Hearing Research 315 (2014) 61–66

Contents lists available at ScienceDirect

Hearing Research

journal homepage: www.elsevier.com/locate/heares

Research paper

Behavioral frequency discrimination ability of partially deafened cats using cochlear implants

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ARTICLE INFO

Article history:
Received 24 January 2014
Received in revised form
15 June 2014
Accepted 24 June 2014
Available online 5 July 2014

ABSTRACT

The aim of this study was to determine the effects of cochlear implant (CI) use on behavioral frequency discrimination ability in partially deafened cats. We hypothesized that the additional information provided by the CI would allow subjects to perform better on a frequency discrimination task.

Four cats with a high frequency hearing loss induced by ototoxic drugs were first trained on a go/no-go, positive reinforcement, frequency discrimination task and reached asymptotic performance (measured by d' − detection theory). Reference frequencies (1, 4, and 7 kHz) were systematically rotated (Block design) every 9–11 days to cover the hearing range of the cats while avoiding bias arising from the order of testing. Animals were then implanted with an intracochlear electrode array connected to a CI and speech processor. They then underwent 6 months of continuous performance measurement with the CI turned on, except for one month when the stimulator was turned off.

Overall, subjects performed the frequency discrimination task significantly better with their CI turned on than in the CI-off condition (3-way ANOVA, $p < 0.001$). The analysis showed no dependence on subject (3-way ANOVA, subject × on-off condition, $p > 0.5$); however, the CI only significantly improved performance for two (1 and 7 kHz) of the three reference frequencies.

In this study we were able to show, for the first time, that cats can utilize information provided by a CI in performing a behavioral frequency discrimination task.

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1. Introduction

Profound sensorineural hearing loss is successfully treated by intracochlear electrical stimulation (ICES) of the auditory nerve via a cochlear implant (CI). Improvement in the speech perception ability of cochlear implantees over the post-implantation period has been shown in various clinical studies (Blamey et al., 2012, 1996a, e.g., Wilson and Dorman, 2008). Initial perceptual quality and rate of improvement over time largely depend on the amount of pre-implantation hearing experience and auditory training.

As selection criteria for CI recipients have eased, more patients with preserved low frequency hearing have received CIs (for review see Turner et al., 2008). Several clinical studies report improvement of overall hearing performance of subjects with residual hearing in one ear (possibly with a hearing aid) in addition to ICES in the other, sometimes referred to as bimodal hearing (Von Ilberg et al., 2011; Mok et al., 2006; Firszt et al., 2008; Ching et al., 2006). For example, Dorman et al. (2007) showed an increase of 20% in performance of patients with CI in one ear and a hearing aid in another on word and sentence recognition tasks when electric stimulation was added (EAS). Other studies report very little or no bimodal benefit (Mok et al., 2006; Tyler et al., 2002). The latter findings might be at least partially explained by the finding that pitch percepts evoked by ICES can correspond to tones up to 3 octaves lower than those predicted from the place of stimulation (Blamey et al., 1996b). The mechanisms that underlie auditory perception in response to combined electric and acoustic stimulation (EAS) remain unclear. Although the residual hearing of partially deaf subjects is usually in the low frequency region, whereas the CI

Abbreviations: ICES, intracochlear electrical stimulation; CI, cochlear implant; EAS, electric and acoustic stimulation; FA, false alarm; CR, correct rejection; Δf/f, ratio between frequency difference and reference frequency; SPL, sound pressure level; d', d-prime

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http://dx.doi.org/10.1016/j.heares.2014.06.005
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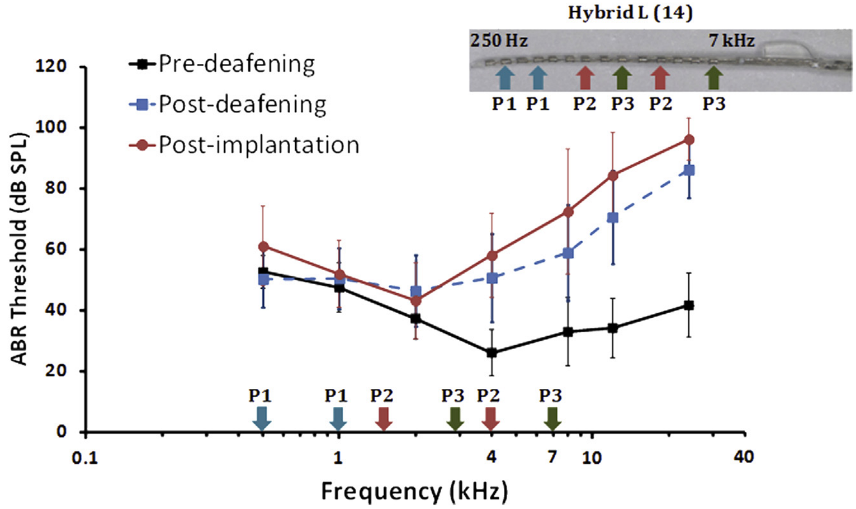

Fig. 1. ABR audiograms of cat C5 before and after bilateral deafening. Values are means ($n = 8$) of thresholds for monaural stimulation of the left and right ears, and error bars represent standard deviation. The inset represents unilateral electrode array placement relative to the characteristic frequencies of the electrode locations in the cochlea. P1, P2, and P3 represent the different pairs' frequencies and electrodes activated during the psychophysical experiment.

usually stimulates the high-frequency region, the degree of overlap between the regions is variable and significant overlap in this region could cause electric and acoustic perception interference.

Frequency discrimination ability is a factor in determining how well human subjects can recognize pitch, and separate auditory streams, which in turn affects speech recognition ability (Rose and Moore, 2005). To study the effects of interactions between electric and acoustic stimulation on frequency discrimination, we developed a novel behavioral task (Benovitski et al., 2014) to test frequency discrimination in the partially deaf cat model. We have previously shown that using this task, cats can learn a frequency discrimination task and demonstrate stable and repeatable performance (Benovitski et al., 2014). The use of a partial hearing, chronically stimulated animal model allows us to determine performance changes on a behavioral frequency discrimination task by adding and removing ICES in the same animal. While other studies have used conditioning to provide animals with behaviorally relevant auditory experience (Kral et al., 2006; Klinke et al., 1999), these studies did not allow performance to be measured. Others have used avoidance conditioning to train cats to detect stimulation thresholds (Vollmer et al., 2001; Beitel et al., 2000; Vollmer and Beitel, 2011) and discriminate changes in modulation frequency (Vollmer et al., 2001). In those experiments individual electrodes were tested one at a time and subjects received only electric but not acoustic stimulation.

The aim of this experiment was to determine whether CI use affects the ability of partially deaf animals to perform a frequency discrimination task. We hypothesized that additional information provided by the CI would allow partially deafened animals to perform better on a frequency discrimination task. To our knowledge, this is the first study to test frequency discrimination in partially hearing animals implanted with a CI.

2. Method

2.1. Subjects

Four healthy cats with otoscopically normal tympanic membranes were used in the present study. All procedures were in accordance with Australian Code of Practice for the Care and Use of Animals for Scientific Purposes and with the guidelines laid down by the National Institutes of Health in the US regarding the care and use of animals for experimental procedures, and were approved by the Royal Victorian Eye and Ear Hospital Animal Research and Ethics Committee. Subjects were partially deafened between 7.4 and 8.3 months of age by daily subcutaneous injections of Kanamycin (200 mg/kg; kanamycin monosulphate, Sigma, USA). After 17 days, hearing condition was checked via tone-specific auditory brain response (ABR) recordings (Coco et al., 2007) and injections continued until a partial high frequency hearing loss was achieved to model an EAS CI recipient (Irving et al., 2014). High frequency hearing loss (normal hearing up to 2 kHz, Fig. 1) was confirmed using a standard ABR. The difference in thresholds between two ears was not significant (4-way ANOVA, ear side × cat × pre/post CI × frequency, $p > 0.9$).

Subjects were implanted unilaterally (left side) with a Hybrid L 14-electrode intra-cochlear array between 13.3 and 14.4 months of age. The tip of electrode array was approximately 10.5 mm from the round window, resulting in the most apical electrode being located at approximately the 4-kHz place as represented in Fig. 1 (for details about the Hybrid L array and implantation procedure see Shepherd et al., 2011).

Each subject was chronically stimulated using a clinical stimulator and speech processor (Cochlear Limited) carried in a harness worn by the animals which did not limit the animal's ability to move (Fallon et al., 2009). A standard stimulation strategy (SPEAK; Mcdermott, 1989) with a clinical electrode-frequency allocation map was used. The 14 electrodes from apex to base were allocated to the following frequencies 187, 312, 562, 812, 1062, 1312, 1562, 1937, 2312, 2812, 3437, 4187, 5187, 6312, and 7937 Hz. The stimulation rate was 500 pulses per second per electrode. During the stimulator-on phases of the behavioral task, the following electrode pairs were preferentially activated by the acoustic stimulus: electrodes 13 and 10 (pair 1), 8 and 4 (pair 2), 5 and 1 (pair 3). The frequency-place map was not optimized to match the characteristic frequencies of the electrode locations in the cochlea, thus overlap of electric and acoustic cochlear stimulation can be expected, as shown in Fig. 1. After the unilateral CI implantation, acoustic signals were not blocked from the implanted nor the contralateral ear meaning that cats were acoustically stimulated in both ears and electrically stimulated in one ear only resulting in a combination of hybrid-bimodal stimulation.

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