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Research paper

Modulation frequency discrimination with single and multiple channels in cochlear implant users

John J. Galvin III [a, b, c, d, *], Sandy Oba [a, b], Deniz Başkent [c, d], Qian-Jie Fu [a, b]

[a] Division of Communication and Auditory Neuroscience, House Research Institute, Los Angeles, CA, USA
[b] Department of Head and Neck Surgery, David Geffen School of Medicine, UCLA, Los Angeles, CA, USA
[c] Department of Otorhinolaryngology, Head and Neck Surgery, University Medical Center Groningen, University of Groningen, Groningen, The Netherlands
[d] Research School of Behavioral and Cognitive Neurosciences, Graduate School of Medical Sciences, University of Groningen, Groningen, The Netherlands

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A B S T R A C T

Temporal envelope cues convey important speech information for cochlear implant (CI) users. Many studies have explored CI users' single-channel temporal envelope processing. However, in clinical CI speech processors, temporal envelope information is processed by multiple channels. Previous studies have shown that amplitude modulation frequency discrimination (AMFD) thresholds are better when temporal envelopes are delivered to multiple rather than single channels. In clinical fitting, current levels on single channels must often be reduced to accommodate multi-channel loudness summation. As such, it is unclear whether the multi-channel advantage in AMFD observed in previous studies was due to coherent envelope information distributed across the cochlea or to greater loudness associated with multi-channel stimulation. In this study, single- and multi-channel AMFD thresholds were measured in CI users. Multi-channel component electrodes were either widely or narrowly spaced to vary the degree of overlap between neural populations. The reference amplitude modulation (AM) frequency was 100 Hz, and coherent modulation was applied to all channels. In Experiment 1, single- and multi-channel AMFD thresholds were measured at similar loudness. In this case, current levels on component channels were higher for single-than for multi-channel AM stimuli, and the modulation depth was approximately 100% of the perceptual dynamic range (i.e., between threshold and maximum acceptable loudness). Results showed no significant difference in AMFD thresholds between similarly loud single- and multi-channel modulated stimuli. In Experiment 2, single- and multi-channel AMFD thresholds were compared at substantially different loudness. In this case, current levels on component channels were the same for single- and multi-channel stimuli ("summation-adjusted" current levels) and the same range of modulation (in dB) was applied to the component channels for both single- and multi-channel testing. With the summation-adjusted current levels, loudness was lower with single than with multiple channels and the AM depth resulted in substantial stimulation below single-channel audibility, thereby reducing the perceptual range of AM. Results showed that AMFD thresholds were significantly better with multiple channels than with any of the single component channels. There was no significant effect of the distribution of electrodes on multi-channel AMFD thresholds. The results suggest that increased loudness due to multi-channel summation may contribute to the multi-channel advantage in AMFD, and that overall loudness may matter more than the distribution of envelope information in the cochlea.

1. Introduction

In cochlear implants (CIs), low-frequency temporal envelope cues (<20 Hz) are important for speech understanding, while higher frequency envelope cues (80–300 Hz) are important for perception of voice pitch. Given the limited spectral resolution of the device, CI users strongly rely on temporal envelope cues for pitch-mediated speech tasks such as voice gender perception (Fu

Abbreviations: CI, cochlear implant; MDT, modulation detection threshold; F0, fundamental frequency; AM, amplitude modulation; AMFD, amplitude modulation frequency discrimination; DR, dynamic range; MDI, modulation detection interference

* Corresponding author. Department of Head and Neck Surgery, David Geffen School of Medicine, UCLA, 10833 Le Conte Avenue, 62-132 CHS, Los Angeles, CA 90095-1624, USA.
E-mail address: Jgalvin@ucla.edu (J.J. Galvin).

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et al., 2004, 2005; Fuller et al., 2014), vocal emotion recognition (Luo et al., 2007), tonal language perception (Luo et al., 2008), and speech prosody perception (Chatterjee and Peng, 2008). Temporal processing in CIs has been widely studied in terms of single-channel modulation detection thresholds (MDTs; Shannon, 1992; Busby et al., 1993; Chatterjee and Oba, 2005; Galvin and Fu, 2005, 2009; Pfingst et al., 2007; Won et al., 2011; Fraser and McKay, 2012; Green et al., 2012). Modulation detection is one of the few single-channel psychophysical measures that have been significantly correlated with speech perception for CI users (Cazals et al., 1994; Fu, 2002) and recipients of auditory brainstem implants (Coletti and Shannon, 2005), underscoring the importance of temporal processing to speech perception. Modulation detection has also been significantly correlated with modulation frequency discrimination (Chatterjee and Ozerbut, 2011), which is typically measured using envelope depths well above MDTs. The perception of changes in modulation frequency is highly relevant for perception of pitch cues in speech (e.g., voice gender, vocal emotion, lexical tones, prosody, etc.). Modulation frequency discrimination has been correlated with CI users' perception of lexical tones (Chatterjee and Peng, 2008; Luo et al., 2008), which depend strongly on perception of voice fundamental frequency (F0).

Previous CI studies have measured various aspects of amplitude modulation frequency discrimination (AMFD). Many studies have shown that, given a fixed amplitude modulation (AM) depth, single-channel AMFD thresholds generally improve as the current level is increased (Morris and Pfingst, 2000; Luo et al., 2008; Chatterjee and Ozerbut, 2011; Green et al., 2012). Guerts and Wouters (2001) found better single-channel AMFD with a fixed modulation frequency difference as the modulation depth was increased. However, Chatterjee and Peng (2008) found no consistent effect for modulation depths between 5% and 30% of the reference amplitude on single-channel AMFD thresholds. Efforts to enhance temporal envelope cues have shown mixed results for AMFD. Green et al. (2004) showed a small but significant advantage for perception of modulated frequency sweeps across multiple channels when the temporal envelope was sharpened ("sawsharp" enhancement). However, subsequently, Green et al. (2005) found poorer vowel recognition with the enhancement relative to the standard continuously interleaved sampling (CIS; Wilson et al., 1991) signal processing strategy, possibly due to its effect on spectral envelope cues. Hamilton et al. (2007) found that presenting modified temporal information to only one of six stimulated channels (rather than all channels as in Green et al., 2005), offered no clear advantage in a variety of speech recognition tasks. Landsberger (2008) found no significant difference in single-channel AMFD thresholds between sine, sawtooth, and sharpened sawtooth temporal envelopes. Kreft et al. (2010) found no significant difference in single-channel AMFD thresholds for pulse trains that were amplitude modulated by sine waves or by rectified sine waves, the latter of which was proposed to more closely resemble normal neural responses to low-frequency pure tones. Chatterjee and Ozerbut (2011) found some evidence of modulation tuning for AMFD thresholds, with increased sensitivity near 100 Hz, above and below which AMFD thresholds increased. When presented at a similar loudness level (i.e., 75% of the dynamic range, or DR), Green et al. (2012) showed no significant effect of carrier pulse rate on single-channel AMFD thresholds, despite better envelope representation with high carrier rates. Taken together, these single-channel studies suggest that, AMFD is strongly affected by current level and modulation depth, with modulation depth interacting with current level.

Although clinical CI speech processors provide multi-channel stimulation, very few studies have directly measured AMFD using multiple channels. Multi-channel envelope processing has mostly been measured using modulation detection interference (MDI) paradigms, in which CI users are asked to detect AM or discriminate between AM frequencies presented to one channel in the presence of competing AM on the same channel or other channels. Chatterjee (2003) found substantial modulation masking (defined as the difference in MDT between a dynamic and steady-state masker) even when masker channels were spatially remote from the target channel. Chatterjee and Oba (2004) found greater MDI for modulation detection when the modulation frequency of the interferer was lower than that of the target. Kreft et al. (2013) found a similar effect of masker-target modulation frequency for AMFD thresholds. In these studies, there was substantial off-channel masking, possibly due to the broad current spread associated with electric stimulation, and possibly due to envelope interactions beyond the auditory periphery.

Intuitively, multi-channel stimulation would be expected to offer some advantage in perception of coherent envelope information, relative to single-channel stimulation. Indeed, Guerts and Wouters (2001) found better AMFD thresholds with multiple channels than with any of the single component channels used for the multi-channel stimuli. However, no explicit adjustment was made for multi-channel loudness summation in Guerts and Wouters (2001). Work by McKay and colleagues (McKay et al., 2001, 2003) showed substantial multi-channel loudness summation independent of electrode spacing. As such, the multi-channel stimuli in Guerts and Wouters (2001) might have been louder than the single-channel stimuli, contributing to the multi-channel advantage. Previous studies (Morris and Pfingst, 2000; Luo et al., 2008; Chatterjee and Ozerbut, 2011; Green et al., 2012) have shown that single-channel AMFD improves with level (and by association, loudness). Interestingly, Galvin et al. (2014) found that multi-channel MDTs were better than MDTs with any of the single component channels. However, when the current levels were reduced in the multi-channel AM stimuli to match the loudness of the single-channel AM stimuli, multi-channel MDTs were significantly poorer than single-channel MDTs. As modulation detection is level-dependent, the reduced current levels required to accommodate multi-channel loudness summation resulted in poorer MDTs. It is unclear how multi-channel loudness summation may affect AMFD, while understanding perceptual mechanisms that may underlie multi-channel temporal processing is crucial and clinically relevant as CI speech processors are fit to accommodate multi-channel loudness summation.

In this study, single- and multi-channel AMFD was measured in CI users. Component electrodes were distributed to target relatively overlapping (narrow configuration) and non-overlapping neural populations (wide configuration). We hypothesized that AMFD would be better with the wide configuration due to multiple, relatively independent envelope cues, In Experiment 1, single- and multi-channel AMFD thresholds were measured at similar loudness. In this case, current levels were higher for single-channel AM stimuli than for multi-channel AM stimuli, due to multi-channel loudness summation. We hypothesized that for similarly loud AM stimuli, AMFD would be poorer with multiple than with single channels due to the reduced current levels needed to accommodate multi-channel loudness summation, similar to the MDT findings data from Galvin et al. (2014). In Experiment 2, single- and multi-channel AMFD thresholds were measured using the same summation-adjusted current levels for component channels. In this case, multi-channel AM stimuli were louder than the single-channel AM stimuli, due to multi-channel loudness summation. We hypothesized that, without adjustment for multi-channel loudness summation, AMFD would be better with multiple than with single channels, as in Guerts and Wouters (2001).