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Hearing History Influences Voice Gender Perceptual Performance in Cochlear Implant Users

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Objectives: The study was carried out to assess the role that five hearing history variables (chronological age, age at onset of deafness, age of first cochlear implant [CI] activation, duration of CI use, and duration of known deafness) play in the ability of CI users to identify speaker gender.

Design: Forty-one juvenile CI users participated in two voice gender identification tasks. In a fixed, single-interval task, subjects listened to a single speech item from one of 20 adult male or 20 adult female speakers and had to identify speaker gender. In an adaptive speech-based voice gender discrimination task with the fundamental frequency difference between the voices as the adaptive parameter, subjects listened to a pair of speech items presented in sequential order, one of which was always spoken by an adult female and the other by an adult male. Subjects had to identify the speech item spoken by the female voice. Correlation and regression analyses between perceptual scores in the two tasks and the hearing history variables were performed.

Results: Subjects fell into three performance groups: (1) those who could distinguish voice gender in both tasks, (2) those who could distinguish voice gender in the adaptive but not the fixed task, and (3) those who could not distinguish voice gender in either task. Gender identification performance for single voices in the fixed task was significantly and negatively related to the duration of deafness before cochlear implantation (shorter deafness yielded better performance), whereas performance in the adaptive task was weakly but significantly related to age at first activation of the CI device, with earlier activations yielding better scores.

Conclusions: The existence of a group of subjects able to perform adaptive discrimination but unable to identify the gender of singly presented voices demonstrates the potential dissociability of the skills required for these two tasks, suggesting that duration of deafness and age of cochlear implantation could have dissociable effects on the development of different skills required by CI users to identify speaker gender.

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INTRODUCTION

Cochlear implants (CIs) enable a partial restoration of hearing in deaf and hard-of-hearing people, but the ability of CI users to accurately perceive speech is highly variable individually (Blamey et al. 2001). Adult CI users with little previous exposure to auditory speech stimuli (who have typically acquired sign language) usually perform at lower levels than CI adults who once had normal hearing (Teoh et al. 2004; Kos et al. 2009). Many subjects from the latter group can achieve near-perfect speech perception scores in quiet, despite the relatively impoverished neural input that CI devices provide (Manrique et al. 1999). Previous clinical studies have identified potential factors underlying this observed variation in CI clinical outcomes: (1) hearing history (including age of the onset of deafness, age at implantation, and duration of CI use, all of which are known to affect anatomical and neurophysiological properties of the auditory system; Blamey et al. 1996; Svirsky et al. 2000; Blamey et al. 2001; Lee et al. 2001; Kirk et al. 2002; Sharma et al. 2005); (2) technological and medical aspects of the implantation (CI parameter settings, location and insertion depth, and characteristics of spiral ganglion cells; Wilson et al. 1991; Friesen et al. 2001; Yukawa et al. 2004; Baskent & Shannon 2005); and (3) communication and socioeconomic factors involved in rehabilitation (O'Donoghue et al. 2000; Sarant et al. 2001; Archbold et al. 2002; Fu & Galvin 2008). Different causes of deafness do not seem to play a major role in the ability to use information provided by the implant (Mitchell et al. 2000; Francis et al. 2004; Nikolopoulos et al. 2006). Disappointingly, prior research examining the contribution of these factors to implantation outcomes has found that, in aggregate, they seem to account for only a small fraction of the observed variability (for example only 20% in the study by Blamey et al. 1996).

Part of the difficulty in accounting for variation in clinical outcomes may stem from the complex, multidimensional nature of speech processing tasks and speech stimuli. It is possible that an examination of more focused and simpler auditory processing tasks with simple auditory stimuli might better reveal the scope of factors accounting for variability in speech processing performance. For example, Gfeller et al. (2007) found that demographic factors such as duration of CI use showed a weak but significant correlation with pitch-ranking abilities, whereas other variables such as the length of profound deafness did not. However, the pitch-ranking tasks used in their study did not use stimuli that were directly relevant to speech processing.

Our aim was to create an experimental paradigm that would use simple auditory tasks based on natural variations in speech stimuli. Pitch constitutes an important nonphonetic perceptual attribute in speech processing, especially for the identification of individual speakers, their age and gender, and voice indexical cues. Previous research has shown that normal-hearing subjects can easily and accurately identify voice gender (Bachorowski & Owren 1999; Owren et al. 2007; Smith et al. 2007), which can also be performed at high levels of accuracy by automated speech recognition systems (Childers & Wu 1991; Wu & Childers 1991). In contrast, CI users show wide performance variation in identifying individual voices and their gender (Cleary & Pisoni 2002; Cleary et al. 2005; Fu et al. 2005; Vongphoe & Zeng 2005; Kovacic & Balaban 2009). A benefit of familiarity with voices for speech intelligibility in noise has been shown for normal-hearing people (Nygaard & Pisoni 1998) and for CI simulations (Loebach et al. 2008).

This study used two different voice gender identification procedures: a fixed single-interval task and an adaptive two-interval task. Two different procedures were used to assess the role that different response strategies might play in gender identification, so that it would be possible to examine the

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relationship of hearing history to slightly different skill sets that might be required by these different strategies. The relationship between perceptual performance and chronological age at testing, age of onset of deafness, age at CI implantation, duration of CI use, and duration of known deafness was examined. The results suggest that some of the variance in performance in each of the two tasks is explained by different hearing history variables, suggesting that different aspects of preimplant experience have dissociable effects on postimplant auditory performance.

SUBJECTS AND METHODS

Subjects

This study was part of a larger project on voice gender perception in CI users; the subject population, stimuli, and methods have previously been described in detail (Kovacic & Balaban 2009). Briefly, 41 juvenile subjects (21 females and 20 males; age range 5.3 to 18.8 yrs; mean age 12.3 yrs) with CIs performed voice gender identification and discrimination tasks. Subjects from the control group were 15 hearing children recruited from a regular elementary school (7 females and 8 males, age range 6.7 to 10.6 yrs, mean age 9.3 yrs) with no known hearing pathologies. The mean age of the control group was younger than the CI experimental group (Mann-Whitney *U* test, control group: mean (SD) = 9.3 (1.3) yrs, n = 15; experimental group: mean (SD) = 12.3 (3.2) yrs, n = 41, $p < 0.001$) to compensate for the reduced hearing experience in CI subjects and their delays in language acquisition (Svirsky et al. 2000; Svirsky et al. 2004; Nicholas & Geers 2007).

Procedure and Stimuli

In the first task (a fixed single-interval two-alternative forced choice), subjects listened to a single 2-sec-long sample of speech from one of 20 adult male or 20 adult female speakers and had to identify the gender of the speaker by pressing an appropriate button (performance was measured by the proportion of correct responses). Each response was followed by feedback (a smiling face for correct responses and the symbol "X" for incorrect responses). Speech items were excerpts from news-like stories spoken by professional announcers recorded at the Croatian national broadcasting radio company (Hrvatski radio). The stimulus onsets were always aligned with the word onsets and the stimulus offsets were never within phoneme boundaries. To maintain the exact duration of 2000 msecs for each speech item, the Pitch-Synchronous Overlap-Add (PSOLA) lengthening algorithm (Moulines & Laroche 1995) was used. To preserve pitch contours, the scaling factor for lengthening was held between 0.84 and 1.25. The mean fundamental frequency (F_0) was obtained for each speech item using the autocorrelation method (Boersma 1993); these varied from 138.6 to 218.7 Hz with the mean value of 183.3 (SE = 5.4) Hz for female speakers and from 81.8 to 164.4 Hz with the mean value of 117.9 (SE = 4.8) Hz for the male speakers.

A second discrimination task (an adaptive two-interval two-alternative forced choice) asked subjects to listen to a pair of different 2-sec-long speech samples presented one after the other of which one was always spoken by an adult female and the other by an adult male. Participants indicated via button press which one was spoken by a female. The adaptive parameter, in the form of the difference in the average fundamental frequency of the two talkers (ΔF_0) over the 2-sec sample, was manipulated using a staircase procedure (Levitt 1971) with threshold at 70.7% correct. Four hundred stimulus pairs with unique ΔF_0 values formed a stimulus set with ΔF_0 values varying in small steps between 142.8 and −23.6 Hz. After correct trials, ΔF_0 was progressively decreased in steps of 10 Hz by the random selection of a stimulus pair with correspondingly smaller ΔF_0 values, whereas after incorrect trials, ΔF_0 was progressively increased in steps of 10 Hz by the random selection of a stimulus pair with correspondingly larger ΔF_0 values. The 2-sec stimuli were obtained from different utterances from the same speakers used in the first task. Performance was estimated by calculating the average ΔF_0 of the last five reversal points that defined the discrimination threshold estimate (DTE). Because of the limited F_0 variation in the population of speakers, measured DTEs could fall in between the minimal and maximal values of −13.5 and 133.1 Hz, indicating best and worst performance, respectively. This adaptive procedure contrasted with the first task by allowing CI subjects (particularly the ones who had trouble identifying single voices) to make short-term comparisons of the pairs of stimuli, without the need for comparisons involving auditory long-term memory. Importantly, Dawson et al. (2002) reported no sequential auditory memory deficits in CI subjects compared with normal-hearing peers. In both tasks, stimuli for CI subjects were delivered through a direct line input to the CI device that was placed in a custom-made isolation chamber (for details see the Appendix in Kovacic & Balaban 2009). Subjects from the control group listened to stimuli with Sennheiser HD 580 headphones presented monoaurally to the right ear at 65 dB SPL (A-level). Apart from this difference in stimulus delivery, the CI (experimental) and the hearing (control) group experienced identical procedures in both tasks. The total duration of the experiment with the two tasks was approximately 30 to 40 min, which included instructions for the subjects and practice trials (a set of six single-interval trials for the identification task and a set of 10 trials for the adaptive task with two different speech items from the same speaker database that were not used in the experimental trials). The study was approved by the ethical committees of the School of Medicine, University of Zagreb, Polyclinic SUVAG, and the Croatian Medical Chamber.

Data Analysis

Three hearing history variables were extracted from clinical records for each subject: (1) chronological age (ChronAge) at the time of the experiment; (2) age at the first diagnosis (Age@Diag) of profound hearing loss (or deafness)*; and (3) age of the first activation after cochlear implantation (Age@Act). Two additional measures were calculated from these variables: (4) duration of CI

*It was not possible to define the exact onset of deafness from medical records because of the nonavailability of objective measures for deafness diagnosis at the time they were made; neonatal hearing screening was not available nationally in Croatia before 2002. Although all subjects had medical records with parental and caregiver reports on the onset of deafness, these were often anecdotal or ambiguous in terms of the exact onset of deafness. Therefore, the age of the first diagnosis of profound hearing loss as officially certified by medical authorities has been taken as the most conservative objective measure for deafness onset, even though it probably overestimates the age at which this occurred.

TABLE 1. Characteristics of the CI participant population

Subject	Sex	Ear	Age at Testing (yrs; mos)	Age at CI Activation (yrs; mos)	Duration of CI Use (yrs; mos)	Age at Diagnosis (yrs; mos)	Known Deafness Duration (yrs; mos)	Proportion of the Correct Responses in the Fixed Procedure	Discrimination Threshold Estimates (Hz)	Performance Group*
CI01	F	R	5; 4	4; 8	0; 7	1; 11	2; 8	0.650	123.60	None
CI02	M	R	10; 6	4; 11	5; 7	2; 2	2; 8	0.600	13.90	One
CI03	M	L	12; 1	8; 5	3; 8	4; 0	4; 5	0.875	7.14	Both
CI04	F	R	15; 8	12; 0	3; 8	2; 5	9; 7	0.450	117.90	None
CI05	M	L	18; 9	15; 4	3; 4	2; 11	12; 5	0.550	89.84	None
CI06	M	R	11; 4	6; 10	4; 5	0; 9	6; 0	0.800	21.50	Both
CI07	M	R	12; 2	8; 11	3; 2	2; 6	6; 5	0.825	51.48	Both
CI08	M	L	6; 9	4; 0	2; 8	2; 0	2; 0	0.550	102.10	None
CI09	M	R	9; 5	5; 3	4; 2	1; 3	3; 11	0.450	123.10	None
CI10	F	L	11; 0	7; 1	3; 11	0; 6	6; 6	0.525	44.22	One
CI11	M	R	11; 1	7; 9	3; 4	3; 2	4; 7	0.600	120.40	None
CI12	M	R	14; 0	10; 7	3; 4	3; 0	7; 7	0.475	116.70	None
CI13	F	R	14; 7	8; 2	6; 5	0; 9	7; 5	0.875	6.28	Both
CI14	M	L	11; 3	7; 7	3; 7	3; 4	4; 3	0.550	122.20	None
CI15	F	R	17; 6	14; 1	3; 4	1; 8	12; 5	0.725	29.58	Both
CI16	M	R	7; 9	4; 6	3; 2	3; 1	1; 5	0.925	4.66	Both
CI17	F	R	14; 5	10; 11	3; 5	4; 8	6; 3	0.850	15.06	Both
CI18	F	R	13; 1	8; 11	4; 2	0; 9	8; 2	0.875	15.16	Both
CI19	F	R	14; 4	10; 10	3; 5	1; 0	9; 10	0.575	113.60	None
CI20	F	R	9; 7	6; 1	3; 6	1; 2	4; 11	0.900	−0.02	Both
CI21	M	R	11; 0	7; 7	3; 5	1; 7	5; 11	0.525	92.16	None
CI22	F	L	18; 5	15; 1	3; 3	2; 10	12; 2	0.500	114.50	None
CI23	F	R	9; 2	2; 1	7; 0	0; 7	1; 5	0.925	5.34	Both
CI24	F	R	14; 9	11; 4	3; 5	3; 4	8; 0	0.800	23.54	Both
CI25	F	R	8; 8	4; 4	4; 4	3; 0	1; 3	0.425	118.50	None
CI26	M	R	17; 3	13; 7	3; 8	2; 3	11; 4	0.750	55.82	Both
CI27	F	R	12; 9	9; 5	3; 4	1; 9	7; 7	0.850	33.04	Both
CI28	F	L	8; 5	5; 1	3; 4	4; 4	0; 8	0.375	104.50	None
CI29	M	R	11; 4	7; 5	3; 11	1; 0	6; 5	0.825	39.68	Both
CI30	M	R	8; 9	4; 8	4; 1	1; 0	3; 7	0.750	22.68	Both
CI31	M	L	15; 7	11; 11	3; 8	3; 7	8; 3	0.875	19.14	Both
CI32	F	R	13; 11	10; 3	3; 7	1; 4	8; 11	0.625	114.90	None
CI33	F	R	14; 0	10; 8	3; 4	3; 5	7; 2	0.500	90.98	None
CI34	F	R	12; 11	8; 10	4; 1	3; 9	5; 0	0.600	24.34	One
CI35	F	R	14; 7	11; 5	3; 2	5; 5	6; 0	0.650	50.28	One
CI36	F	R	10; 5	6; 4	4; 1	2; 2	4; 1	0.800	51.94	Both
CI37	M	R	15; 10	12; 6	3; 4	1; 9	10; 8	0.625	32.60	One
CI38	M	R	10; 11	7; 8	3; 3	1; 5	6; 2	0.850	−7.00	Both
CI39	M	R	9; 1	5; 0	4; 1	2; 6	2; 5	0.525	94.12	None
CI40	M	L	14; 4	9; 10	4; 5	1; 8	8; 2	0.600	113.80	None
CI41	F	L	10; 0	5; 11	4; 0	3; 3	2; 8	0.575	114.20	None
Mean†			12.3	8.5	3.8	2.4	6.2			
SD†			3.2	3.3	1.0	1.2	3.2			

** Performance groups: "None" refers to subjects with poor identification and discrimination; "One" refers to subjects with poor identification, but good discrimination; "Both" refers to subjects with good identification and discrimination.*

† Means and SD of historical variables are given in decimal notation.

use (DurCI; defined as ChronAge − Age@Act), and (5) duration of known deafness or hearing impairment† (DurDeaf; defined as Age@Act − Age@Diag). Table 1 lists these data for all participants in this study.

†The duration of known deafness or hearing impairment (DurDeaf) cannot be regarded as a fully auditory-deprived period, because in most subjects, there were attempts at recovering hearing using hearing aids (auditory amplification) if any residual hearing was available. However, all the participants in this study conformed to the established criteria for CI in Croatia, which requires profound deafness and no beneficial use of hearing aids to be eligible (Kekic 2002).

RESULTS

Table 1 lists hearing history variable values and performance in the two tasks for each individual CI user. Relationships between chronological age at testing and the other four hearing history variables are shown in Figure 1. Strong relationships seen between the chronological age at testing and the age of first CI activation (Fig. 1A) and between chronological age and the duration of deafness (Fig. 1D) reflect the fact that a large group of Croatian deaf children of different ages had implants suddenly made available to them between 2000 and 2002 due to funding from anonymous benefactors.

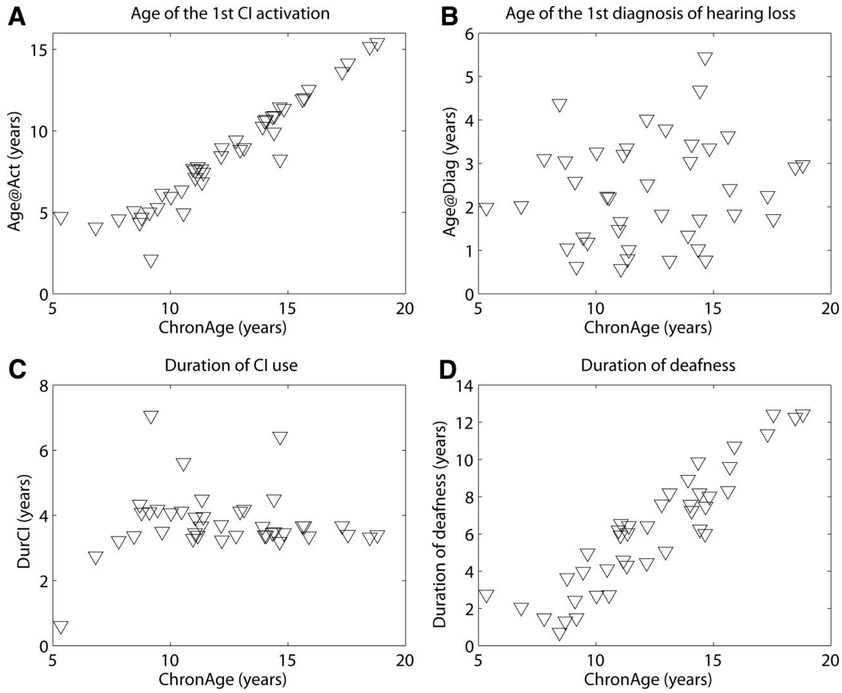

Fig. 1. Relationship between hearing history factors and chronological age of the CI subjects: (A) age of the first CI activation; (B) age of the first diagnosis of the hearing loss; (C) duration of CI use; and (D) duration of deafness. Each triangle represents data from one individual CI user.

Figure 2 shows that the identification and speech-based F_0 adaptive discrimination tasks yielded three performance categories of CI subjects: (1) those with both good identification and discrimination (at least 65% or more correct responses in the first task—the proportion needed to significantly differ from chance performance according to the binomial distribution; and DTEs $<$70 Hz in the second, which is the difference between the mean female F_0 and mean male F_0—a difference of about 0.6 octaves); participants from this group were referred to as Both in Table 1, (2) those with poor identification but good discrimination (chance performance in the identification task, DTEs $<$70 Hz in the adaptive discrimination task); participants from this group were referred to as One in Table 1, and (3) those with poor identification and poor discrimination (chance performance in the identification task, DTEs $>$70 Hz in the adaptive task); participants from this group were referred to as None in Table 1. This pattern of results contrasts sharply with the results of the control group: all hearing subjects achieved perfect or near-perfect scores in both tasks (a mean of 98.0 $\pm$ 0.4% correct responses for the identification task; 12 of 15 hearing subjects did not make any incorrect responses in the adaptive task with the three remaining subjects showing two reversals only at $\Delta F_0 < 0$ Hz). This demonstrates that both tasks were very easy for hearing children and that the stimulus set was not of abnormal difficulty.

The full and partial correlations among the five hearing history variables are listed in Table 2 for all subjects, subjects with good identification, and subjects with good discrimination. In general,

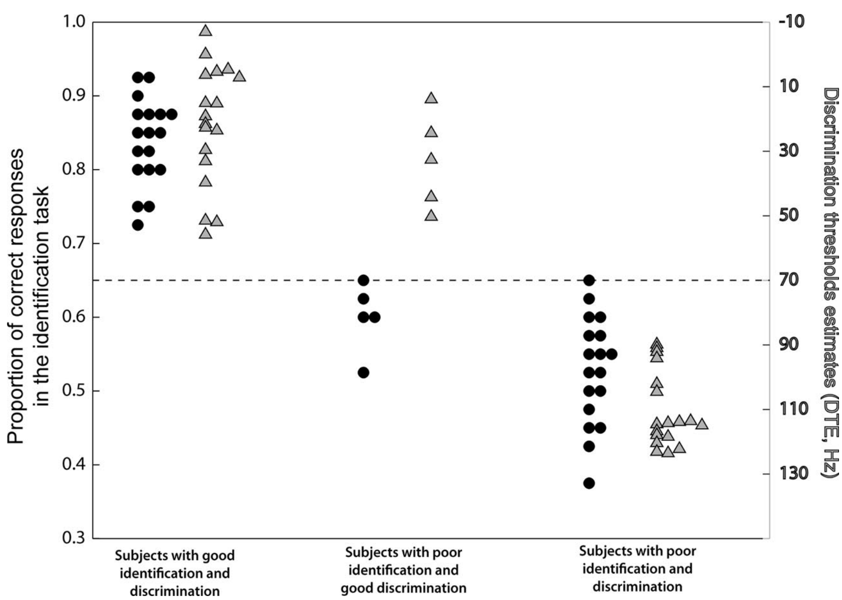

Fig. 2. Performance in the two voice gender perception tasks. Proportions of correct responses in the fixed, single-interval voice gender identification are indicated by black circles (referenced to the y axis on the left); thresholds for the adaptive discrimination procedure (DTEs) are indicated by the gray triangles (referenced to the y axis on the right). Each data point represents the performance of a single participant.

TABLE 2. Correlation matrices for hearing history variables

	Age@Act	Age@Diag	DurCI	DurDeaf
All subjects				
ChronAge	0.96* (0.42)	0.15 (0.32)	0.05 (1.0)	0.92* (0.32)
Age@Act	—	0.24 (0.73)	−0.25 (−0.42)	0.93* (0.73)
Age@Diag	—	—	−0.32* (−0.32)	−0.13 (−1.0)
DurCI				−0.13 (−0.32)
N = 41	—	—	—	
Subjects with good identification in the fixed procedure				
ChronAge	0.94* (0.39)	0.28 (0.24)	−0.15 (1.0)	0.92* (0.24)
Age@Act	—	0.42 (0.80)	−0.46† (−0.39)	0.92* (0.80)
Age@Diag	—	—	−0.51* (−0.24)	0.03 (−1.0)
DurCI	—	—	—	−0.29 (−0.24)
N = 18				
Subjects with DTE thresholds < 70 Hz in the adaptive procedure				
ChronAge	0.95* (0.35)	0.31 (0.30)	−0.24 (1.0)	0.89* (0.30)
Age@Act	—	0.42* (0.79)	−0.54* (−0.35)	0.89* (0.79)
Age@Diag	—	—	−0.44* (−0.30)	−0.04 (−1.0)
DurCI	—	—	—	−0.37 (−0.30)
N = 23				

Entries in regular type are Pearson product-moment correlations, with partial correlations given in parentheses.
* *Nominally significant at* $p < 0.05$ level.
† $0.05 < p < 0.06$.

older subjects had implants that were activated at later ages and tended to have a longer duration of deafness than younger subjects (Table 2A and Fig. 1A and D). Age at CI activation and duration of deafness were also correlated: subjects who had their implants activated later had longer durations of deafness. Age at diagnosis is confounded with duration of CI use: subjects who were diagnosed at younger ages tended to have a longer period of CI use. In addition, for subjects with good adaptive discrimination, there was a correlation between age at activation and duration of CI use: subjects with older ages at activation tended to have shorter durations of CI use. Finally, these subjects also showed a general correlation between age at activation and age at diagnosis: subjects diagnosed later tended to have later ages of CI activation.

There were no significant differences in the means of any of the five hearing history variables among the three performance groups of subjects (Kruskal-Wallis one-way analysis of variances; ChronAge: $H[2, N = 18, 5, 18] = 0.886$, $p = 0.64$; DurDeaf: $H[2, N = 18, 5, 18] = 0.311$, $p = 0.86$; Age@Act: $H[2, N = 18, 5, 18] = 0.225$, $p = 0.89$; Age@Diag: $H[2, N = 18, 5, 18] = 1.976$, $p = 0.37$; DurCI: $H[2, N = 18, 5, 18] = 1.165$, $p = 0.56$).

Linear regressions between the five variables and subject performance in the identification task were assessed for the subjects with above-chance identification performance. Subjects who performed at chance in both this task and in adaptive identification were not included in this analysis, because it is unclear whether their failure to use voice gender information was caused by a failure of sufficient information to reach their auditory central nervous system (CNS) or by a failure in the use of the information that entered the auditory CNS. In the case of subjects who performed above chance, it is certain that some kind of pitch and/or vocal-tract size-related information was being conveyed centrally, and that subjects had some kind of auditory categorical information that they could refer, which contains attributes of male and female voices (Kovacic & Balaban 2009). Analysis of the data from these participants revealed that Age@Act and DurDeaf covaried significantly with voice gender identification scores (panels A and B in Fig. 3, score = 0.916 − 0.009 × Age@Act, $r^2 = 0.26$, $t(16) = -2.346$, $p = 0.03$ and score = 0.913 − 0.012 × DurDeaf, $r^2 = 0.34$, $t(16) = -2.888$, $p = 0.01$ respectively). Reanalysis of Figure 3A with the outlying data point in the lower left corner removed (this was the only data point [shown in gray] whose residual value from the regressed line exceeded 3 SDs from the mean residual value) increased r^2 considerably from 0.26 to 0.48 ($t[16] = -3.753$, $p = 0.002$) for Age@Act and from 0.34 to 0.56 ($t[16] = -4.378$, $p = 0.0005$) for DurDeaf. Nonparametric correlations between identification scores and Age@Act and DurDeaf were also significant (Age@Act: Spearman rank correlation, $\rho = -0.53$, N = 17, $Z[16] = -2.1$, $p = 0.04$, Kendall rank correlation, $\tau = -0.39$, N = 17, $Z[16] = -2.175$, $p = 0.03$; DurDeaf: Spearman rank correlation, $\rho = -0.49$, N = 17, $Z[16] = -1.975$, $p = 0.05$, Kendall rank correlation, $\tau = -0.37$, N = 17, $Z[16] = -2.088$, $p = 0.04$). A stepwise multiple linear regression with DurDeaf and Age@Act retained only DurDeaf in the final model ($F[16] = 8.339$, $p = 0.01$). Repeating this multiple regression analysis with the effects of the DurDeaf variable removed from Age@Act yielded no changes to the model. Therefore, within the group of CI subjects who could identify the gender of single voices at better-than-chance levels, the duration of deafness before CI implantation seems to be a major factor contributing to their performance; the multiple regression analyses indicate that age of CI activation supplies no additional contribution beyond its correlation with duration of deafness.

The same analyses were also repeated with the addition of the five subjects who had good adaptive voice gender discrimination thresholds but who had chance performance in voice gender identification. Although it is clear that these subjects have pitch or vocal-tract size-related information being com-

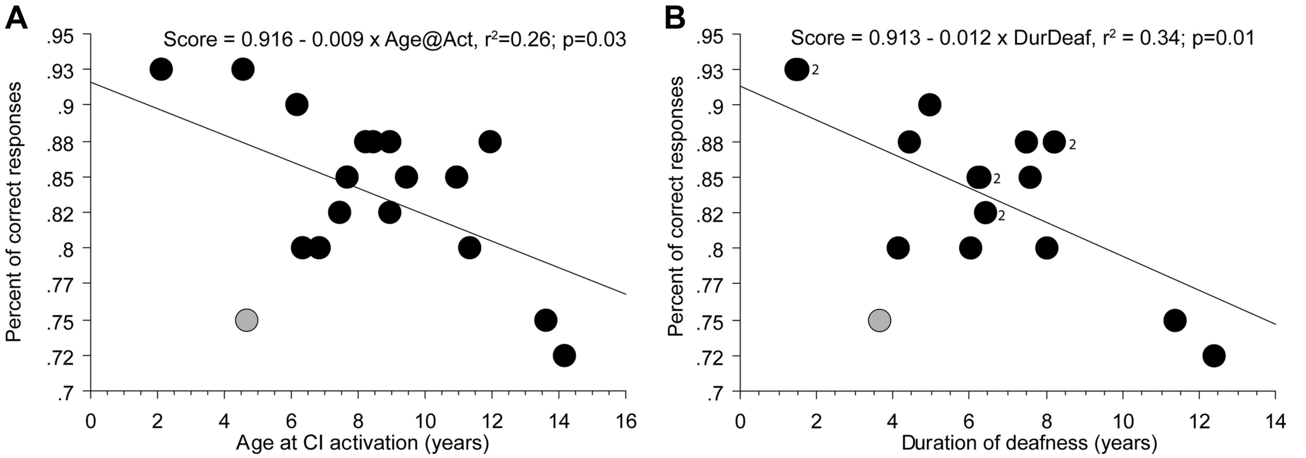

Fig. 3. The relationship of two hearing history variables to perceptual performance in the fixed single-interval voice gender identification task. (A and B) Individual data points (circles) and linear regressions (solid line) between (A) age at CI activation or (B) duration of deafness and proportions of correct responses. Label "2" indicates two overlapping data points. The regression equation for all data points included is given at the top of the panel, together with the coefficient of determination (r^2) and significance level (p). When the outlying data point (shown in gray) is removed, r^2 increases to 0.48 ($p = 0.002$) for Age@Act and to 0.56 ($p = 0.0005$) for DurDeaf.

municated to their auditory CNS, they lack the ability to apply this information to decisions about the gender of singly presented voices. The inclusion of this group renders the relationship with DurDeaf nonsignificant, with both linear regression and nonparametric correlation (DurDeaf for the dataset without the outlier shown in Fig. 3A: Spearman rank correlation, $\rho = -0.243$, N = 22, $Z[21] = -1.114$, $p = 0.27$, Kendall rank correlation, $\tau = -0.161$, N = 22, $Z(21) = -1.05$, $p = 0.29$). The effect of duration of deafness on single-voice identification performance seems to be limited to the group of participants who are able to apply the information provided by their implants to single-voice gender decisions. One possible explanation for this result may be that these participants can access long-term categorical information containing the attributes of male and female voices and that the quality of such information may be negatively influenced by the duration of deafness.

In the adaptive discrimination task, linear regression analysis was carried out for all the subjects with good discrimination (N = 23; this includes the 5 subjects who were unable to identify gender of singly presented voices but who were able to perform voice gender discrimination, in addition to the 18 subjects who were able to identify the gender of single voices). Subjects with poor adaptive discrimination (all of whom had chance performance in single-voice gender identification) were not included in this analysis because, as above, it was not clear whether any pitch or vocal-tract size-related information was being communicated to their auditory CNS. In this adaptive discrimination task, Age@Act was the sole variable that significantly covaried with DTE magnitudes (DTE = 3.766 + 2.408 × Age@Act, $r^2 = 0.17$, $t[21] = 2.065$, $p = 0.05$, Fig. 4). If the analysis is further restricted to subjects who performed even better with DTE of 40 Hz or less, the r^2 increases from 0.17 to 0.22 ($t[16] = 2.2$; $p = 0.05$). On the other hand, if the five subjects who were unable to identify the gender of single voices were excluded from the analysis, this relationship became nonsignificant (DTE = 2.962 + 2.25 × Age@Act, $r^2 = 0.15$, $t[16] = 1.66$, $p = 0.12$). Nonparametric analyses of correlations between DTEs and all five historical variables also found that Age@Act was the only variable significantly correlated with adaptive discrimination performance (Spearman rank correlation, $\rho = 0.447$, N = 23, $Z[22] = 2.095$, $p = 0.04$, Kendall rank correlation, $\tau = 0.304$, N = 23, $Z[22] = 2.034$, $p = 0.04$).

Performance on voice gender identification and voice gender adaptive discrimination was significantly negatively related for subjects who performed better than chance in both tasks (Spearman rank correlation, N = 18, $\rho = -0.75$, $Z[17] = -3.089$, $p = 0.002$).

Overall, these results can be summarized into the following main findings. (1) Three groups of participants were observed. Those who performed significantly above chance in the fixed single-interval identification task and with thresholds $<$70 Hz in the adaptive discrimination task; those who performed at chance in the identification task but had thresholds $<$70 Hz in the discrimination task; and those who performed at chance in

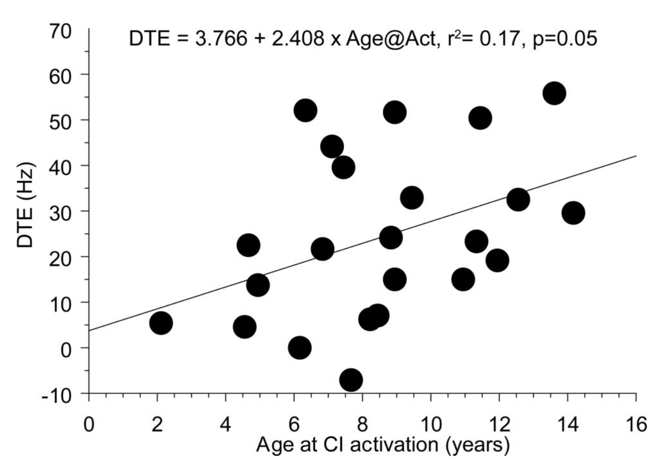

Fig. 4. The individual relationship (circles) and linear regression (solid line) between age at CI activation and the discrimination threshold estimates (DTE) in the adaptive, two-interval discrimination procedure. The regression equation is given at the top of the panel with the coefficient of determination (r^2) and significance level (p).

both tasks. (2) There were no differences in group means of hearing history variables across the three groups despite the differences in performance. (3) For those who could identify the gender of the voices at an above-chance level (N = 18), duration of deafness, and to a lesser extent age at implantation, was significantly negatively correlated with performance. Linear regression revealed that only duration of deafness influenced the performance significantly. Inclusion of the five intermediate subjects rendered these relationships nonsignificant. (4) For those who had discrimination scores in the adaptive task <70 Hz (N = 23), age at activation was significantly positively correlated with performance. Those who had later ages at activation had higher discrimination thresholds. Removing the five intermediate users rendered the relationship nonsignificant. (5) A significant negative relationship was observed between tasks for those participants who performed above chance on the identification task and had thresholds <70 Hz on the discrimination task.

DISCUSSION

These findings show that there is still considerable variability in the ability to identify voice gender among CI subjects despite greatly simplified tasks, compared with standard speech perception tests where such variability was also observed (Blamey et al. 2001). The correlational analysis of relationships between performance and hearing history variables revealed that gender identification performance for single voices was inversely related to the period of auditory deprivation before cochlear implantation in a group of juvenile CI users who could all perform the task at better-than-chance levels. In addition, performance in the adaptive discrimination task was weakly related to age at first activation of the CI device, with earlier implanted subjects achieving better scores. Although duration of deafness and age at first CI activation were highly correlated with each other in the population examined here (Table 2), multiple regression analyses were able to separate their effects on these tasks, and the presence of a group of subjects with chance gender identification scores but good discrimination threshold estimates indicates that the skill sets used in these two perceptual tasks could be dissociable (Fig. 2, see also Kovacic & Balaban 2009).

A pitch ranking study by Gfeller et al. (2007) presented CI subjects with a sequential pair of tones and asked them to identify the interval containing the higher pitch. This task is analogous to the adaptive discrimination task used in this study, involving short-term comparison of relevant acoustic cues among sequentially presented items. Gfeller et al. (2007) found no relationship between duration of deafness and task performance, in agreement with the results of this study. Because they did not report age of implantation of their CI subjects, it is unclear whether age of implantation was related to pitch-ranking ability.

Auditory discrimination tasks may be relatively easier than identification tasks because they offer more information (two intervals) and a possibility for a comparison across some reference dimension (in our case it is fundamental frequency F_0 of the speaker). This was one of our motivations for introducing a discrimination-like task, because we were concerned from pilot studies that there would be a relatively high proportion of subjects who would not be able to identify voice gender from a single speech item. In the adaptive task used in this study, subjects were requested to choose the female speaker from a pair of speech items; the results suggest that this task was easier for some subjects, as shown by the emergence of a subgroup of subjects who were unable to do the identification task but could identify the gender correctly in the adaptive discrimination. These subjects could use a direct comparison strategy to identify gender of the speaker correctly.

We hypothesize that duration of deafness and age at implantation could differentially influence the development of independent skills that contribute to performance on the two tasks studied here. For example, one interpretation posits that long- and short-term memory for auditory objects and features play different roles in these tests, with gender identification emphasizing a subject's ability to compare an individual voice to categorical long-term memories for male and female voices and adaptive discrimination emphasizing a subject's ability to compare the two voice stimuli in short-term memory. A longer period of deafness before implantation may negatively impact a person's ability to form detailed, long-term auditory categorical memories for the sound attributes of familiar objects by depriving the brain of auditory input during a time when multimodal categorical memories are established, while leaving the basic capabilities for learning to compare different sound attributes in short-term memory relatively intact. Kral and Eggermont (2007) stressed the significance of developmentally related top-down and bottom-up influences on cortical plasticity and their role in limiting the acquisition of new auditory categories. If the establishment of neural mapping relations between the auditory characteristics of objects and their other attributes needs to take place early in life, and is somewhat resistant to changes later on, then subjects who were deaf during this period may form object representations that do not include auditory attributes such as pitch and timbre. Such individuals may be able to hear the pitch differences between male and female voices but be unable to relate these to their long-term categorical representations of the general attributes of males and females. Deafness for part of this period may impact the quality and extent to which detailed auditory attributes are included in object representations, and this would account for the findings seen here. Conversely, in subjects whose implants provide the auditory CNS with basic information about voice pitch or vocal-tract size-related information, earlier implant activation may provide the opportunity for more practice at comparing a variety of attributes of successive sounds in short-term memory. It may also enable long-term physiological changes (that may depend on age) that additionally facilitate sound comparison abilities and thus lead to the development of a relatively greater facility with comparing the attributes of two sounds in a testing situation.

The hypothesis that duration of deafness and age at implant activation affect the development of different, dissociable performance attributes needs to be more rigorously evaluated with additional subject groups and additional testing paradigms, which may also aid in a more precise identification of the specific mechanisms affected by these variables.

The moderate value of the coefficient of determination for the linear regression between voice gender identification performance and duration of deafness (0.34 or 0.56 depending on the analysis) and the weaker coefficient of determination for the regression between discrimination performance and age of first CI activation (0.17 or 0.22 depending on the subject set) suggest that perceptual performance for even simple attributes such as voice gender involve multiple explanatory variables. These presumably include technological and medical aspects of the implants such as their CI parameter settings, location, insertion depth, and the state of the spiral ganglion cells they are stimulating, as well as rehabilitative issues. One technological factor, the quality of the voice gender cues that the CI processor transmits to its user, has been analyzed by Kovacic and Balaban (2009) who found no differences in transmission quality between subjects who could and subjects who could not perform voice gender identification or discrimination. With regard to rehabilitative issues, Fu and Galvin (2008) have shown that auditory-based training plays an important role in improving CI auditory perceptual abilities. The relatively low correlation values seen in these data call for further studies that would test other possible variables mentioned in the Introduction as part of an explanation for performance variability. However, this is a separate issue from the central focus of the present study: how hearing history may affect voice gender perception in tasks that appear to rely on different behavioral performance strategies.

The age of onset of deafness seems to have no substantive influence on ultimate adaptive identification performance, subject to the provision that cochlear implantation happens early enough. A similar pattern of results was obtained by Nikolopoulos et al. (2006), who did not observe differences between congenitally deaf and postmeningitic CI users in speech perception tests. Interestingly, all subjects with good discrimination in these experiments had been using their CI devices for at least 3 yrs. It would be interesting to know whether voice gender identification abilities may saturate after a certain period of exposure subsequent to cochlear implantation, a possibility that needs to be examined more rigorously in future work.

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