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Review

Binaural hearing with electrical stimulation

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ABSTRACT

Bilateral cochlear implantation is becoming a standard of care in many clinics. While much benefit has been shown through bilateral implantation, patients who have bilateral cochlear implants (CIs) still do not perform as well as normal hearing listeners in sound localization and understanding speech in noisy environments. This difference in performance can arise from a number of different factors, including the areas of hardware and engineering, surgical precision and pathology of the auditory system in deaf persons. While surgical precision and individual pathology are factors that are beyond careful control, improvements can be made in the areas of clinical practice and the engineering of binaural speech processors. These improvements should be grounded in a good understanding of the sensitivities of bilateral CI patients to the acoustic binaural cues that are important to normal hearing listeners for sound localization and speech in noise understanding. To this end, we review the current state-of-the-art in the understanding of the sensitivities of bilateral CI patients to binaural cues in electric hearing, and highlight the important issues and challenges as they relate to clinical practice and the development of new binaural processing strategies.

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1. Introduction

The trend for bilateral implantation of cochlear implants (CIs) is growing. As of 2010, it is estimated that 5% of CI patients worldwide are bilateral (Peters et al., 2010). One of the motivations for bilateral implantation has been to restore spatial hearing abilities, which include segregation of speech from background noise or competing sounds, and improved sound localization ability. In normal hearing (NH) people, sound localization abilities in the horizontal plane depend primarily on acoustic cues arising from differences in arrival time and level of stimuli at the two ears. Localization of unmodulated signals up to approximately 1500 Hz is known to depend on the interaural time difference (ITD) arising from disparities in the fine-structure of the waveform. The prominent cue for localization of high-frequency signals is the inter-aural level difference (ILD) cue (Blauert, 1997). However, it has also been well established that, for higher frequency signals, ITD information can be transmitted by imposing a slow modulation, or envelope, on the carrier (Bernstein, 2001). The use of modulated signals with high-frequency carriers is particularly relevant to stimulus coding by CI processors that utilize envelope cues and relatively high stimulation rates (Seligman et al., 1984; Skinner et al., 1994; Vandali et al., 2000; Wilson and Dorman, 2007; Wilson et al., 1991). The studies reviewed in this paper have deliberately manipulated these cues to various extents, in an effort to understand whether bilateral CI users are sensitive to the cues that NH listeners rely on and use almost effortlessly.

When tested in the sound field, CI users using two implants have demonstrated improved sound localization ability compared to using one (e.g., see: Litovsky et al., 2009, 2004; Tyler et al., 2007; Van Hoesel and Tyler, 2003); however, they still do not perform as well as NH listeners, even after many years of experience (Chang et al., 2010; Kerber and Seeber, 2012; Litovsky, 2011a,b; Loizou et al., 2009). Factors limiting performance in bilateral CI users fall into numerous categories and include those in the areas of hardware and engineering, surgical precision, and pathology of the auditory system in deaf persons. While other factors, such as the speech processing strategies used, and microphone characteristics, are also thought to be important, these will not be discussed here.

1.1. Hardware- and software-based limitations

Bilateral CI users are essentially fit with two separate monaural systems. Speech processing strategies in clinical processors utilize

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pulsatile, non-simultaneous multi-channel stimulation, whereby a bank of bandpass filters is used to filter the incoming signal into a number of frequency bands (ranging from 12 to 22), and sends specific frequency ranges to individual electrodes. The envelope of the signal is extracted from the output of each band and is used to set stimulation levels for each frequency band, thus fine-structure is discarded. Although ITDs in the envelopes may be present, because the processors have independent sampling clocks, the ITD can vary dynamically and unreliably (Litovsky et al., 2012; Van Hoesel, 2004). In addition, the microphones are not placed in the ear in a manner that maximizes the capture of directional cues such as spectrum and level cues. Microphone characteristics, independent automatic gain control and compressions settings distort the monaural and interaural level directional cues that would otherwise be present in the horizontal plane.

1.2. Surgical-based limitations

The anatomical positioning of the electrode array in the cochlea is such that the most apical placement is typically near the place of stimulation on the basilar membrane with best frequencies of 1000 Hz or higher (e.g., Stakhovskaya et al., 2007). Furthermore, surgical insertion of the electrode array is not precise enough to guarantee that the electrode arrays in the two ears are physically matched for insertion depth. This is likely to cause imprecise matching of inputs at the two ears because current clinical programming is likely to deliver stimuli bearing different frequency ranges to electrodes that are anatomically placed at comparable places in the two cochleae (Kan et al., 2013). Bilateral fitting strategies have been suggested and recent developments have shown promising results for improving ILD discrimination ability (Parkinson and Smith, 2013).

1.3. Limitations due to pathology in the auditory system

There is likely to be both a peripheral and central degeneration due to lack of stimulation (Shepherd and McCreery, 2006). At fairly peripheral levels in the auditory system there is known to be degradation in size and function of neural ganglion cells following a prolonged period of auditory deprivation (Leake et al., 1999). Profound deafness in the early developmental period seems to result in loss of normal tonotopic organization of the primary auditory cortex, although there is some reversal following reactivation of afferent input (e.g., Kral et al., 2009). We are interested in this potential reactivation and possible regaining of perceptual sensitivity to sensory input. While plasticity of sensory systems is most pronounced during infancy, when the establishment of neural architecture first occurs, plasticity is known to continue into adulthood such that neural systems remain capable of undergoing substantial reorganization in response to altered inputs due to trauma or an adaptive byproduct known as perceptual learning (see Irvine and Wright, 2005 for review).

Ideally, binaural speech processors that provide bilateral CI users with similar cues used by NH listeners would be available; however such devices do not exist in forms other than research platforms. Development of such devices would depend on knowledge about the extent to which bilateral CI users are sensitive to, and able to utilize, binaural cues. In order to examine these issues in more detail, a growing number of studies have been performed using bilaterally-synchronized research devices allowing precise stimulus control at the electrode level, in order to understand the potential and limitations of electrical stimulation for restoring binaural hearing in CI patients. In this article, we will review this literature and the potential clinical applications of this research. A thorough understanding of the sensitivities of bilateral CI users to different acoustic cues that can be presented through electrical stimulation will help inform the engineering of binaural CI speech processors and focus development efforts on the aspects of the acoustic signals that will be important to preserve in the conversion between acoustic and electric signals. In this paper, we will first review the body of work that has been conducted to investigate the binaural sensitivities of bilateral CI users at a single electrode pair level, followed by more recent work where multiple electrode pairs are stimulated together, which is closer to real-world listening. We will also discuss some general implications of these results and highlight their significance on future engineering efforts.

2. Single electrode stimulation

The modern multi-channel cochlear implant was designed to take advantage of the tonotopic organization of the cochlea in order to present stimuli from broadband sound sources with some degree of spectral resolution. Electrode arrays inserted into the cochlea have a number of electrode contacts (typically 12–22) designed to stimulate the auditory nerves in a limited region of the cochlea, and thereby allowing for different pitches to be perceived. When studies involve binaural stimulation, there has to be an understanding as to how stimulation in the two ears is combined.

Much of the earliest work was undertaken to determine whether electrical stimulation at the two ears would be combined into a single fused auditory percept, and how this percept could be altered by varying the interaural time, amplitude and place of stimulation. The ability to fuse the electrical stimulation at the two ears into a single auditory percept is particularly important for studying binaural sensitivity, because non-fusion indicates an inability to combine interaural information which may lead to an inability to compare interaural disparities such as ITDs and ILDs. Studies have been typically conducted using synchronized research processors that allow direct stimulation of single interaural electrode pairs with electrical stimuli that had precise ITDs and ILDs. Some of the earliest studies (Lawson et al., 1998; Van Hoesel et al., 1993; Van Hoesel and Clark, 1997) demonstrated that electrical stimulation at the two ears could be fused into a single percept, and that the auditory image could be lateralized with changes in interaural amplitude. However, the ability to use ITDs for lateralization was typically much poorer and heavily dependent on the place of stimulation in each ear.

2.1. Interaural place matching

The early work highlighted the importance of carefully selecting the electrode stimulated in each ear for maximizing ITD sensitivity. This is largely because neural survival and the interaural insertion depths of electrodes may differ across the ears. The difference in interaural insertion depth would lead to differences in the anatomical place of stimulation in each ear for electrodes of the same number. A schematic of the type of interaural place of stimulation mismatch is illustrated in Fig. 1. If we consider the tonotopic organization of the cochlea and models of binaural sound localization, which assume ITDs are interaurally compared at each frequency (e.g., Colburn, 1977; Jeffress, 1948), a mismatch in the interaural place of stimulation will cause a mismatch in the frequencies being compared by the brain, likely leading to a decrease in ITD sensitivity. Prior work (Van Hoesel et al., 1993; Van Hoesel and Tyler, 2003; Van Hoesel, 2008) has shown that when studying ITD sensitivity, selecting interaurally pitch-matched electrodes typically yields the smallest ITD just noticeable differences (JNDs). However, when the stimulating electrodes on one side was held constant and the stimulating