talkers showed a reliable $F1$ change. For sentence 3, with an average of 2.6–4.7 s of auditory deprivation, one talker (T2) showed a statistically significant $F1$ decrease and two talkers (T6 and T8) showed a significant $F1$ increase. In addition, two talkers (T7 and T8) showed a significant $F2$ decrease. Talkers T3, T4, T5, T9, and T10 did not show any reliable changes in $F1$ or 2 for any sentence. The processor-on versus -off (absolute) differences that were significant ranged from 47.5 to 85.5 Hz for $F1$ and ranged from 94 to 278 Hz for $F2$.

Correlation analyses were performed to examine the relationship between the extent of absolute $F1$ and/or $F2$ changes in processor-off conditions and the length of auditory feedback deprivation across all three sentence types. For $F1$, a moderate, positive correlation was found for sentence 1 ($r=0.65$; $p<0.001$; $n=10$) and sentence 2 ($r=0.75$; $p<0.001$; $n=10$). For $F2$, a moderate, positive correlation was found for sentence 1 ($r=0.55$; $p<0.001$; $n=10$). None of the remaining correlations were significant. Correlation analyses were also conducted to examine the relationship between the extent of $F1$ and/or $F2$ changes in processor-off conditions and (a)

Table 2. F ratios and Cohen's d values for talkers who showed significant processor-on versus -off differences for $F1$ and $F2$ for the three sentence types, as confirmed by planned comparisons with Bonferroni corrections ($p<0.0167$).

S1	$F1$	T1 [$F(1,22)=12.1$; $d=1.5$]
	$F2$	T6 [$F(1,22)=10.9$; $d=1.0$]; T8 [$F(1,22)=8.82$; $d=1.3$]
S2	$F1$	*ns*
	$F2$	T6 [$F(1,22)=12.7$; $d=1.1$]; T7 [$F(1,22)=15.3$; $d=1.3$]; T8 [$F(1,22)=21.7$; $d=1.3$]
S3	$F1$	T2 [$F(1,22)=16.1$; $d=1.3$]; T6 [$F(1,22)=14.1$; $d=1.0$]; T8 [$F(1,22)=9.16$; $d=0.7$]
	$F2$	T7 [$F(1,22)=26.1$; $d=1.9$]; T8 [$F(1,22)=46.4$; $d=2.5$]

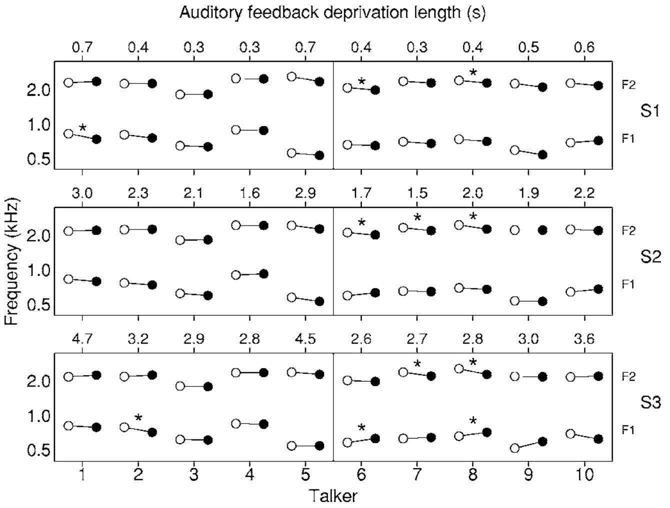

Fig. 2. Mean $F1$ and $F2$ values for vowel /ɛ/ produced in three sentences (S1, S2, and S3) by talkers 1–10 in processor-on and processor-off conditions. The average duration of auditory feedback deprivation in seconds is represented at the top of the dot plot for each talker. A star [*] indicates a significant processor-on versus -off difference as confirmed by planned comparisons with Bonferroni corrections ($p<0.0167$).

the age of implantation and (b) the length of hearing experience for all three sentence types. A moderate, negative correlation was found between $F1$ and the age of implantation for sentence 2 ($r=-0.67$; $p<0.001$; $n=10$). None of the remaining correlations were significant.

A subset of the phonetic transcription data was examined for the five talkers (T1, T2, T6, T7, and T8) who showed significant processor-on versus -off difference in order to explore whether the measured acoustic effects were perceptible to trained listeners. Narrow transcriptions by the two transcribers were compared to evaluate the extent of agreement between them. Of the 216 comparisons, there were 21 instances of disagreement, which were resolved by a

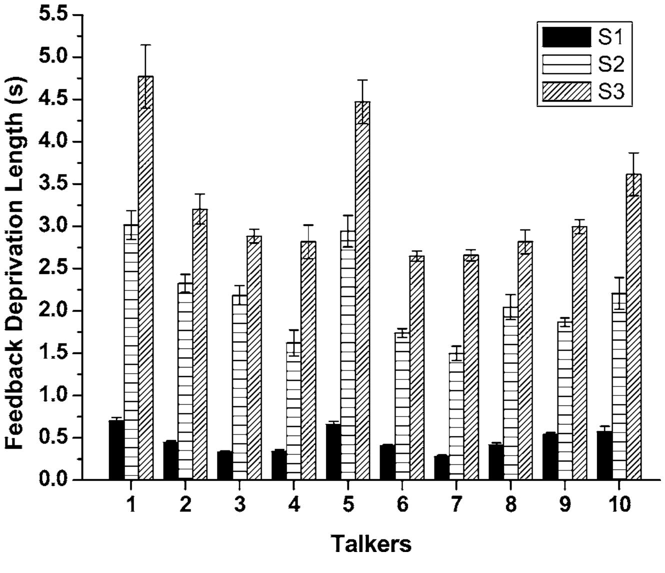

Fig. 3. Mean auditory feedback deprivation length (s) computed from sentence onset to vowel midpoint for sentences (S1, S2, and S3) produced by talkers 1–10 in processor-off conditions.

third transcriber. For sentence 1 produced by talker T1, phonetic transcription by both transcribers revealed more instances of substitution of /ɛ/ with /æ/ in processor-on (approximately 75% of the time) compared to the processor-off condition (approximately 50%). These substitutions are consistent with the acoustic findings of lowered $F1$ in processor-off compared to the processor-on condition. For talker T8, phonetic transcription by both transcribers showed several instances (average of 22%) of substitution of /ɛ/ with /æ/ in the processor-off condition only. This is also consistent with the acoustic findings of decrease in vowel $F2$ and an increase in vowel $F1$ in the processor-off condition. For talker T2, phonetic transcription by both transcribers revealed more instances of nasalized vowels in processor-off (approximately 91%) compared to the processor-on (approximately 72%) condition. The increase in nasality may be related to the decrease in vowel $F1$ in the processor-off condition. Lastly, for talkers T6 and T7, phonetic transcription by both transcribers did not reveal any noteworthy differences in vowels produced in the processor-on versus -off conditions.

3. General discussion

Auditory feedback deprivation resulted in $F1$ and $F2$ changes in the vowel /ɛ/ for a subset of talkers. While $F1$ shifts were characterized by both increases and decreases, significant $F2$ shifts were always lower in the absence of auditory feedback, suggesting vowel centralization. Centralization of vowels refers to the notion that vowels tend to drift toward the neutral vowel or middle of the vowel space due to impoverished feedback, leading to a constricted vowel space in some deaf individuals (Monsen, 1976). The vowel /ɛ/ is typically characterized by a higher $F2$ and a slightly lower $F1$ frequency when compared to a neutral vowel. Thus, a decrease in $F2$ and an increase in $F1$ for vowel /ɛ/ would be evidence of centralization. Five of the ten talkers showed significant $F1$ and/or $F2$ shifts when auditory feedback was removed. For those talkers who showed the largest acoustic effects for $F1$ and $F2$, phonetic transcription data revealed perceptible phonetic differences between the processor-on versus -off conditions.

Correlation analyses showed a positive relationship between the extent of formant frequency change and the duration of auditory deprivation, suggesting that larger changes in speech occurred for longer durations of auditory feedback deprivation. In addition, correlation analyses showed that the extent of $F1$ change was inversely related to the age of implantation, suggesting that children who were implanted at later ages showed smaller $F1$ changes in the absence of auditory feedback compared to children who received implants at younger ages.

Auditory deprivation experienced by children with hearing impairments could lead to limitations in terms of developing accurate representations between articulatory movements and their acoustic outcomes. Thus, responses to altered feedback may be different in children with hearing impairments compared to individuals with normal hearing. While it is not practical to have a control group for experiments using an on-off paradigm, the data from the present study showed that the responses to altered feedback by some children aided with cochlear implants were similar to those of normal-hearing adults. That is, consistent with the findings of Purcell and Munhall (2006a), three talkers in the present study showed significant shifts in $F1$ and/or $F2$ when auditory deprivation lasted approximately between 0.4–0.7 s. One might hypothesize that the talkers for whom rehabilitation efforts have been successful are likely to demonstrate auditory-feedback-based corrective changes in their speech similar to those of normal-hearing individuals. In fact, all the children who showed significant acoustic effects demonstrated good speech perception scores, had implant experience of approximately 6–8 years, and demonstrated relatively high average speech intelligibility scores compared to the average speech intelligibility scores for the other five talkers who did not show any significant $F1$ or $F2$ shifts. It is possible that deaf children with good speech perception abilities and intelligible speech are able to use feedback and feedforward controllers efficiently and interactively (see Max *et al.*, 2004) to fine-tune their speech in a manner similar to normal-hearing adults.

In conclusion, vowel formant frequency shifts were noted in five talkers in the absence of auditory feedback. Three of the five talkers showed $F1$ and/or $F2$ shifts when auditory feedback was eliminated for as briefly as 400–700 ms, suggesting that the time involved in implementing auditory feedback-based corrective changes in speech produced by some deaf children is similar to that of normal-hearing adults. Data from the present study provides evidence that auditory deprivation can produce small but perceptible acoustic changes in vowels produced by some pediatric cochlear-implant users. Future investigations are clearly necessary to extend the present study to a larger set of acoustic measures involving consonants as well as vowels.

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