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Effects of auditory feedback on fricatives produced by cochlear-implanted adults and children: Acoustic and perceptual evidence

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Acoustic analyses and perception experiments were conducted to determine the effects of brief deprivation of auditory feedback on fricatives produced by cochlear implant users. The words /si/ and /ʃi/ were recorded by four children and four adults with their cochlear implant speech processor turned on or off. In the processor-off condition, word durations increased significantly for a majority of talkers. These increases were greater for children compared to adults, suggesting that children may rely on auditory feedback to a greater extent than adults. Significant differences in spectral measures of /ʃ/ were found between processor-on and processor-off conditions for two of the four children and for one of the four adults. These talkers also demonstrated a larger /s/-/ʃ/ contrast in centroid values compared to the other talkers within their respective groups. This finding may indicate that talkers who produce fine spectral distinctions are able to perceive these distinctions through their implants and to use this feedback to fine tune their speech. Two listening experiments provided evidence that some of the acoustic changes were perceptible to normal-hearing listeners. Taken together, these experiments indicate that for certain cochlear-implant users the brief absence of auditory feedback may lead to perceptible modifications in fricative consonants. © *2006 Acoustical Society of America.* [DOI: 10.1121/1.2167149]

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I. INTRODUCTION

A growing body of evidence suggests that restoration of auditory feedback following cochlear implantation results in improvements in speech production by profoundly deaf individuals. Pre- versus post-implantation comparisons have revealed significant changes in speech over a span of weeks to months following the restoration of auditory feedback. These long-term changes include: shortened vowel durations, decreases in vowel F_0, lowered vowel intensity (SPL), shifts in the first and second formant frequencies of vowels toward more normal ranges, more appropriate voice onset times of stop consonants, and fricative spectral shifts toward more normal ranges (e.g., Tartter *et al.*, 1989; Economou *et al.*, 1992; Perkell *et al.*, 1992; Matthies *et al.*, 1994; Lane *et al.*, 1997; Kishon-Rabin *et al.*, 1999). These results confirm clinical findings that deaf individuals show marked improvements in a variety of speech attributes following restoration of auditory feedback. Perceptual data have indicated that these acoustic changes correspond with improvements in intelligibility and quality ratings. For example, normal-hearing judges perceived tokens produced by deaf persons after implantation to be qualitatively better than those produced before implantation (e.g., Tartter *et al.*, 1989; Kishon-Rabin *et al.*, 1999).

In addition to the long-term effects of auditory feedback, researchers also have explored the short-term effects of auditory feedback deprivation lasting anywhere from a few minutes to hours. These studies help address the minimal time window within which auditory feedback can have an effect on speech production. Most of these studies use a processor-on versus -off paradigm, in which an investigator can turn the cochlear-implant processor off to control the length of auditory deprivation and examine effects of complete absence of auditory feedback on speech production (e.g., Svirsky and Tobey, 1991; Svirsky *et al.*, 1992; Richardson *et al.*, 1993; Higgins *et al.*, 1999). In these studies where auditory deprivation lasted anywhere from 20 min–24 h, the following acoustic changes were noted: Formant frequency centralization for some vowels (e.g., /ɛ/ and /ɪ/), lengthened vowel durations, increases in SPL and F_0, and decreases in spectral contrast between /s/ versus /ʃ/. The findings of studies using the processor-on versus -off paradigm suggest that temporary changes in auditory feedback may result in significant modifications in both the segmental and suprasegmental properties of speech. These data are consistent with the idea that auditory feedback is used to calibrate or update the settings of the speech production mechanism. In other words, a cessation of auditory feedback presumably results in a loss of calibration and consequently a drift in speech parameters (e.g., Matthies *et al.*, 1996). To date, the effects of shorter periods of auditory deprivation (seconds to minutes) on speech production has not been thoroughly examined. Such information would be valuable because it would contribute to our understanding of the time window involved in calibration. Therefore, the first objective of this study was to investigate whether brief deprivation of auditory feedback (approximately 15–20 s) resulted in significant changes in the speech produced by cochlear implant users.

A number of experiments with normal-hearing individuals also have investigated the short-term effects by examining modifications in the ongoing speech in response to altered auditory feedback (e.g., Kawahara and Williams, 1996; Houde and Jordan, 1998; Burnett *et al.*, 1998; Jones and Munhall, 2000). For instance, several studies have shown shifts in vowel fundamental frequency (F_0) within 100–150 ms following altered auditory feedback (e.g., Kawahara and Williams, 1996; Natke *et al.*, 2003). While some investigators have argued that these latencies would be too slow to assist in the online control of F_0 (e.g., Donath *et al.*, 2002; Natke *et al.*, 2003), others have suggested that auditory feedback may be used to regulate F_0 across the length of a syllable, depending on the naturalness of the speaking task (e.g., Xu *et al.*, 2004). Although the exact implications of these short-term shifts in F_0 remain debatable, most researchers agree that auditory feedback may be used to calibrate/update the settings of the "internal model" or representation in normal-hearing individuals (e.g., Kawahara and Williams, 1996; Jones and Munhall, 2000; Larson *et al.*, 2001).

The concept of an "internal model" has been elaborated in a recent theory that addresses the role of auditory feedback in speech production (Perkell *et al.*, 1997; Perkell *et al.*, 2000). According to this theory, speech sounds are produced with reference to an internal model that is acquired during childhood. This model is a mapping between the vocal tract configuration and its acoustic output and is learned with the help of auditory, somato-sensory, and visual feedback. With maturation, the internal model becomes more robust and feedback is used intermittently to calibrate or maintain the settings of the model. Thus, an absence of auditory feedback may result in a loss of calibration of the suprasegmental and segmental properties of speech and consequently lead to a drift in speech. If the internal model is dependent on feedback for its development and if it is also assumed that congenitally deafened children have less overall experience in shaping their internal model compared to postlinguistically deafened adults, then it may be predicted that briefly eliminating auditory feedback will produce greater changes in the speech of children than adults. Therefore, a second objective of this study was to compare feedback-related changes in the speech of deaf children and deaf adults.

While there is evidence for acoustic changes in speech production in the absence of auditory feedback, data on the perceptual consequences of short-term acoustic changes are limited. An investigation by Tye-Murray and colleagues (Tye-Murray *et al.* 1996), examined if changes that occurred between processor-on versus processor-off speaking conditions were perceptible to experienced listeners. Broad and narrow phonetic transcriptions of speech produced by 11 prelinguistically deafened children did not reveal any significant differences across the two speaking conditions in terms of place of articulation, height, or the voicing features of consonants and vowels. However, it is possible that phonetic transcription measures were not sensitive enough to capture the subtle acoustic variations that occurred in speech produced under altered auditory feedback conditions. Therefore, a final objective of this study was to utilize a quality rating scale measure to examine if normal-hearing judges can perceive acoustic changes in speech produced in the temporary absence of auditory feedback.

In summary, the objective of the present study was to investigate the short-term effects of auditory feedback on fricative-vowel words produced by adults and children in the presence and absence of auditory feedback delivered via cochlear implants. Fricative-vowel words were selected as stimuli for several reasons. First, sibilant sounds require relatively precise articulation with few obvious visual cues. As such, they may be considered prime targets for articulatory disruption under altered auditory feedback conditions. Second, /s/ and /ʃ/ have well-defined spectral properties that can be described and classified by spectral moments analysis (mean, variance, skewness, and kurtosis; Forrest *et al.*, 1988). Acoustic analyses and listening experiments were designed to: (a) examine effects of brief deprivation of auditory feedback on word durations and spectral measures of fricative-vowel words; (b) investigate group differences in measured parameters and examine whether children demonstrate larger speech changes than adults in the absence of auditory feedback; and (c) assess whether the auditory feedback-influenced acoustic changes are perceptible to normal-hearing adult listeners.

II. ACOUSTIC ANALYSES OF FRICATIVE-VOWEL WORDS

A. Methods

1. Participants

Participants included four postlinguistically deafened adults (A1–A4) and four congenitally deafened children (C1–C4). All were native, monolingual speakers of American English. Information concerning age, gender, etiology of deafness, age of implantation, and length of implant use are reported in Table I. To constrain potential variability associated with the use of different speech coding strategies, only participants using a Nucleus multichannel cochlear implant with the SPEAK speech coding strategy were included. All participants had used their implants for at least four years and had used the oral-aural mode of communication. Participants were paid for their participation.

2. Speech materials and procedures

Speech materials included the words /si/ and /ʃi/. Participants were seated comfortably in a sound-treated room. They were shown the words "see" and "she" written on index cards and were asked to produce each of these two words eight times in succession following a prompt by the examiner. The words were produced under two conditions: (a) with cochlear implant device turned on [processor-on] and (b) immediately after the device was turned off [processor-off]. In the processor-off condition, the device was turned off for approximately 15–20 s during the production of the eight tokens of "see" and "she." A total of 32 fricative-vowel words were elicited from each of the participants, yielding a set of 256 productions (2 consonants $\times$ 2 conditions $\times$ 8 repetitions $\times$ 8 talkers [4 adults and 4 children]). Speech samples were audio-recorded in a sound-treated room using

TABLE I. Demographic information for child and adult participants in the study.

Talker	Age (yrs)	Sex	Etiology	Implanted age (yrs)	Length of CI use (yrs)
C1	7:11	M	Congenital	2:4	5:7
C2	7:1	F	Congenital	2	5:1
C3	7	F	Congenital	2:1	4:11
C4	10:9	F	Congenital	5:5	5:5
A1	58	F	Meniere's disease	52	6:0
A2	46	F	Oto-sclereosis	39	7:0
A3	46	F	Pendrid syndrome	32	14:0
A4	41	F	Unknown	37	~4

an AIWA HD-X3000 digital audiotape (DAT) recorder with a Shure SM94 condenser microphone placed 10 in. from the speaker's mouth. Digital audio recordings were transferred to computer hard disk at a sampling rate of 48 kHz and a 16 -bit rate using a Townsend DAT Link+. Data were down-sampled from 48 to 22 kHz for analyses. Spectral moments of fricative consonants and word durations (speaking rate) were derived from these recordings.

Centroid, variance, skewness, and kurtosis were estimated from spectral displays with a 20-ms full Hamming window centered at the fricative midpoint using TF32 software (Milenkovic, 2002). Spectral moments analysis treats the acoustic spectrum as a random probability distribution from which the four moments are derived: Centroid (spectral mean), variance (energy spread around the spectral peak), skewness (tiltedness or symmetry of the spectrum), and kurtosis (peakedness of the spectrum) (Forrest *et al.*, 1988; Tjaden and Turner, 1997). Word durations (beginning of the fricative to vowel offset) were measured using both waveform and spectral displays. The beginning of frication noise was defined as the first visible evidence of high-frequency energy preceding the vowel, while vowel offset was defined as the zero crossing of the last glottal pulse in the vocalic portion of the syllable.

B. Results

Cochlear implant users have different histories of profound deafness and psychophysical capabilities due to different patterns of nerve survival. For these reasons, individuals who have cochlear implants may be expected to respond differently to the absence of stimulation (Svirsky *et al.*, 1992). To examine these individual talker characteristics, data for each talker were analyzed separately. Group comparisons were also made to address the question of whether children as a group differed from adult talkers in their responses to deprivation of auditory feedback. The primary aim of the group analyses was to test the hypothesis that the magnitude of changes in speech patterns with and without feedback will be larger in children compared to adults. Therefore, a difference measure ($\triangle$, the absolute value of processor off minus on) was used in group comparisons. Effect size ("*d*"), a measure of the magnitude of treatment effect is reported along with the rest of the statistics for both individual and group data (see Cohen, 1988).

1. Individual subject data

A three-factor [Condition × Consonant × Trial] analysis of variance (ANOVA) was conducted separately for each talker for the following variables: spectral moments (centroid, skewness, variance, and kurtosis) and word durations. Two planned comparisons were conducted (with *Bonferroni* corrections and a family-wise p value set at $p < 0.025$) to test the hypotheses that acoustic measures for /si/ and /ʃi/ were significantly different in processor-on versus processor-off conditions.

a. Fricative spectral moments measures Centroid: As shown in Fig. 1 (left panel), centroid values were significantly higher in processor-on versus -off condition for /ʃ/ produced by talker C1 [$F(1,7)=20.43$; $p=0.002$; $d=1.76$]. In addition, centroid values were significantly lower in

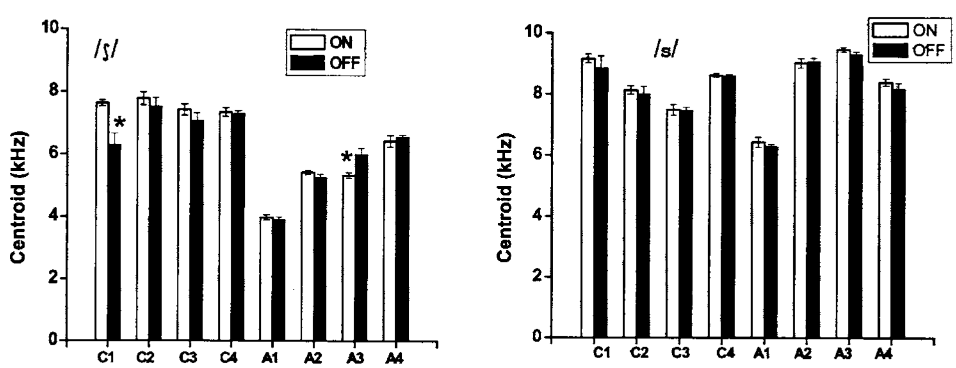

FIG. 1. Average centroid values of fricatives /ʃ/ and /s/ produced by deaf children (C1–C4) and deaf adults (A1–A4) in processor-on and -off conditions. Error bars represent the standard error across eight repetitions. A star [*] indicates significant difference ($p < 0.025$).

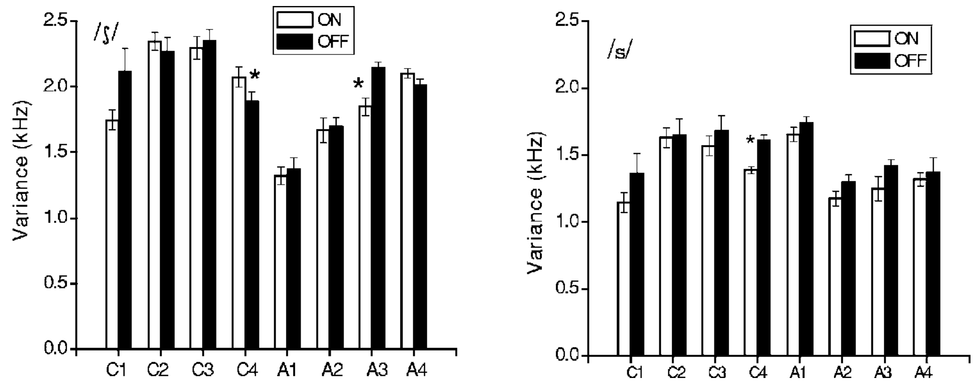

FIG. 2. Average variance values of fricatives /ʃ/ and /s/ produced by deaf children (C1–C4) and deaf adults (A1–A4) in processor-on and -off conditions. Error bars represent the standard error across eight repetitions. A star [*] indicates significant difference ($p<0.025$).

processor-on versus -off conditions for /ʃ/ produced by talker A3 [$F(1,7)=9.23$; $p=0.0006$; $d=1.63$]. No reliable differences were observed for the remaining talkers. As shown in the right panel, there were no significant differences between processor conditions for consonant /s/ for any of the talkers.

Variance: Figure 2 shows variance measures in processor-on versus processor-off conditions for all talkers. As shown in the left panel, talkers C4 [$F(1,7)=17.15$; $p=0.02$; $d=0.94$] and A3 [$F(1,7)=10.26$; $p=0.003$; $d=1.96$] demonstrated significant differences for /ʃ/ across the processor conditions. While C4 showed a significant increase in variance values, talker A3 showed a decrease in variance values in processor-on compared to -off conditions. Also, as illustrated in the right panel, significant decreases were found for /s/ produced in processor-on compared to -off conditions by talker C4 [$F(1,7)=11.53$; $p=0.009$; $d=2.5$]. No reliable differences were observed for the other talkers.

Skewness: Significant changes were noted for /ʃ/ for C1 [$F(1,7)=9.51$; $p=0.01$; $d=1.72$], and A3 [$F(1,7)=9.08$; $p=0.003$; $d=1.40$] in processor-on versus processor-off conditions [see Fig. 3, left panel]. C1 showed negative skewness coefficients in processor-on and positive values in processor-off conditions. On the other hand, A3 showed higher, positive skewness coefficient values in processor-on compared to -off conditions. No reliable differences were observed for the other talkers. For /s/, none of the talkers showed any significant differences between processor conditions [see right panel]. Skewness coefficients were negative for /s/ in a majority of talkers, except talker A1. As shown in the Fig. 3 (right panel), talker A1 showed positive skewness coefficients in both processor-on and -off conditions. It should be noted that these values are typical for /ʃ/ productions.

Kurtosis: Talkers A1 and A3 showed a relatively large processor-on versus -off differences for /ʃ/ compared to the rest of the talkers. Similarly, C4, A2, and A3 showed relatively large processor-on versus -off differences for /s/ compared to the rest of the talkers. However, these differences should be considered as trends, as they did not reach statistical significance.

b. Word durations Previous studies have reported no differences in mean duration of /s/ versus /ʃ/ and mean duration of /sVC/ versus /ʃVC/ syllables (e.g., Jongman *et al.*, 2000) and none were found in the present study. Therefore, duration data were collapsed across the two words, /si/ and /ʃi/. As shown in Fig. 4, turning the speech processor off resulted in significantly longer word durations for all four children and was confirmed by a significant main effect of condition: C1 [$F(1,7)=15.80$; $p=0.0054$; $d=0.62$]; C2 [$F(1,7)=6.76$; $p=0.03$; $d=1.39$]; C3 [$F(1,7)=10.76$; $p=0.01$; $d=0.86$]; and C4 [$F(1,7)=7.09$; $p=0.03$; $d=1.13$]. Two adults (A2 and A3) also lengthened word durations in the processor-off condition: A2 [$F(1,7)=16.98$; $p=0.004$; $d=1.70$], and A3 [$F(1,7)=6.26$; $p=0.04$; $d=0.64$]. In contrast, talker A4 demonstrated significantly shorter word durations in processor-off condition [$F(1,7)=5.86$; $p=0.04$; $d=1.00$], while A1 did not show significant changes in word durations as a function of processor condition. Increases in both fricative and vowel durations contributed to prolonged word durations following cessation of auditory feedback.

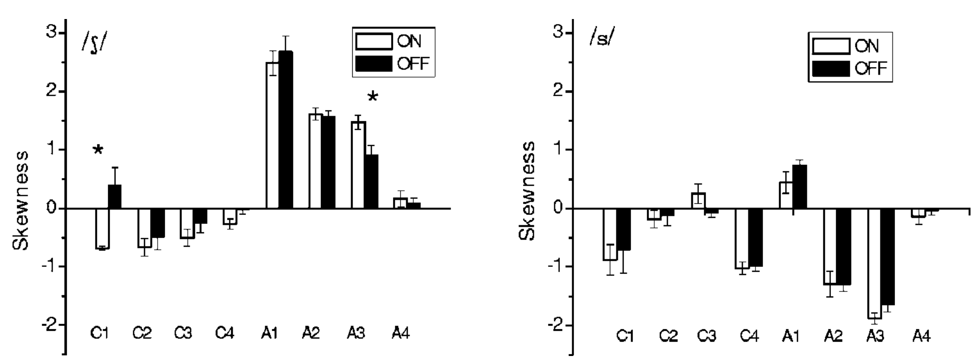

FIG. 3. Average skewness values of fricatives /ʃ/ and /s/ produced by deaf children (C1–C4) and deaf adults (A1–A4) in processor-on and -off conditions. Error bars represent the standard error across eight repetitions. A star [*] indicates significant difference ($p<0.025$).

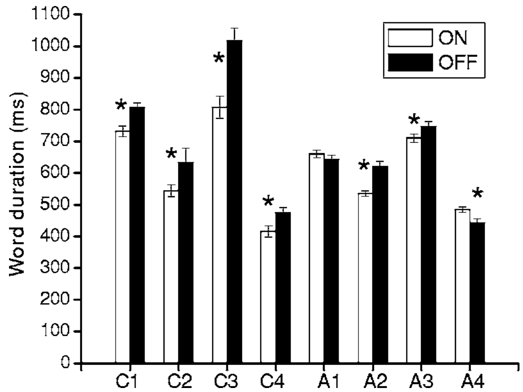

FIG. 4. Average word durations in processor-on and -off conditions for words produced by deaf adults and children. Error bars represent the standard error across eight repetitions of words /si/ and /ʃi/. A star [*] indicates significant difference ($p < 0.025$).

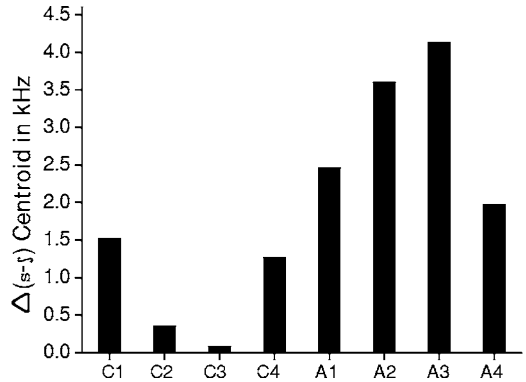

FIG. 5. Average /s/-/ʃ/ (△) centroid values for four deaf children (C1–C4) and four deaf adults (A1–A4) in processor-on conditions.

2. Congenitally deafened children versus postlinguistically deafened adults

A subset of children (C1, C4) and adults (A3) showed significant changes in spectral moments while a majority of the participants showed significant changes in word duration in processor-on versus -off conditions. Therefore, analyses examining whether the magnitude of processor-on versus processor-off differences is greater in children's compared to adults' speech were restricted to word duration data. A second series of group comparisons examined whether children and adults differ in production of /s/-/ʃ/ contrast in centroid values in the processor-on condition.

a. Fricative spectral moments measures Table II shows averaged spectral moments measures for /s/ and /ʃ/ produced by congenitally deafened children and postlinguistically deafened adults. The spectral moment measures derived for postlinguistically deafened adults were generally comparable to ranges reported for normal-hearing adults: Centroid (Nittrouer, 1995); variance, skewness (/s/ only), and kurtosis coefficients (Jongman *et al.*, 2000). Similarly, spectral moment measures derived for congenitally deafened children were comparable to ranges reported for normal-hearing children: Centroid (Pentz *et al.*, 1979; Nittrouer, 1995), skewness coefficients, and kurtosis coefficients for /ʃ/ only (Uchanski and Geers, 2003).

As shown in Table II, congentially deafened children showed higher centroid values and greater variability for /ʃ/ than postlinguistically deafened adults. Further, the variance values for /ʃ/ also were higher for children compared to adults. These findings may suggest developmental differences in /ʃ/ productions.

Figure 5 shows /s-ʃ/ contrasts in processor-on condition for each of the child and adult talkers. From this figure, it is clear that talkers C1 and C4 produced the largest /s/-/ʃ/ contrast among the children, while A3 produced largest /s/-/ʃ/ contrast among the adults. These three talkers also showed significant changes in fricative spectral moments in processor-on versus -off conditions. A closer inspection of Table II also shows that in the processor-on condition, adults produced an average /s/-/ʃ/ centroid difference values of approximately 3 kHz, while children produced a /s/-/ʃ/ centroid

TABLE II. Mean (*M*) and standard deviations (*SD*) of spectral moments for fricatives produced by congenitally deafened children (C1–C4) and postlinguistically deafened adults (A1–A4) in processor-on and processor-off conditions. Values for centroids and variance are reported in kilohertz. Skewness and kurtosis coefficients are dimensionless.

		Centroid				Variance				Skewness				Kurtosis			
		/s/		/ʃ/		/s/		/ʃ/		/s/		/ʃ/		/s/		/ʃ/	
		ON	OFF	ON	OFF	ON	OFF	ON	OFF	ON	OFF	ON	OFF	ON	OFF	ON	OFF
C1	*M*	9.15	8.84	7.62	6.29	1.14	1.36	1.74	2.11	−0.87	−0.70	−0.68	0.39	1.33	1.33	0.07	−0.15
	SD	0.41	1.10	0.28	1.03	0.20	0.418	0.21	0.49	0.73	1.12	0.10	0.87	1.71	2.46	0.59	1.25
C2	*M*	8.12	7.99	7.77	7.52	1.62	1.65	2.34	2.27	−0.17	−0.12	−0.65	−0.49	−0.80	−0.52	−0.81	−0.62
	SD	0.40	0.73	0.58	0.76	0.20	0.34	0.19	0.28	0.41	0.46	0.42	0.59	0.46	1.24	0.48	0.83
C3	*M*	7.49	7.47	7.41	7.07	1.56	1.67	2.29	2.34	0.25	−0.06	−0.49	−0.24	−0.004	0.17	−0.87	−1.14
	SD	0.50	0.30	0.50	0.68	0.20	0.32	0.24	0.25	0.48	0.23	0.40	0.46	0.98	0.94	0.78	0.37
C4	*M*	8.61	8.58	7.33	7.28	1.38	1.61	2.07	1.88	−1.01	−0.98	−0.26	−0.02	1.18	0.46	−0.81	−0.73
	SD	0.17	0.15	0.40	0.28	0.07	0.10	0.21	0.19	0.29	0.23	0.25	0.22	1.18	0.80	0.33	0.27
A1	*M*	6.43	6.29	3.97	3.89	1.65	1.73	1.32	1.37	0.44	0.74	2.48	2.68	0.11	−0.02	7.02	8.21
	SD	0.48	0.20	0.22	0.23	0.14	0.14	0.18	0.23	0.52	0.23	0.60	0.73	0.72	0.57	4.16	4.77
A2	*M*	9.02	9.06	5.41	5.25	1.17	1.29	1.66	1.69	−1.28	−1.28	1.61	1.56	3.97	2.96	2.01	1.83
	SD	0.44	0.34	0.18	0.30	0.15	0.16	0.26	0.18	0.61	0.34	0.31	0.29	2.43	1.43	1.59	1.30
A3	*M*	9.46	9.30	5.32	5.99	1.24	1.41	1.84	2.14	−1.88	−1.64	1.47	0.90	6.05	4.02	1.29	−0.48
	SD	0.19	0.25	0.24	0.55	0.25	0.13	0.18	0.12	0.25	0.35	0.33	0.47	1.97	1.67	1.22	0.96
A4	*M*	8.39	8.17	6.41	6.53	1.31	1.36	2.10	2.01	−0.13	−0.03	0.16	0.08	−0.31	−0.48	−1.29	−1.29
	SD	0.32	0.55	0.52	0.23	0.13	0.30	0.10	0.12	0.39	0.21	0.37	0.25	0.42	0.85	0.160	0.18

difference of approximately 800 Hz. Similarly, in the processor-off condition, adults produced an average contrast in centroid values of approximately 2.78 kHz between /s/ and /ʃ/, while children produced an average contrast of approximately 1.17 kHz. Analyses examining group differences for /s/-/ʃ/ contrast indicated that children produced a significantly less distinct /s/-/ʃ/ contrast in comparison to adults for both processor-on [$F(1,7)=91.09$; $p=0.0001$; $d=2.41$] and processor-off conditions [$F(1,7)=47.32$; $p=0.0001$; $d=1.4$].

b. Word duration Group comparisons were conducted to examine whether children showed larger processor-on versus -off differences in word duration using a one-way ANOVA. Note that processor on minus off difference values [$\triangle$] were used in these analyses. Previous studies have reported no differences in mean duration of /s/ versus /ʃ/ and mean duration of /sVC/ versus /ʃVC/ syllables (e.g., Jongman, *et al.* 2000). Therefore, duration data were collapsed across the two words, /si/ and /ʃi/.

Results indicated larger processor-on versus processor-off differences for word durations produced by children [Mean (M): 169.75 ms; Standard deviation (SD): 148.35] compared to adults (M: 78.48 ms; SD: 53.52) and was confirmed by a significant main effect of group [$F(1,7)=79.51$; $p=0.0001$; $d=0.81$]. However, word durations are generally longer in children's compared to adults' speech. Therefore, to account for these relative differences, the $\triangle$ word duration values also were adjusted by computing the proportion of change in each talker group [defined as (on-off)/(on) expressed as absolute values]. The proportion of change in processor-on versus -off conditions was 0.27 and 0.13 for children and adults, respectively. This finding confirms that the proportion of change in word duration was, in fact, longer for children's words compared to those of adults, and was not merely a by-product of the relatively longer duration of children's utterances.

C. Summary

Auditory deprivation lasting for approximately 15–20 s resulted in significant spectral changes in /ʃ/ produced by two children (C1, C4) and one adult (A3). These talkers also demonstrated a larger /s/-/ʃ/ contrast in centroid values, compared to the other talkers in their group. Further, results showed significant changes in word durations in the absence of auditory feedback for a majority of talkers. Group comparisons revealed a significantly larger change in word durations in processor-on versus -off conditions for children compared to adults. In addition, children produced a significantly less distinct /s/-/ʃ/ contrast compared to adults. A quality rating study was conducted to examine the perceptual relevance of these acoustic findings.

III. RATING EXPERIMENT

The objective of this experiment was to determine whether the acoustic changes that resulted from changes in auditory feedback status were perceptible to normal-hearing listeners. Speech samples produced by congenitally deafened children and postlinguistically deafened adults were presented to normal-hearing listeners to determine whether the acoustic changes that occurred in the absence of auditory feedback were detectable. Based on the acoustic findings of developmental differences for /ʃ/, and the finding of processor-on versus -off differences for /ʃ/ produced by children, it was predicted that quality ratings provided by listeners would be significantly poorer for /ʃ/ produced by children in processor-off compared to -on conditions.

A. Methods

1. Listeners

Ten native speakers of American English with a background in Speech-Language-Pathology served as listeners. All listeners had taken a graduate-level course in phonetics. None reported any speech or hearing problems.

2. Stimuli

Stimuli for this experiment included the fricatives /s/ and /ʃ/ excised from the words /si/ and /ʃi/ used in the acoustic analyses. The beginning of each fricative was identified by the onset of high frequency noise components, and the fricative end was identified as the intensity minimum immediately preceding the onset of vowel periodicity (Jongman *et al.* 2000). A total of 256 stimuli [8 talkers $\times$ 2 consonants $\times$ 2 conditions $\times$ 8 repetitions] were included in the rating experiment. Fricative noises excised from the fricative-vowel words were included as stimuli to minimize any potential influences of the following vowel during fricative judgments.

3. Procedure

Listeners were asked to assign quality ratings on a 100 mm Visual Analog Scale (VAS) displayed on the computer monitor. The VAS was used to gather perceptual data since it is frequently used in the evaluation of pathological voices and has been shown to correlate well with instrumental measures (e.g., Rabinov *et al.*, 1995; Yu *et al.*, 2002).

Listeners were informed that they would hear fricatives produced by cochlear-implanted children and adults under different talking conditions. They were asked to attend to the overall quality of the fricative noise and to provide ratings on a poor-good quality continuum based on how well the fricative represented the intended phonetic category. Sounds were presented diotically while the intended target ("s" or "sh") was displayed on the monitor. The listeners assigned ratings for fricative productions by moving a slider on a 100 mm Visual Analog Scale on the computer monitor to a desired point on a poor-good quality continuum. Listeners used a computer mouse to position the slider. The experiment was self-paced and listeners were allowed to listen to stimuli any number of times before assigning a rating by pressing the replay button. The experiment lasted approximately 45 min.

B. Results

A three-way repeated measures ANOVA was performed with condition (ON, OFF), consonant (/s/, /ʃ/), and group (children, adults) as within-subject factors. Results showed that listeners assigned higher ratings for fricative consonants produced in processor-on than in processor-off conditions (M: 63.09; SD: 16.55 versus M: 57.86; SD: 20.43), and was confirmed by a significant main effect of condition [$F(1,9)$

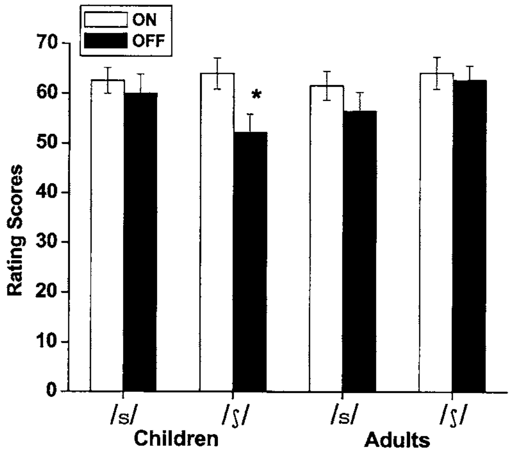

FIG. 6. Average rating scores assigned by ten listeners for fricative consonants /ʃ/ and /s/ spoken by deaf children (C1–C4) and deaf adults (A1–A4) in processor-on and -off conditions. A star [*] indicates significant differences in rating scores ($p < 0.0125$).

$=57.48$; $p < 0.05$]. This finding indicates that listeners are sensitive to speech production differences due to processor-on versus -off conditions. Analyses also revealed a significant three-way interaction: Group × condition × consonant [$F(1,9)=19.32$; $p < 0.05$]. Figure 6 shows rating scores assigned by the ten listeners for /s/ and /ʃ/ produced by children and adults in processor-on and processor-off conditions. *Bonferroni* corrections for multiple comparisons (with family-wise *p* value set at $p < 0.0125$) confirmed that listeners assigned a significantly higher rating for the consonant /ʃ/ (*M*: 64; *SD*: 17.61 versus *M*: 52.16; *SD*: 21.13) produced by children in the processor-on compared to the processor-off condition [$F(1,9)=64.53$; $p=0.0001$; $d=0.37$].

Overall, the results correspond well with the acoustic findings of significant changes in the consonant /ʃ/ produced by children in the processor-on compared to -off conditions. However, informal comments by some of the participants revealed a potential problem with this experiment, namely, that excised fricatives sound unnatural and may not always be perceived as speech. Therefore, an identification experiment was conducted to rule out this possibility and to assess the intelligibility of fricative-vowel words produced in both processor-on and -off conditions.

IV. IDENTIFICATION EXPERIMENT

The purpose of this experiment was to determine the identification accuracy of fricative-vowel words in both processor-on and processor-off conditions. Words produced by congenitally deafened children and postlinguistically deafened adults were presented to normal-hearing listeners to determine how well they could identify fricative-vowel words spoken in processor-on versus processor-off speaking conditions.

A. Methods

1. Listeners

Ten listeners participated in this experiment. These listeners were different from those who participated in the quality rating experiment. Participants were native speakers of American English with a background in Speech-Language-Pathology. All listeners had taken a graduate-level course in phonetics and none reported speech or hearing problems.

2. Stimuli

Stimuli for the identification experiment included the fricative-vowel words /si/ and /ʃi/ used in the acoustic analyses. Whole words rather than excised fricative consonants were used in this experiment to avoid the use of truncated speech segments which may sound unnatural. A total of 256 stimuli (8 talkers × 2 words × 2 conditions × 8 repetitions) were used in this experiment.

3. Procedure

Listeners heard words /si/ and /ʃi/ produced by cochlear-implanted children and adults. The task was to identify what they heard, by clicking on one of the response boxes on a computer monitor labeled "see" or "she." The experiment lasted approximately 15 min.

B. Results

A three-way repeated measures ANOVA was performed with condition (ON, OFF), consonant (/s/, /ʃ/), and group (children, adults) as within-subject factors. In contrast to the rating experiment, results did not reveal a significant main effect for condition. However, similar to the rating experiment, analyses revealed a significant three-way interaction: Group × condition × consonant [$F(1,9)=16.45$; $p=0.0001$]. Planned comparisons with *Bonferroni* corrections (family-wise *p* value set at $p < 0.0125$) confirmed that identification accuracy was significantly higher for /ʃ/ (*M*: 98.43; *SD*: 3.68 versus *M*: 91.25; *SD*: 16.21) produced by children in processor-on compared to -off conditions [$F(1,9)=11.04$; $p=0.0001$; $d=0.34$].

Figure 7 shows identification scores for words (/si/ and /ʃi/) produced by each of the eight talkers in processor-on and -off conditions. There were fairly strong ceiling effects, with the identification scores for the words /si/ and /ʃi/ produced by all talkers in the processor-on condition in the range of 90–100%. These high scores confirm that a majority of the fricative-vowel words were accurate productions and that they were highly intelligible. To examine the difference in identification accuracy for these words in processor-on versus -off conditions, identification data were analyzed separately for each of the talkers. A two-way repeated measures ANOVA was performed with condition (ON, OFF), and words (/si/, /ʃi/) as within-subject factors. Planned comparisons with *Bonferroni* corrections (family-wise *p* value set at $p < 0.025$) were performed to test the prediction that the identification accuracy was significantly different for words /si/ and /ʃi/ produced in processor-on versus processor-off conditions. As shown in Fig. 7, the identification accuracy

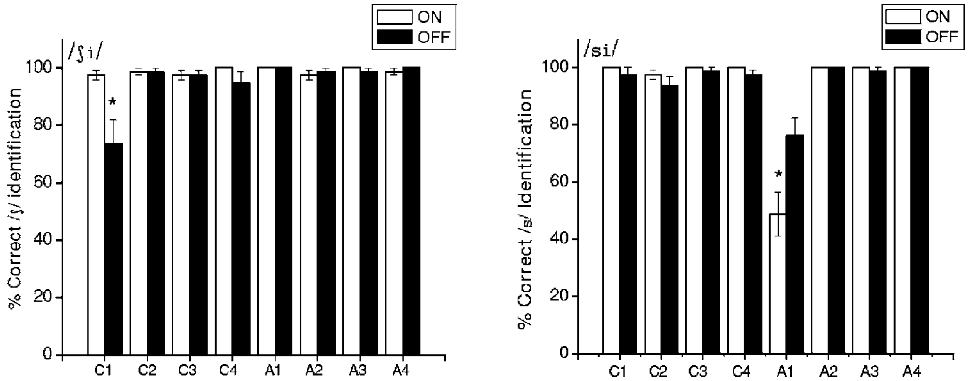

FIG. 7. Average identification accuracy scores based on listening judgments provided by ten normal-hearing listeners for words /ʃi/ and /si/ spoken by deaf children (C1–C4) and deaf adults (A1–A4) in processor-on and -off conditions. A star [*] indicates significant differences in identification scores ($p < 0.025$).

for /ʃi/ produced by talker C1 was significantly higher in processor-on compared to processor-off conditions [$F(1,9) = 18$; $p = 0.0001$; $d = 0.72$]. Identification accuracy was higher for /ʃi/ produced by C4 in processor-on compared to processor-off conditions, however, these values failed to reach significance. Surprisingly, analyses also showed significantly lower identification accuracy for /si/ produced by A1 [$F(1,9) = 31.57$; $p = 0.0001$; $d = 0.59$] in processor-on compared to processor-off conditions. No reliable differences in processor-on versus -off conditions were found for rest of the talkers.

C. Perception Experiments Summary

The main results of the rating experiment were significantly higher ratings in processor-on versus -off conditions and significantly higher ratings for consonant /ʃ/ produced by children in processor-on compared to -off conditions. Results of the identification experiment confirmed this finding, by showing higher identification accuracy for /ʃ/ produced by children in processor-on compared to -off conditions. In addition, data from the identification experiment showed higher accuracy for /ʃ/ produced by talker C1 in processor-on versus -off conditions.

V. GENERAL DISCUSSION

Fricative spectral moments and word durations were measured from speech samples produced by adults and children with and without auditory feedback provided by a cochlear implant device. In the brief absence of auditory feedback (approximately 15–20 s), significant changes in fricative spectral measures were noted for a subset of talkers (C1, C4, and A3). Data further revealed that these processor-on versus processor-off differences in the spectral measures were present primarily for /ʃ/, rather than /s/. These data are similar to other studies which note significant spectral differences for /ʃ/ in processor-on versus processor-off conditions (Matthies *et al.* 1996).

There are at least two possible explanations for why significant changes were found for /ʃ/, and not /s/. One reason may be that the alveolar ridge provides an anchor point for the articulation of /s/ in the absence of auditory feedback. There is no such well-defined landmark for articulation of /ʃ/. Thus, the articulation of /ʃ/ is likely to drift in the absence of auditory feedback (Matthies *et al.* 1996). Another explanation may involve saturation effects. It has been documented that /s/ is characterized by strong saturation effects (quantal effects) compared to /ʃ/ (see Perkell *et al.* 2004). In other words, the production of /s/ results in stable acoustic cues, despite variability in articulation in the absence of feedback. Thus, in the absence of auditory feedback, the production of /ʃ/ is more likely to drift than /s/.

In the brief absence of auditory feedback, significant changes also were noted in word durations (speaking rate) for seven of the eight talkers. Of these seven talkers, six showed increases and one showed a decrease in word duration during the processor-off condition. These results confirm the prediction that suprasegmental properties are influenced by temporary changes in auditory feedback status to a greater extent than segmental aspects of speech (Perkell *et al.*, 1997; Perkell *et al.*, 2000). The finding that feedback-related changes were observed both for adults and children also replicates the findings of Tobey *et al.* (2000), who reported that syllable durations were significantly shorter in processor-on versus -off conditions in young cochlear-implanted children. The increases in word duration in the absence of auditory feedback are most likely a result of the adaptive strategies used by deaf speakers to maximize feedback via proprioceptive and tactile channels (e.g., Svirsky *et al.*, 1992; Higgins *et al.*, 1999). The fact that talker A4 showed a decrease in word duration in the absence of auditory feedback might suggest individual differences in the use of adaptive strategies by deaf talkers. Similar results have been reported by several other studies that have attributed these individual variations in speech production to differences in speech intelligibility, speech perception ability, etiology of deafness, electrode insertion depth and viability of neural population (Svirsky *et al.*, 1992; Perkell *et al.*, 1992; Richardson *et al.*, 1993; Tye-Murray *et al.*, 1996).

Overall, the present duration data demonstrated that in the brief absence of auditory feedback, a majority of talkers decreased their speaking rate. However, there was a fair amount of individual talker variability with respect to changes in fricative spectral measures resulting from a change in hearing status. This individual talker variability must be explained as it addresses the issue of speech perception and production links. As expected, C1 lengthened word durations in the processor-off condition. In addition, C1 showed a greater /s/-/ʃ/ contrast in the absence of auditory feedback. These findings are consistent with the idea that some talkers attempt to produce clear speech when auditory feedback is impoverished (e.g., Krause and Braida, 2004).

Only a subset of talkers (C1, C4, and A3) showed fricative spectral changes in the absence of auditory feedback. Why did these talkers demonstrate these changes and not others? Perkell and colleagues (Perkell *et al.*, 2004) noted that talkers who produce a distinct sibilant contrast are also adept at perceiving fine acoustic differences between /s/ and /ʃ/. In the present data, A3 produced the greatest sibilant contrast among the adults, while C1 and C4 produced the greatest sibilant contrast among the children (see Fig. 5). It is possible that these talkers were able to perceive fine acoustic differences in the sibilants through their implants and use the feedback information to fine tune their speech. Analogously, talkers who rely on auditory feedback to fine tune their speech may demonstrate modifications in speech when it is absent or altered. These preliminary findings emphasize the linkage between speech perception and production, which merits careful examination in future studies.

It was predicted that congenitally deafened children would show larger processor-on versus -off differences than postlinguistically deafened adults. This expectation was confirmed in the word duration data. Children demonstrated greater processor-on versus -off differences in word duration than adults. Group comparisons also revealed differences in the production of /ʃ/, but not for /s/, suggesting that some of the children are continuing to refine /ʃ/ production.

Further analyses revealed that postlinguistically deafened adults, as a group, produced a significantly larger /s/-/ʃ/ contrast than congenitally deafened children. This finding indicates a developmental difference in fricative production and further suggests that 7–11 year old congenitally deafened children, with 3–5 years of implant experience, are continuing to refine their fricative production, for which auditory feedback delivered through their cochlear implants may be crucial.

Two listening experiments were conducted to examine whether the acoustic changes that occurred in the absence of auditory feedback were perceptible to normal-hearing listeners. Results from the rating experiment showed lower ratings for processor-off compared to -on conditions, suggesting that VAS can be a sensitive tool to assess speech production changes in the absence of auditory feedback. As expected, results also showed lower ratings for /ʃ/ produced by children in processor-off compared to -on conditions. These data corroborate the findings of the acoustic analyses and further suggest that some congenitally deafened children produced perceptible acoustic changes in fricatives when speaking in the absence of auditory feedback.

A second listening experiment was designed to examine the overall intelligibility of the fricative-vowel words produced in processor-on and -off conditions. Results showed that the identification accuracy for words produced by all eight talkers ranged from 90–100 %, suggesting that the fricative consonants were well produced. Based on the acoustic analyses, it was expected that the identification accuracy for talkers C1, C4, and A3 would be different in processor-on versus -off conditions. Consistent with the predictions, identification accuracy for both C1 and C4 were higher in processor-on versus -off conditions, although the differences were significant only for C1. Talker A3 produced significant acoustic changes in /ʃ/ in processor-on versus -off conditions. However, this talker also demonstrated the largest /s/-/ʃ/ absolute centroid difference of her talker group. Thus, for this talker, the processor-on versus -off acoustic differences while appreciable, may not have been sufficient to result in a perceptual change for the listeners. Identification accuracy for A1 was significantly different for /s/ in processor-on versus -off conditions. The skewness coefficients for /s/ produced by A1 were more in the range of /ʃ/ in both processor-on and -off conditions. It is possible that listeners were sensitive to variations in skewness coefficient, leading to confusions and errors in judgment for /s/ produced in both processor-on versus -off conditions. The identification data also corroborated some of the findings of the rating experiment by showing lower identification accuracy for /ʃ/ produced by children in processor-off compared to -on conditions. Taken together, the rating and identification experiments suggested that some deaf individuals may produce perceptible acoustic changes in their speech as a result of brief auditory feedback deprivation.

In summary, in the brief absence (approximately 15–20 s) of auditory feedback significant changes occurred in word duration for a majority of talkers. In addition, perceptible spectral changes were demonstrated in fricative consonants produced by a subset of talkers. There are at least three possible explanations for why only some talkers showed modifications in speech when auditory feedback was briefly eliminated. First, the brief lack of auditory feedback alters the parameter settings of the internal model, leading to modifications in speech. If so, this would fit well with the predictions in the literature that the internal model for both segmental and suprasegmental aspects of speech (e.g., Perkell *et al.*, 2000; Jones and Munhall, 2000) is responsive to changes in the acoustic environment. Second, some talkers may deliberately use a different speaking strategy in the absence of auditory feedback. In other words, some deaf talkers may attempt to speak clearly to maximize feedback via tactile and proprioceptive channels (e.g., Higgins *et al.*, 1999; see also Krause and Braida, 2004). Third, individuals with deafness may have two internal models; one acquired prior to cochlear implantation and another acquired after cochlear implantation.[1] The fact that some talkers demonstrated immediate modifications in speech when auditory feedback was removed might reflect a switch from the use of the current internal model to the one acquired prior to implantation. These different accounts should be examined carefully in future studies. Our understanding of the feedback and feedforward systems for speech production is evolving. Future experiments comparing the effects of short-term changes in auditory feedback (spanning milliseconds to seconds) on a variety of segmental and suprasegmental measures of speech produced by individuals with normal hearing and deafness may be able to address the precise nature of the feedback and feedforward systems for speech production.

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