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Neurophysiological evidence of impaired musical sound perception in cochlear-implant users

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A B S T R A C T

Objective: Music perception with a cochlear implant (CI) can be unsatisfactory because current-day implants are primarily designed to enable speech discrimination. The present study aimed at evaluating electrophysiological correlates of musical sound perception in CI users to help achieve the long-term goal of improved restoration of hearing in those individuals.

Methods: Auditory discrimination accuracy in adult CI users ($n = 12$) and matched normal-hearing controls ($n = 12$) was measured by behavioral discrimination tasks and mismatch negativity (MMN) recordings. Discrimination profiles were obtained by using a set of clarinet sounds (original/vocoded) varying along different acoustic dimensions (frequency/intensity/duration) and deviation magnitudes (four levels).

Results: Behavioral results and MMN recordings revealed reduced auditory discrimination accuracy in CI users. An inverse relationship was found between MMN amplitudes and duration of profound deafness.

Conclusions: CI users have difficulties in discriminating small changes in the acoustic properties of musical sounds. The recently developed multi-feature MMN paradigm (Pakarinen et al., 2007) can be used to objectively evaluate discrimination abilities of CI users for musical sounds.

Significance: Measuring auditory discrimination functions by means of a multi-feature MMN paradigm could be of substantial clinical value by providing a comprehensive profile of the extent of restored hearing in CI users.

1. Introduction

Cochlear implants (CI) enable hearing in deaf individuals suffering from sensorineural hearing loss. These bionic devices transform the acoustic signal into electric pulses and stimulate directly the residual fibers of the auditory nerve. Although electrical hearing is highly unnatural and impoverished, CI users can learn to recognize meaningful sounds (Krueger et al., 2008), and some even reach nearly unrestricted conversation skills (Anderson et al., 2006). However, most CI users report difficulties in music perception, even after many years of implant usage (Gfeller et al., 2000; McDermott, 2004; Veekmans et al., 2009). Beyond the beneficial effects on cognitive and emotional functions (Jancke, 2008; Sarkamo et al., 2008), good music perception is highly desirable in view of its social significance, and would considerably improve quality of life in CI users (Drennan and Rubinstein, 2008). To foster this goal, the present study investigated the neural and behavioral correlates of musical sound perception in adult CI users and normal-hearing (NH) individuals.

CIs are designed to transmit acoustic cues critical for speech discrimination. They preserve the temporal envelopes fairly well (Drennan and Rubinstein, 2008), but key structural features of music such as high spectral resolution and temporal fine-structure information are compromised (Gfeller et al., 2005). Since resolving multiple harmonics of complex sounds is important for the perception of pitch and timbre (Drennan and Rubinstein, 2008), CI users have difficulties in melody, timbre and pitch discrimination tasks (for reviews, see McDermott, 2004; Zeng, 2004). Similar difficulties

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have also been reported for NH listeners presented with implant simulations of musical sounds (Cooper et al., 2008), suggesting that degraded acoustic signals may not provide sufficient information for satisfactory music and tone perception with CI (Gfeller et al., 2005; Moore and Shannon, 2009). However, there is a remarkable variance across CI users with regard to speech and music perception ability (Gfeller et al., 2002a; Krueger et al., 2008). Therefore, other factors may greatly influence music perception as well, among them auditory memory or musical experience prior to and during deafness (Gfeller et al., 2000, 2005). This latter aspect points to the importance of auditory cortex plasticity, because the central auditory system's key function may be to efficiently obtain meaning from the CI signal (Moore and Shannon, 2009). After implantation, CI users need time to adapt to the artificial, electrical input, as it is evidenced by improved clinical performance (Krueger et al., 2008; Oh et al., 2003; Pantev et al., 2006) and increased auditory cortex activity with prolonged CI usage (Pantev et al., 2006; Suarez et al., 1999). Moreover, musical training can improve the recognition and appraisal of musical sounds (Gfeller et al., 2002b). Accordingly, the highly variable outcome of the CI procedure may be at least partly the result of individual auditory system differences to fully utilize the information provided by the implant (Friesen et al., 2001; Moore and Shannon, 2009). To substantiate this hypothesis, it is important to better understand how the auditory cortex of CI users processes acoustic signals in general, and how CI users process musical sounds in particular.

Auditory processing in CI users can be objectively evaluated by means of auditory event-related potentials (AEP) (Debener et al., 2008; Lonka et al., 2004; Pantev et al., 2006; Ponton et al., 1996; Sandmann et al., 2009; Sharma et al., 2002). The mismatch negativity (MMN) is an AEP component elicited by infrequent auditory stimuli deviating in some physical or higher-order feature from a regular standard sound (Naatanen et al., 1978, 1990, 2001). MMN signals the detection of this deviation and may thus, according to the current theoretical frameworks (Baldeweg, 2006; Winkler, 2007), indicate the violation of a predictive regularity extracted from the preceding sequence of standard stimuli. For the present study, it is important that the MMN reflects the output of a change-detection process in the auditory system and thus provides an objective index of auditory discrimination accuracy. Because it is sensitive to small, nearly indiscriminable acoustic changes and it is largely independent of attention, the MMN is a useful tool for the diagnostic assessment of central auditory-cortex functions (Naatanen et al., 2007; Sussman, 2007). Several MMN studies on CI users exist (Groenen et al., 1996; Kelly et al., 2005; Kraus et al., 1993; Lonka et al., 2004; Roman et al., 2005a) and they have shown increased MMN amplitudes for increasing magnitude of frequency deviations, suggesting that CI users can encode different deviation magnitudes of acoustic differences (Kelly et al., 2005; Titterington et al., 2003). However, only one previous MMN study has evaluated music perception in CI users by means of chord sequences, reporting smaller timbre-evoked MMN responses in CI users compared to NH listeners (Koelsch et al., 2004). In order to better explore impaired musical sound perception with CI, the present study investigated whether CI users show magnitude-of-deviation effects in different acoustic dimensions. We employed a variation of a recently developed multi-feature MMN paradigm (Naatanen et al. 2004; Pakarinen et al., 2007) which enabled us to systematically evaluate discrimination accuracy for different types of changes in harmonic tones (frequency, intensity and duration) and different deviation magnitudes (four levels). Given the large set of stimuli and the careful control of acoustic stimulus properties, the study allowed the thorough examination of electrophysiological correlates of musical sound perception in CI users. Thus, the study should be considered a fundamental step towards the understanding of neurophysiological mechanisms of musical sound perception with CI.

2. Methods

2.1. Participants

Twenty-four adult volunteers (12 females, 12 males) participated in the present study. All participants were consistent right-handers (Annett, 1970) and had no history of neurological or psychiatric illness. Twelve of the participants were CI users, four of them were implanted bilaterally, and eight of them were implanted unilaterally (Table 1). All CI users were post-lingually deafened adults. Among the unilaterally implanted CI users, six individuals were implanted in the right ear and two in the left ear. All implantees used a Nucleus CI system with a Freedom processor (Patrick et al., 2006), and they had been using their cochlear implants continuously for at least 12 months prior to the experiment. There was a considerable age variance across the participants (mean age 55, range 38–70, standard deviation 9.8 years). Therefore, each CI user was matched with a NH listener for sex and age who served as control and had normal hearing, as defined by less than 20 dB hearing loss in the tested ear (500–4000 Hz). A music questionnaire on listening habits and musical education in

Table 1
Subject demographics of the CI group.

Subject	Gender	Age	Implanted	Stimulated ear	Aetiology	Age at onset of profound deafness (years)	Duration of deafness (years)	Cochlear implant use (months)	Second cochlear implant use (months)	Freiburg monosyllabic words test in quiet (%)	Oldenburg sentences in noise test (dB)
1	Male	56	Unilaterally	Right	Progressive	52	1	46*	–	100	2.1
2	Female	60	Bilaterally	Left and right	Congenital	51	1	85*	79*	Left: 70, right: 75	Left: −9, right: −6.7
3	Female	52	Bilaterally	Right	Progressive	36	15	14*	195	100	−4.7
4	Female	47	Unilaterally	Left	Progressive	42	2	50*	–	75	Not measurable
5	Male	70	Unilaterally	Right	Progressive	64	1	67*	–	90	−2.3
6	Female	55	Bilaterally	Left and right	Congenital	42	7	156*	40*	Left: 100, right: 75	Left: −4.5, right: −2.5
7	Male	69	Unilaterally	Left	Progressive	55	2	102*	–	80	−0.2
8	Male	65	Bilaterally	Left	Sudden deafness	31	13	38*	240	60	5
9	Male	52	Unilaterally	Right	Progressive	44	1	54*	–	85	−10.5
10	Male	42	Unilaterally	Right	Meningitis	37	4	12*	–	75	−4.3
11	Female	38	Unilaterally	Right	Progressive	37	1	12*	–	100	−8
12	Female	58	Unilaterally	Right	Progressive	56	1	18*	–	90	−7

The asterisk indicates that the corresponding CI was stimulated in the present study.