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Gender Categorization in Cochlear Implant Users

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Purpose: In this study, the authors examined the ability of subjects with cochlear implants (CIs) to discriminate voice gender and how this ability evolved as a function of CI experience.
Method: The authors presented a continuum of voice samples created by voice morphing, with 9 intermediate acoustic parameter steps between a typical male and a typical female. This method allowed for the evaluation of gender categorization not only when acoustical features were specific to gender but also for more ambiguous cases, when fundamental frequency or formant distribution were located between typical values.
Results: Results showed a global, though variable, deficit for voice gender categorization in CI recipients compared with subjects with normal hearing. This deficit was stronger for ambiguous stimuli in the voice continuum: Average performance scores for CI users were 58% lower than average scores for subjects with normal hearing in cases of ambiguous stimuli and 19% lower for typical male and female voices. The authors found no significant improvement in voice gender categorization with CI experience.
Conclusions: These results emphasize the dissociation between recovery of speech recognition and voice feature perception after cochlear implantation. This large and durable deficit may be related to spectral and temporal degradation induced by CI sound coding, or it may be related to central voice processing deficits.

Key Words: voice processing, voice, deafness, cochlear implants, gender, speech perception

A *cochlear implant* (CI) is an effective neuroprosthesis that allows persons who are deaf to recover auditory abilities, especially speech recognition. Indeed, speech recognition scores in CI subjects often exceed 80% for sentences or words in quiet (Rouger et al., 2007; UK Cochlear Implant Study Group, 2004; Wilson & Dorman, 2008). Efficient encoding of temporal envelope information in speech and intense speech therapy following implantation are probably responsible for these remarkable outcomes. However, other aspects of speech perception remain difficult for CI users, including speech understanding in noise (Fu, Shannon, & Wang, 1998; Munson & Nelson, 2005), prosody recognition, and music perception (El Fata, James, Laborde, & Fraysse, 2009; Gfeller et al., 2002; Kong, Cruz, Jones, & Zeng, 2004; Leal et al., 2003). These difficulties can be related to the limitations of current CIs, which provide significantly fewer effective frequency channels than those involved in normal hearing (see McKay, 2005, for review). CI users usually experience difficulties in recognizing paralinguistic information due to degradation of the acoustic signal after acoustic-to-electric coding. Indeed, sound coding results in significant spectral degradation because the original sound spectrum is necessarily divided into a limited number of frequency bands that correspond to the number of activated cochlear electrodes, which are alternately stimulated depending on the sound processor. Further, not only is the auditory information spectrally degraded, but fine temporal structure—which is important for certain aspects of speech recognition (Lorenzi, Gilbert, Carn, Garnier, & Moore, 2006; Zeng et al., 2005)—is also not represented.

By manipulating spectral and temporal components of speech, researchers have shown that linguistic information is not supported by the same spectrotemporal modulation as is paralinguistic information (Elliott & Theunissen, 2009). Indeed, several studies have revealed a dissociation between speech recognition recovery and discrimination of human voice features, such as identity or emotion (Cleary & Pisoni,

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2002; Cleary, Pisoni, & Kirk, 2005; Vongphoe & Zeng, 2005). In addition, in a previous study, we showed that CI recipients presented a large deficit in distinguishing the human voice from environmental noise when relevant speech information, such as the longer-term temporal envelope, was not available (Massida et al., 2011). It is important to take into account such a deficit in voice and voice feature perception because it has a large negative impact on CI users' social communication.

In the present study, we focused on the ability of CI users to discriminate a specific feature of the human voice: gender. In the hierarchical model of voice perception proposed by Belin, Fecteau, and Bedard (2004), recognition of voice attributes such as identity cues can be performed after a first low-level acoustic analysis, which distinguishes the human voice from environmental sounds. Voice gender perception relies on several acoustical cues; the main ones are voice fundamental frequency (F0), which determines voice pitch, and the formant distribution that underlies voice timbre. F0 constitutes an important cue for voice gender recognition because F0 values for a female voice typically differ from F0 values for a male voice by one octave or more (see Titze, 1989). *F0* reflects vocal fold vibration frequency and, therefore, relates mainly to size and tension. *Voice timbre* is often referred to as *voice quality* and also provides useful information regarding voice gender. *Formants* are composed of harmonics of F0 and result from resonances in the vocal tract, mostly the supralaryngeal cavities. Vocal tract size, length, and shape greatly differ between genders (in adults), and so, formant frequencies differ between males and females. According to Lavner, Gath, and Rosenhouse (2000), the third and fourth formants are particularly useful for conveying identity cues to the listener.

In previous studies, researchers used a two-alternative forced choice (2AFC) design between one typical male voice and one typical female voice to test the subjects' ability to discriminate gender. Fu, Chincilla, and Galvin (2004) found that when using such a paradigm, CI subjects presented a performance level of correct gender identification that ranged from 70% to 95%. In addition, the researchers used a noiseband vocoder that mimicked the processing of sound by a CI, which allowed them to perform a direct comparison between CI subjects and subjects with normal hearing. Gender recognition performance in CI users was comparable to that of subjects with normal hearing with four to eight channels, a result that highlights the role of both spectral and fine temporal cues in voice gender discrimination (Fu et al., 2004; Fu, Chinchilla, Nogaki, & Galvin, 2005).

However, the voice F0 distribution among the general population is highly variable (Andrews & Schmidt, 1997), and in CI users, it appears that gender categorization is impaired in cases of ambiguous F0 values within the region of overlap of distributions for males and females (Kovacic & Balaban, 2009). To evaluate precisely the impairment of voice gender perception in CI users when voice attributes are ambiguous, we used a task involving stimuli created by morphing a male voice to a female voice; this process included several acoustical intermediates on a continuum between one typical male voice and one typical female voice (Pernet & Belin, 2012). Such a paradigm allowed us to quantify CI users' ability to perform voice gender categorization in a tightly controlled fashion, especially when acoustical features presented varying degrees of ambiguity. The present study had two main goals. The first goal was to precisely quantify the deficit of CI users' gender categorization, especially when acoustic cues of the voice (pitch and timbre) were ambiguous. We hypothesized that CI subjects' performance would be particularly affected when voice features were ambiguous. The second objective was to analyze the development of CI users' performance in such a categorization task as a function of experience with the CI. Further, most studies on auditory recovery in CI subjects have revealed much variability in performance levels (Rouger et al., 2007; Wilson & Dorman, 2008). The origin of such variability is diverse, stemming from the etiology of deafness; the severity of deafness (residual hearing); and other sources, including the CI sound-coding strategy. To rule out such sources of variability, we performed a longitudinal analysis on a selected group of subjects from the time of implantation up to more than 18 months of experience. On the basis of our previous findings concerning human voice discrimination, we expected that gender discrimination would not be influenced by time after implantation (Massida et al., 2011). This hypothesis was based on the differences between acoustic cues required for linguistic and paralinguistic information perception and by the hierarchical organization of voice processing in the brain (Campanella & Belin, 2007).

Materials and Method

Subjects

Fourteen native French speakers (7 males, 7 females; M_{age} = 24.6 years, *SD* = 2.9 years) with normal hearing were included in this study. Subjects' histories were collected through a questionnaire, and none of the subjects had a history of auditory, neurological, or psychiatric disorders.

A total of 42 CI subjects participated in the study. They were divided into two groups (see Table 1). The *transversal group* included 32 adults with unilateral CIs (15 males, 17 females; M_{age} = 54.5 years, *SD* = 15.0 years; right CI = 15 subjects, left CI = 17 subjects). The *follow-up group* included 10 adults with unilateral CIs (five males, five females; M_{age} = 51.9 years, *SD* = 16.0 years; right CI = five subjects, left CI = five subjects).

The CI subjects were, on average, older than the control subjects with normal hearing, but their age ranged from 20 to 80 years. Hearing can be affected by age (Arehart, Souza, Muralimanohar, & Miller, 2011; Gratton & Vazquez, 2003), which might be evident when, for example, a gender discrimination task is performed through a CI simulation (Schvartz & Chatterjee, 2012; Souza, Arehart, Miller, & Muralimanohar, 2011). However, we found no correlation between age and performance level in our discrimination tasks, albeit for our relatively limited group of subjects. As a result, we adopted the strategy of comparing the subjects' performance in voice discrimination with that obtained from

Table 1. Summary of subjects.

Subject number	Postactivation delay	Age (yrs)	Hearing loss (yrs)	Model of implant	Processor	Strategy	Hearing aid
			Transversal group				
1	1st day	63	>20	Cochlear	Freedom	ACE	
2		46	>30	Cochlear	Freedom	ACE	
3		48	>40	Advanced Bionics	Auria	HiRes-S	
4		43	>30	Cochlear	Freedom	ACE	
5		21	>10	Cochlear	Freedom	ACE	
6		67	>10	Cochlear	Freedom	ACE	Y
7		48	>30	Cochlear	Freedom	ACE	
8		47	>40	MedEl	OPUS 2	FSP	Y
9		53	>40	Cochlear	Freedom	ACE	Y
10	1–6 months	67	>30	Cochlear	Freedom	ACE	
11		45	3	Cochlear	Freedom	ACE	Y
12		71	>40	Advanced Bionics	Harmony	HiRes-S	Y
13		35	>30	Cochlear	Freedom	ACE	Y
14	6–18 months	21	>10	Cochlear	Freedom	ACE	Y
15		51	>30	Advanced Bionics	Auria	HiRes-S	Y
16		40	>30	Cochlear	Freedom	ACE	Y
17		63	>20	Cochlear	Freedom	ACE	Y
18		53	<5	Advanced Bionics	Auria	HiRes-S	Y
19		81	NA	Advanced Bionics	Auria	HiRes-S	Y
20		74	2	Cochlear	Freedom	ACE	Y
21		48	>30	Cochlear	Freedom	ACE	Y
22		71	NA	Cochlear	Freedom	ACE	
23	> 18 months	48	>30	Cochlear	Freedom	ACE	Y
24		41	>30	Cochlear	ESPrit 3G	ACE	
25		38	>30	Cochlear	ESPrit 3G	ACE	
26		61	>40	Advanced Bionics	Auria	HiRes-S	
27		75	>10	Cochlear	ESPrit 3G	ACE	
28		59	>20	Cochlear	ESPrit 3G	ACE	
29		59	NA	Cochlear	Sprint	ACE	
30		58	>40	Cochlear	ESPrit 3G	SPEAK	
31		68	>10	Cochlear	Sprint	ACE	
32		75	>20	Cochlear	ESPrit 22	SPEAK	
			Follow-up group				
33	Longitudinal	63	>20	Cochlear	Freedom	ACE	
34		46	>30	Cochlear	Freedom	ACE	
35		48	>40	Advanced Bionics	Auria	HiRes-S	
36		21	>10	Cochlear	Freedom	ACE	
37		48	>30	Cochlear	Freedom	ACE	
38		47	>40	MedEl	OPUS 2	FSP	Y
39		53	>40	Cochlear	Freedom	ACE	Y
40		67	>30	Cochlear	Freedom	ACE	
41		45	3	Cochlear	Freedom	ACE	Y
42		81	NA	Advanced Bionics	Auria	HiRes-S	Y

Note. The last column indicates which subjects used a hearing aid in daily life. NA = not applicable.

a homogeneous group of young subjects with normal hearing with no evidence of hearing loss.

Voice discrimination was tested during regular visits to the Ear, Nose, and Throat department (CHU Purpan) following the standard rehabilitation program. Postactivation delay varied from 1 day to 131 months, and subjects were divided into four subgroups according to duration of implant use. All subjects had postlingually acquired profound bilateral deafness of diverse etiologies (meningitis, chronic otitis, otosclerosis, etc.) and durations. Only two subjects presented with sudden deafness, which had occurred 2 and 3 years, respectively, before receiving CIs. In all other subjects, the deafness was progressive. Duration of hearing loss for each subject is shown in Table 1. Because of this progressive hearing impairment, the duration of deafness could not be reliably defined, and as a consequence, we did not attempt to correlate this measure with any of the performance levels presented by these subjects. Further, 16 subjects from the transversal group and four from the follow-up group had a hearing aid in the nonimplanted ear and used it in daily life. These subjects were always tested with the implant alone. We analyzed separately the performances of those subjects (slope values of the psychometric categorization function) who used a hearing aid daily, but we did not observe a difference when comparing them to the subjects who used the CI alone.

Information concerning the subjects is provided in Table 1 for both the transversal and the follow-up groups. All subjects gave written informed consent prior to their inclusion in the study.

Stimulus Material

All stimuli used in our experiment were developed at the Voice Neurocognition Laboratory (University of Glasgow, Scotland). In this experiment, we used a subtest of the Voice Perception Assessment (VPA) battery (Watson et al., 2009), a subtest that was also used in a previous study by Pernet and Belin (2012). The task requires subjects to categorize by gender voice stimuli from a morphing-generated voice continuum between a male and a female voice, speaking the same syllable (*had*). The two extreme voices each correspond to an average voice with a spectrum made of 16 voices of the same gender. Morphing was performed using STRAIGHT (Hideki Kawahara, University of Wakayama; Kawahara, Masuda-Katsuse, & de Cheveigné, 1999) in MATLAB. STRAIGHT performs an instantaneous pitch-adaptive spectral smoothing to separate the contributions of the glottal source (including F0) from supralaryngeal filtering (distribution of spectral peaks, including the first formant F1) to the voice signal. STRAIGHT decomposes voice stimuli into five parameters—F0, formant frequencies, duration, spectrotemporal density, and aperiodicity—and each parameter can be independently manipulated. *Anchor points* (i.e., time-frequency landmarks) were determined in both extreme voices based on easily recognizable features of the spectrograms. The temporal landmarks were identified as the onset, offset, and initial burst of the sound. Spectrotemporal anchors were the first and second formants at onset of phonation, onset of formant transition, and end of phonation. Using the temporal anchors, elements of the continuum were equalized in duration (39.2 ms; i.e., 17,289 data points at 44100 Hz). Morphed stimuli were then generated by resynthesis based on a logarithmic interpolation of female and male anchor templates and spectrograms in steps of 10%. Thus, we obtained a continuum of 11 voices ranging from 100% female (resynthesized female stimulus) to 100% male (resynthesized male stimulus) with nine gender-interpolated voices in 10% steps (90% female–10% male, 80% female–20% male, … 10% female–90% male; see Figure 1, Panels A and B). Values of F0, F1, F2, F3, and F4 for each position in the continuum are presented in Table 2.

In addition, we tested voice–nonvoice discrimination in 11 subjects, as we had done in a previous study with CI subjects (Massida et al., 2011). This test assesses a CI subject's ability to distinguish human voice sounds from environmental sounds. Two sets of 500-ms stimuli were created: The first set contained 55 different human voice stimuli, including 29 speech stimuli (phonemes presented in a /h/*vowel*/d context, words in different languages, or nonsemantic syllables) and 26 nonspeech stimuli (e.g., laughs, coughs). The second set contained 55 nonvoice stimuli consisting of a wide variety of environmental sounds, including sounds from cars, telephones, bells, and streaming water. Neither group contained animal vocalizations. All subjects were tested on open-set recognition for French dissyllabic words obtained from the standard speech-language therapist's Fournier lists presented through loudspeakers.

Stimulus Presentation and Procedure

Subjects were tested in a sound-attenuated chamber with volume adjusted to 72 dB SPL. For subjects with normal hearing, the intensity was measured at the ear, whereas for CI subjects, intensity was measured at the distance of the subject from the loudspeakers. Subjects with normal hearing were tested at the CerCo Laboratory and CI subjects in the ENT department. Stimuli (16-bit, mono, 22050-Hz sampling rate) were presented binaurally to the control group via Sennheiser EH250 headphones, as in the regular speech recognition assessments. The stimuli were presented to the CI users in the sound field through loudspeakers (KINYO, model PS-240).

The 11 voices of the continuum were each presented 10 times in a pseudorandom order (110 stimuli presentations). The task for subjects with normal hearing and CI subjects was a 2AFC categorization, in which subjects were asked to choose either *male* or *female*. Subjects with normal hearing were tested with a 1-s intertrial delay and were instructed to respond as quickly and accurately as possible using the left or right control buttons of the computer keyboard corresponding to their answer (*male* or *female*). The response keys were counterbalanced across subjects. CI subjects were tested with a 1.5-s intertrial delay and were instructed to answer as accurately as possible, with no reference to reaction time. Despite the longer intertrial delay, the short duration of the stimuli (39.2 ms) made the task more difficult for the CI subjects, and in a few trials, some subjects did not provide a response. Such cases were more often present in subjects tested on the first day of activation of the implant—in 8% of trials ($M = 7.8$, $SD = 11.1$). In experienced subjects, such behavior occurred in less than 2% of trials ($M = 2.2$, $SD = 3.6$). These trials were excluded from the analysis, and only definite responses were retained. For each voice on the continuum, we measured the percent of *female* responses. The test lasted about 5 min for NHS and 7–10 min for CI subjects.

For the follow-up group, CI subjects were tested on the first day of implant activation and then at all sessions with the hospital speech therapist: at 1 month, 3 months, 6 months, 9 months, 12 months, and 18 months after implant activation. The procedure was the same each time.

For the voice–nonvoice discrimination task, 11 CI subjects were also tested in the same acoustic conditions as for the gender discrimination task (loudspeakers at 72 dB SPL), using a 2AFC categorization, in which subjects were asked to choose either *voice* or *nonvoice*. CI subjects were tested with a 1.5-s intertrial delay and were instructed to answer as accurately as possible, using the left or right control buttons of the computer keyboard corresponding to their answer (*voice* or *nonvoice*). The response keys were counterbalanced across subjects.

Figure 1. A: Spectrograms corresponding to the two extremities of the vocal continuum (100% female and 100% male). B: Spectral representation of the 11 elements of the vocal continuum. C: Psychometric curve of gender categorization in subjects with normal hearing (NHS). D: Representative example of the performance of cochlear implant subjects with various delays postimplantation.

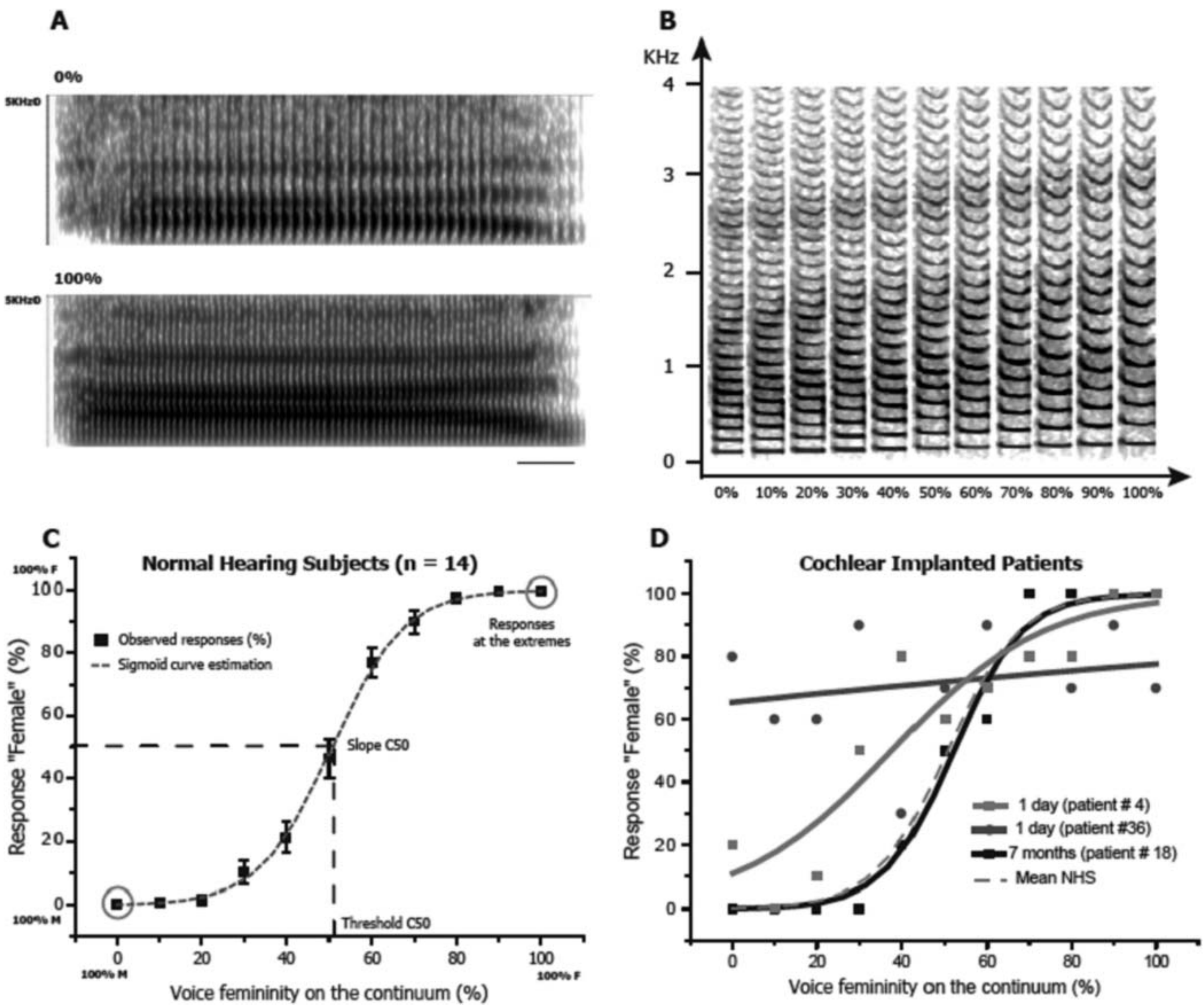


Table 2. Values of F0, F1, F2, F3 and F4 for each position of the voice stimuli across the male (Position 1) to the female voice (Position 11) in the continuum.

Position	Mean F0 (Hz)	Mean F1 (Hz)	Mean F2 (Hz)	Mean F3 (Hz)	Mean F4 (Hz)
1	125.86	752.77	1436.59	2598.76	3859.52
2	133.08	777.39	1480.86	2663.10	3977.32
3	140.49	791.59	1506.54	2688.29	4042.53
4	148.20	810.47	1547.96	2738.83	4114.92
5	155.83	830.00	1585.38	2780.41	4153.51
6	163.99	856.36	1632.17	2815.70	4198.26
7	173.10	877.23	1668.88	2846.01	4200.36
8	182.24	904.72	1711.57	2881.42	4241.36
9	191.73	922.13	1740.51	2906.60	4281.48
10	202.10	941.89	1777.30	2946.08	4319.14
11	212.71	967.21	1803.72	2963.55	4360.48

Analysis

As a primary measure, we used the rate of *female* responses for each of the 11 voices, from the male voice to the female voice. A Boltzmann sigmoidal function was fitted to these points using a nonlinear least-squares procedure (Levenburg-Marquart; Origin Version 6.1). Categorization was studied among several criteria: First, we measured on the curve the abscissa for which the subjects responded *female* on 50% of the trials (hereafter termed the *C50 threshold*). Second, we estimated the slope of the psychometric function, which is maximal at the center of symmetry of the curve—that is, the point for subjective equality. We calculated the slope using an original MATLAB function, and the slope corresponded to the value of the derivative function of the sigmoid psychometric curve at the point for subjective equality. We used the slope value, which is particularly sensitive when the stimulus is ambiguous, as the main criterion of voice gender categorization ability. In a typical categorization task, the slope reflects an abrupt shift from male to female categorization (see Figure 1, Panel C). In the case of a deficit in gender discrimination, subjects' responses would be more variable for a given stimulus, especially for the ambiguous voices. Such behavior would be expressed as a flatter psychometric function and, consequently, a lower slope value. Third, we analyzed the percent correct of gender recognition for typical male and female voices at the ends of the continuum.

To analyze the global effect of the implantation delay on C50 threshold, slope, and correct recognition measures, we used an analysis of variance (ANOVA) for independent measures. The Bonferroni–Dunn test was used for post hoc analysis. We used a *t* test to measure differences between CI subjects and subjects with normal hearing and between recognition of male and female voices.

Concerning voice–nonvoice discrimination performance, we measured *d′*, which is a criterion of perception sensitivity independent of decision bias, relying on hit rate and false alarm rate according to the signal detection theory (Swets, Harris, McElroy, & Rudloe, 1966; Tanner & Swets, 1954).

Results

Subjects With Normal Hearing

As explained in the Materials and Method section, the advantage of the gender categorization task is that we can analyze several criteria to evaluate subjects' performance. Figure 1, Panel C illustrates the performance of the subjects with normal hearing during the categorization task. Subjects correctly categorized the voice at the extremes (M = 99.6%, SD = 1.9), which corresponded to resynthesized unambiguous voices of typical adults (100% male or 100% female). When the voice stimuli were morphed and corresponded to ambiguous voices (50% on the continuum), subjects showed categorization performance at chance level. In between, the performance of the subjects shifted progressively toward the major feature (predominantly male or predominantly female) of the morphed voice. Globally, the psychometric curves of the subjects can be fitted with a sigmoid function, from which two supplementary criteria can be computed for comparison with subjects' performance: the C50 threshold, which corresponded to the stimulus of the continuum and elicited a chance-level categorization, and the slope of the sigmoid at the center of symmetry of the curve. For the subjects with normal hearing, the mean threshold C50 value was 53.8% (SD = 6.6) and, thus, corresponded closely to the most ambiguous stimulus. The mean slope value was 4.3 (SD = 1.9).

Subjects With Cochlear Implants: Transversal Group

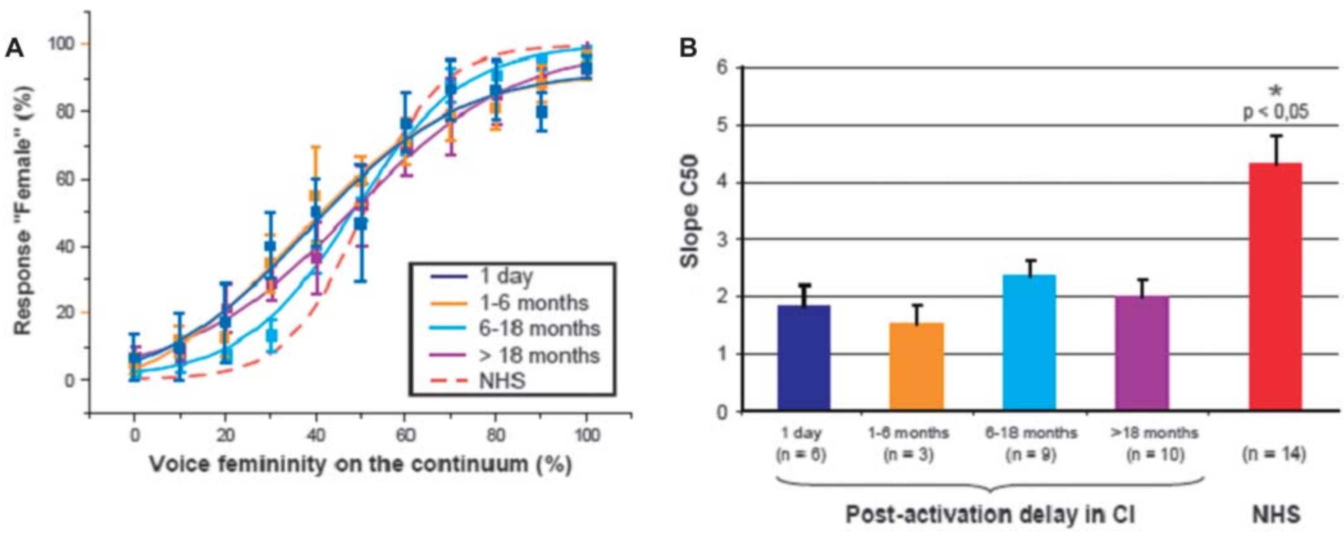
We analyzed the performance of 32 CI subjects who were distributed in four subgroups according to duration of CI experience (postactivation delay). Globally, our test revealed a strong and durable deficit in voice gender categorization for CI subjects.

Gender categorization. Performance of CI subjects varied according to duration of CI experience, and most of the CI subjects presented a strong impairment when they were tested during the first month of CI use. Figure 1, Panel D illustrates representative responses of subjects in the CI group, characterized by a high variability compared with those of the subjects with normal hearing (dashed line). Some subjects managed to perform the task as accurately as subjects with normal hearing (black line), whereas others presented responses systematically biased toward female voices (see, e.g., Subject 36) for most stimuli of the continuum. Such behavior corresponded to that of subjects whose CIs had been recently implanted (less than 1 month), and in four of these subjects (three on the first day of implant activation and one after 1 month of implant activation), the slope and C50 threshold could not be computed because of a lack of a good fit of the psychometric curve to a sigmoidal function (R^2 = .0179; χ^2 = 170.4).

For each postactivation delay, the performances of CI subjects in gender categorization remained significantly lower than those observed in subjects with normal hearing. This could be directly assessed by a simple inspection of the psychometric functions: The CI subjects evaluated on the first day of activation demonstrated poor abilities to categorize gender (Figure 2, Panel A), but their responses were not at chance level—their proportion of *female* responses varied along the continuum. Gender categorization did not improve with CI experience; mean slope values ranged from 1.8 (SD = 0.9) for CI subjects tested on the first day of activation to 2.3 (SD = 9.0) for CI subjects evaluated between 6 and 18 months postactivation and 2.0 (SD = 0.9) for subjects evaluated more than 18 months after implantation (see Figure 2, Panel B). In addition, correlation between mean slope and CI subjects' age did not reveal any significant influence of age in gender categorization performance (R^2 = .0131).

The performances of CI subjects remained globally inferior to those observed in the normal hearing group (M_{slope} = 4.3, SD = 1.9). In all CI subject groups, whatever

Figure 2. Panel A: Psychometric curves of cochlear implant (CI) subjects. Each curve represents the mean curve of a group of CI subjects at different delays postimplantation. Values of subjects with normal hearing are indicated by the dashed line curve. Panel B: Slope values computed at the C50 (i.e., the abscissa for which the subjects responded *female* on 50% of the trials). Slope values were significantly higher in subjects with normal hearing than in any group of CI subjects(*), and no significant difference was found across groups of CI subjects.

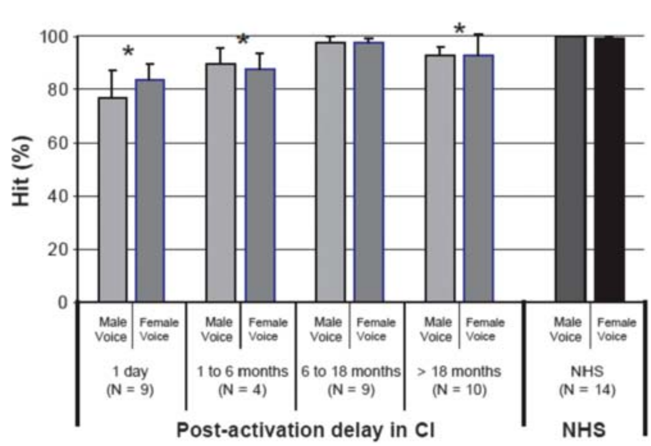


the postactivation delay (Figure 2, Panel B), the slope of the psychometric curve remained significantly lower than that of the normal hearing group, $t(1) = 3.52$ and $t(1) = –3.006$, respectively ($p < .05$).

The C50 threshold value characterizes the position on the continuum for which subjects respond at chance level. Compared with subjects with normal hearing ($M_{\text{threshold}} = 53.8\%$, $SD = 6.6$), CI subjects seemed to categorize female voice earlier in the continuum, whereas the morphed voice is composed of a slightly higher proportion of male voice features. Such a shift could be due either to the implant insertion depth or to the specific parameters of the individual's CI processor. However, it is not possible to make a conclusion about this specific variability because, in an ANOVA, this apparent difference from subjects with normal hearing was observed in only two subgroups of subjects, whereas there was no significant difference in thresholds between CI subject groups, $F(3, 24) = 0.918$, $p > .05$, power = 0.216. The difference was significant only for subjects whose CIs were newly implanted (first day of activation), $t(1) = –2.265$, $p = .034$, and for subjects with 6–18 months of experience with the implant, $t(1) = –2.827$, $p = .011$. Intragroup threshold analyses for the CI subjects did not show any differences related to postactivation delay. On the first day of activation, the mean threshold was 43.1% ($SD = 10.2$) and increased to 46.9% ($SD = 16.3$) for subjects evaluated at or after 18 months of CI experience.

Gender recognition. We assessed gender recognition by analyzing the subjects' responses for the two extreme voices of the continuum: 100% male voice and 100% female voice. Compared with subjects with normal hearing, CI subjects at activation had a significant deficit in recognizing both male, $t(1) = –2.818$, $p = .01$, and female, $t(1) = –3.202$, $p = .004$, voices (see Figure 3). However, this deficit was lower than the deficit quantified from the slope analysis: The scores of subjects whose CIs were newly implanted were only 19% lower (male and female voices combined) than those of subjects with normal hearing (i.e., for typical male and female voices). Conversely, when considering the slope values, which corresponded to the categorization of the most ambiguous voices, the CI subjects' slope values at activation were reduced by 58% compared with those of the subjects with normal hearing.

Figure 3. Performance of CI subjects in voice gender recognition corresponding to the hit scores (%) for the unambiguous male or female voices.



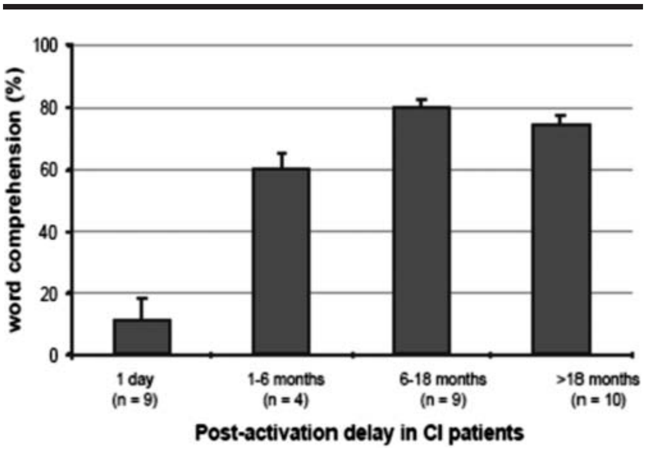
Improvement of gender recognition directly correlated with a subject's level of CI experience, but the results of our ANOVA showedthat this trend did not reach significance: male voice, $F(3, 28) = 2.170$, $p > .05$, power = 0.485; female voice, $F(3, 28) = 1.923$, $p > .05$, power = 0.434. In addition, only the intermediate group of CI subjects with postactivation delays of 6–18 months showed performances similar to those of the subjects with normal hearing, $t(1) = 2.786$, $p = .01$. As for gender categorization, there was no significant relationship between CI subjects' age and their recognition scores (male voice, $R^2 = 0.124$; female voice, $R^2 = .013$).

Last, it is important to mention that there was no difference between performances for male and female voice recognition at any period postimplantation, $t(1) = -0.820$ and $t(1) = 0.430$, respectively ($p > .05$). Thus, characteristic gender voices were equally identified by CI subjects.

Voice discrimination. A limited number of subjects ($n = 11$) were also tested for their ability to discriminate the human voice from environmental sounds (see Massida et al., 2011). Our previous study showed a deficit in such a task in early stages after implantation, with an improvement in performance after several months of experience. In the current limited set of subjects, we confirmed the weak performance of CI subjects in such a task, even after more than 18 months of experience with the CI (mean $d' = 1.5$, $SD = 0.7$). Such values were significantly lower than those observed in subjects with normal hearing (mean $d' = 4.3$, $SD = 0.5$ in Massida et al., 2011). A statistical analysis did not reveal a correlation between performance in discriminating voices from nonvoices (d') and gender categorization (threshold, slope, and correct recognition of the gender; in all cases, $p > .05$).

Speech recognition. As previously reported, an ANOVA revealed that CI users demonstrated a significant improvement of word recognition scores following implantation, $F(3, 28) = 52.626$, $p < .0001$, power = 1. The CI users' scores reached 75% ($SD = 8.7$) disyllabic word recognition at 6–18 months postimplantation (see Figure 4). However, CI subjects'

Figure 4. Recovery of auditory speech recognition scores in CI subjects.



performance remained below that of subjects with normal hearing, even after more than 18 months of experience with the CI, $t(1) = -16.5$ and $t(1) = 10.9$, respectively ($p < .0001$).

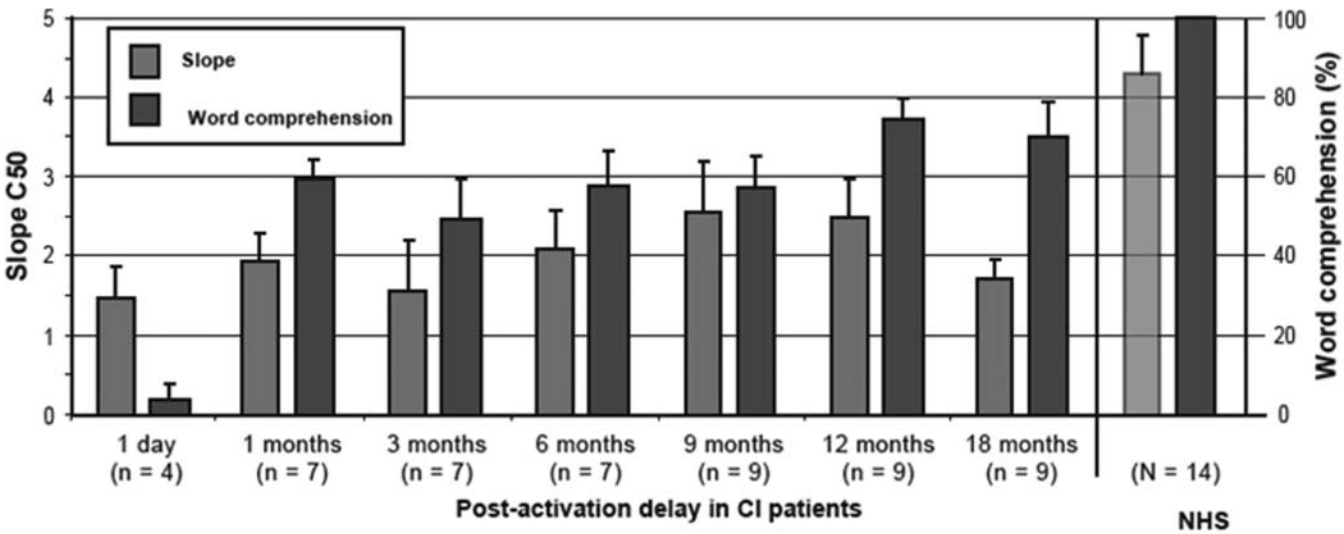
We looked for a correlation between performance levels in speech recognition and gender categorization. In the full set of CI subjects ($n = 32$), which encompassed novices and experienced users, an analysis revealed no significant correlation (Fisher's test, $r^2 = .01$ and $r^2 = .03$, respectively, $p > .05$) between word recognition scores (in %) and any performance criteria for gender categorization (slope, C50 threshold, male and female voice recognition). We further examined the relationship between speech recognition scores and gender categorization performance using a within-subjects ANOVA, which revealed the independence between the two variables regardless of the delay postimplantation, $F(3, 28) = 52$ and $F(3, 28) = 48$, respectively ($p < .0001$). This result adds further evidence that the recovery of speech recognition is independent of the recovery level in voice gender discrimination.

Subjects With Cochlear Implants: Follow-Up Group

We performed a longitudinal follow-up of 10 subjects, from the first day of CI activation to 18 months postactivation. It was unfortunate that the number of subjects was limited and performance was too variable across the different postimplantation delays to allow a reliable paired statistical analysis: The analysis of this follow-up group tended to confirm the results obtained in the transversal group. Indeed, performance in gender categorization did not seem to improve with CI experience, whereas the improvements in mean speech recognition score ranged from 14% to 70% correct (see Figure 5). At any delay postimplantation, the mean slope value for this CI subjects group was always lower than for the subjects with normal hearing and was similar to that observed in the transversal group. As for the transversal group, there was no significant relation between postactivation delay and gender categorization slope (Fisher's test, $r^2 = .0008$, $p > .05$). The C50 threshold showed a high variability, with mean values ranging between 38% and 56%, but these values did not differ significantly from those for the subjects with normal hearing. Gender recognition, evaluated for typical male and female voices, tended to improve from the first day of activation; however, as obtained in the transversal group, performance never reached performance levels of the subjects with normal hearing.

The transversal and longitudinal group analyses led to very similar results, showing a deficit in gender categorization that did not improve significantly with CI experience. Because of differences in the postactivation delay, direct statistical comparisons were precluded. However, by simple observation of time of implantation, the performance level (mean slope) was similar in the transversal and follow-up groups (1.8 vs. 1.5, respectively). In a similar way, after more than 18 months of CI experience, the two groups (transversal and longitudinal) presented very comparable slope values (2.0 and 1.7, respectively). In spite of a regular repetition of the gender discrimination test in the longitudinal group, no

Figure 5. Longitudinal follow-up of a second group of 10 CI subjects: performance in voice gender categorization and in speech recognition.



improvement was observed—a result that rules out the implication of learning mechanisms.

Discussion

The voice gender recognition test that we used is part of the VPA test. It consists of a speaker discrimination task between sounds on a voice continuum obtained by morphing between a male and a female voice. This test allowed us to reveal a clear deficit of CI recipients in voice gender categorization, independent of the duration of CI experience. The test is highly sensitive; therefore, can be used to evaluate pitch- and timbre-related paralinguistic aspects of auditory recovery in CI subjects.

Voice Processing in CI Recipients

Cochlear implantation reactivates the auditory system of subjects who are profoundly deaf by electrical stimulation through the implantation of 12–22 electrodes into the cochlea. Despite the fact that such a device provides relatively poor-quality spectral information (Shannon, Zeng, Kamath, Wygonski, & Ekelid, 1995), CI recipients benefit from an excellent recovery of speech recognition performance (UK Cochlear Implant Study Group, 2004), although performance remains below that of subjects with normal hearing. Further paralinguistic aspects of speech perception, especially those concerning the processing of voice and voice features, remain deficient. Indeed, voice gender identification is known to be impaired in CI recipients (Fu et al., 2004, 2005; Kovacic & Balaban, 2009). However, in such tasks at a population level, the deficit of CI subjects appears to be satisfactory—usually 70%–90% correct identification, according to the study and the type of test. Such performance levels are not considerably lower than those for speech recognition, which typically reach about 80% correct (i.e., for disyllabic words in experienced CI recipients; Rouger et al., 2007). However, CI subjects present a large amount of variability in voice gender identification that is related to their hearing history (Kovacic & Balaban, 2010). Here, using a continuum of morphed voices, we were able to show that the deficit in CI subjects' gender discrimination is much more substantial than previously shown when compared with subjects with normal hearing. The VPA allowed us to assess the subjects' performance using male and female voices with varying pitch and formant characteristics. In such a test, categorization scores within the continuum, expressed by the slope of the psychometric function, were more than 50% lower than those observed in subjects with normal hearing, even after a long period of CI experience. In addition, such a deficit remained nearly constant, independent of the duration of CI use, considering the fact that performance for new and experienced users did not differ significantly.

These results should be compared with our previous analysis of voice–nonvoice discrimination in CI subjects (Massida et al., 2011). In agreement with previous work (Proops et al., 1999; Tye-Murray, Tyler, Woodworth, & Gantz, 1992), we showed that CI subjects' performance was highly impaired when discriminating environmental sounds from voice stimuli. As in the present results for gender categorization, the performance level of experienced CI subjects in voice discrimination was weak—more than 63% lower than that observed in control subjects. Again, the ability of CI subjects to perform such a voice–nonvoice discrimination task did not improve with the delay post-implantation. In a similar way, the other features that can be extracted from a human voice—such as talker identity, emotion, and familiarity—were also only weakly recognized by CI recipients (Cleary et al., 2005; Fu et al., 2004; Vongphoe & Zeng, 2005). In contrast, some CI subjects have developed specific auditory strategies to recognize some aspects of paralinguistic information, such as speech prosody. Although voice pitch stands as the main acoustic cue to perceive this category of stimuli, some CI listeners may also rely on intensity properties to perceive speech prosody. For instance, intensity variation may contribute to their auditory analysis when CI subjects have to distinguish a question from a statement (Peng, Lu, & Chatterjee, 2009). Further, integration of auditory and visual information (eyebrows movements, head nods) might assist in speech and affective prosody (Foxton, Riviere, & Barone, 2010; Munhall, Jones, Callan, Kuratate, & Vatikiotis-Bateson, 2004).

In conclusion—and aside from the possibility that CI subjects may develop adaptive strategies to increase discrimination of voice cues (see Li & Fu, 2011), including the use of other sensory modalities (Barone & Deguine, 2011)—most of the auditory processes that are required for voice perception (Belin, Fecteau, & Bedard, 2004) are severely impaired in CI recipients. This impairment very likely is a consequence of the relatively crude auditory information delivered by the CI.

Voice Gender Discrimination in CI Recipients

Voice gender recognition relies on several acoustic cues, including F0 and formant structure, both of which differ largely between male and female voices (Klatt & Klatt, 1990). Consequently, gender discrimination can be considered as a pitch-related task, consisting of the temporal pitch corresponding to F0 and the spectral pitch corresponding to the position of formants; both work in the same sense (i.e., lower for male voice, higher for female voice). However, the signal processing necessary for the CI removes fine-structure information that typically supports temporal pitch extraction, and the limited number of implanted electrodes constitutes a major limitation on the performance of CI subjects for spectral pitch perception. Indeed, in using complex sounds with different F0s, CI subjects present much higher thresholds in pitch discrimination than do subjects with normal hearing (Cousineau, Demany, Meyer, & Pressnitzer, 2011; Laneau, Wouters, & Moonen, 2006; Rogers, Healy, & Montgomery, 2006; Vandali et al., 2005; Zeng, 2002). Even for the frequency range for which they present the lowest threshold, CI subjects cannot achieve difference limens lower than 5%–10% of F0 (Geurts & Wouters, 2001). Such results are compatible with the results obtained in the present study when considering gender discrimination performance for unambiguous male or female voices at the extremes of the continuum. CI subjects obtained, on average, 90% correct, depending on the duration of CI experience, which is compatible with the F0 distance that separated the most distant male and female voices (126 Hz vs. 212 Hz).

However, the performance scores of CI subjects decreased when the voice became more ambiguous—that is, after reducing the differences in both pitch and formant structure. When approaching the androgynous voice, subjects' responses became more variable, leading to the psychometric function having a slope value that was much lower than that for the controls (subjects with normal hearing). Kovacic and Balaban (2009) used a different method, involving an adaptive procedure to evaluate voice gender perception as a function of voice F0 differences. In a sample of 20 individual talkers from each gender, some F0 values were contained in an overlapping frequency range (between 138 Hz and 163 Hz) that closely matched the central region of our continuum. Recognition scores for these voices were significantly affected, dropping to chance level even in good CI performers. Thus, F0 is undoubtedly a prominent cue in voice gender identification, but other individual acoustic characteristics also play a role.

Indeed, both spectral and temporal cues are involved in gender discrimination, especially when the F0 distance is reduced, as shown by the performance of subjects with normal hearing stimulated with a processor that simulates a CI processor (Fu et al., 2004, 2005; Gonzalez & Oliver, 2005). Correct gender discrimination scores among subjects ranged from 75% to 95%, which was similar to those of subjects with normal hearing listening to between four and eight spectral channels. In subjects with normal hearing who were listening to vocoded stimuli, speech detection and gender recognition improved as the number of spectral channels increased. Speech detection significantly improved when spectral channels increased from four to eight. In particular, voice gender recognition improvement was more observed for the switch from eight to 16 spectral channels. Concerning the manipulation of the temporal information in each spectral condition, speech detection was not influenced by envelope filters: Performance remained stable when envelope cutoff frequency was increased from 40 Hz to 80 Hz, to a maximum of 320 Hz. In contrast, gender recognition performance scores were significantly more accurate for higher envelope cutoff frequencies; this finding suggests that providing more temporal cues to CI subjects enhances their perception of voice features. However, listeners use timbre perception, formants structure, and temporal modulation–processing abilities to obtain relevant cues regarding voice gender, especially when there is a small F0 difference, as in our morphed voice in the middle part of the continuum. For large F0 differences, reducing temporal cues did not alter voice gender discrimination, even when stimuli were degraded through a 16-channel processor (Fu et al., 2005).

Although our results showed that CI subjects displayed a strong deficit in gender categorization (see also Kovacic & Balaban, 2009), their performance was above chance level once the stimulus progressively moved away from the androgynous voice on the continuum. This finding implies that the CI subjects had developed adaptive strategies to compensate for the low spectral resolution provided by the CI. Our preliminary results in a pitch- and timbre-covarying condition indicate that although perception of pitch is poor in CI users, pitch remains the main feature for voice gender discrimination (Massida, 2010). Timbre manipulations did not affect gender recognition. More work is needed to understand how pitch cues are used by CI subjects in pitch-related tasks, from paralinguistic to musical domains.

To our knowledge, the impact of device experience on voice perception has never been specifically studied, although researchers have shown that several factors of a subject's hearing history are important, such as age onset of deafness as well as age of implantation (Kovacic & Balaban, 2010). Such results were observed both in the transversal group and in the follow-up group, in which individual subjects were tested regularly for more than 18 months. Both gender categorization and gender recognition tended to improve, but these trends did not reach statistical significance. These results suggest that in spite of a strong adaptation to the relatively poor information delivered by the implant, CI recipients have not been able to develop specific strategies—including more effective use of either temporal cues or spectral cues—to categorize voices that are less typically male or female.

Gender Discrimination and Speech Recognition in CI Recipients

Our results showed a clear dissociation between the recovery of speech recognition and the capacity of CI subjects to discriminate voice gender. Although functional speech recognition is acquired during the first year post-implantation, gender discrimination remains very poor, even after several years of CI experience. Similar results were observed for voice–nonvoice recognition (Massida et al., 2011). However, although a dissociation between speech recognition and perception of paralinguistic features is usually shown in subjects with CIs (Dorman, Gifford, Spahr, & McKarns, 2008; Vongphoe & Zeng, 2005), some researchers have observed a correlation between phoneme perception and gender discrimination in CI recipients. Significant positive correlations were found for phoneme recognition in noise and voice gender recognition scores when intergender voice F0 was < 50 Hz (Li & Fu, 2011). Aside from the functional spectral resolution in CI users, this finding highlights the prominent role of temporal modulation detection in the 150–200 Hz range and would also be supported by individual differences in high-level central processes (Li & Fu, 2011).

Conclusion

The VPA is an original protocol that allows precise evaluation of the ability of CI recipients to discriminate, in particular, voice gender across a frequency range that covers most of the continuum between a typical male and female voice. The CI recipients' performance on the VPA revealed a strong impairment in the discrimination of more ambiguous voices, whereas the recognition of typical male and female voices approached that of the subjects with normal hearing. Such impairment is permanent and does not disappear after several months or years of experience with the implant. The deficit found for CI subjects reflects the degradation of both spectral and temporal cues by CI sound coders, in agreement with the weak ability of CI users to perform pitch discrimination. Further, our results are complementary to previous work that showed a durable impairment in CI users in processing features of voice, from voice discrimination to perception of gender, familiarity, and emotional content. Apart from a deficit due to the limitations of the implant processor, functional integrity of the cortical areas devoted to voice processing (Belin et al., 2004) is probably affected by the duration of auditory deprivation (Rouger et al., 2012).

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