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Research paper

Contribution of bimodal hearing to lexical tone normalization in Mandarin-speaking cochlear implant users

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ABSTRACT

Native Mandarin normal-hearing (NH) listeners can easily perceive lexical tones even under conditions of great voice pitch variations across speakers by using the pitch contrast between context and target stimuli. It is however unclear whether cochlear implant (CI) users with limited access to pitch cues can make similar use of context pitch cues for tone normalization. In this study, native Mandarin NH listeners and pre-lingually deafened unilaterally implanted CI users were asked to recognize a series of Mandarin tones varying from Tone 1 (high-flat) to Tone 2 (mid-rising) with or without a preceding sentence context. Most of the CI subjects used a hearing aid (HA) in the non-implanted ear (i.e., bimodal users) and were tested both with CI alone and CI + HA. In the test without context, typical S-shaped tone recognition functions were observed for most CI subjects and the function slopes and perceptual boundaries were similar with either CI alone or CI + HA. Compared to NH subjects, CI subjects were less sensitive to the pitch changes in target tones. In the test with context, NH subjects had more (resp. fewer) Tone-2 responses in a context with high (resp. low) fundamental frequencies, known as the contrastive context effect. For CI subjects, a similar contrastive context effect was found statistically significant for tone recognition with CI + HA but not with CI alone. The results suggest that the pitch cues from CIs may not be sufficient to consistently support the pitch contrast processing for tone normalization. The additional pitch cues from aided residual acoustic hearing can however provide CI users with a similar tone normalization capability as NH listeners.

1. Introduction

In Mandarin Chinese, tones, just like consonants and vowels, carry lexical meanings. The four Mandarin tones are primarily characterized by different pitch levels and contours (Tone 1: high-flat, Tone 2: mid-rising, Tone 3: low-falling-rising, and Tone 4: high-falling; e.g., Chao, 1948). Tonal information is important for Mandarin speech recognition especially in noise (e.g., Chen et al., 2013) because there are many Mandarin words that differ only by tone. For example, the syllable/yi/can mean 'cloth' in Tone 1, 'aunt' in Tone 2, 'already' in Tone 3, and 'easy' in Tone 4. Mandarin tone recognition involves a sophisticated process because the pitch cues to tones vary greatly across speakers with different voice characteristics such as the fundamental frequency or F0 (the most significant acoustic correlate of pitch). For example, a high-F0 tone (e.g., Tone 2) produced by a low-F0 male speaker may have similar F0s as a low-F0 tone (e.g., Tone 3) produced by a high-F0 female speaker. Normal-hearing (NH) listeners can recognize Mandarin tones effortlessly even across multiple speakers, possibly using a perceptual mechanism that normalizes the pitch differences across speakers and preserves perceptual constancy of lexical tones (e.g., Moore and Jongman, 1997; Huang and Holt, 2009).

Pitch cues in the preceding context may be used to adjust target tone recognition and achieve tone normalization. Earlier studies (e.g., Leather, 1983; Fox and Qi, 1990) however reported a weak dependence of Mandarin tone recognition of NH listeners on context pitch cues. In their experimental settings, Fox and Qi (1990) tested the recognition of a Tone 1-Tone 2 series that varied only in onset F0 with a preceding context being either Tone 1 or Tone 2. Note that the Tone-2 context may have provided the necessary F0

Abbreviations: F0, fundamental frequency; NH, normal hearing; CI, cochlear implant; HA, hearing aid; RMS, root mean square; dB, decibel; RM, repeated measures; ANOVA, analysis of variance

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range for listeners to compare with the onset F0s of the target tones throughout the test, resulting in the conclusion of no context effect on Mandarin tone recognition. More recently, Moore and Jongman (1997) and Huang and Holt (2009) both found that, with carefully designed context stimuli (e.g., a natural preceding sentence produced by either a high- or a low-F0 speaker), NH listeners used context pitch cues to shape their recognition of Mandarin contour tones (e.g., a Tone 2-Tone 3 series) and had more (resp. fewer) low-tone responses (e.g., Tone 3) in a high-F0 (resp. low-F0) context. This suggests a contrastive context effect on Mandarin tone recognition.

Previous studies with NH listeners have also considered the potential mechanisms of tone normalization or context-dependent tone recognition. Moore and Jongman (1997) attributed the contrastive context effect to a speaker-contingent process in which listeners may have used the context pitch cues to identify the speaker and then calibrated target tone recognition based on the perceived speaker identity. However, tone normalization may also be associated with a general auditory process in which the mean pitch level of the preceding sentence may have exerted a contrastive influence on the perception of the target pitch level, independent of the perceived speaker identity. The hypothesis of a general auditory mechanism for tone normalization was supported by Huang and Holt (2009). They found that non-speech contexts consisting of harmonic complex tones or pure tones had a similar contrastive effect on target tone recognition as speech contexts. This suggests that tone normalization may not require speaker, articulatory, or phonetic information in the context. In a follow-up study, Huang and Holt (2011) found that tone recognition was also contrastively affected by speech contexts with the F0 removed by high-pass filtering and masked by low-frequency noise. This suggests that central, instead of peripheral, auditory processing may be responsible for tone normalization, because the pitch of the missing-F0 context was thought to be derived from the harmonic templates at a central level beyond the cochlea (e.g., Yost, 2009).

Cochlear implants (CIs) bypass the dysfunctional cochlea and directly stimulate the surviving auditory nerves using electric pulses to partially restore hearing sensation to profoundly deaf people. Current CIs use 12–22 electrodes to encode temporal envelope cues of incoming sounds in different frequency bands, providing most CI users with good speech recognition in quiet. However, the small number of electrodes and the large current spread of electric stimulation have prevented CIs from resolving both the F0 and the harmonics of incoming sounds that carry spectral cues for pitch perception in NH listeners. On the other hand, weak temporal cues to pitch may be available from the pulse amplitude modulations at the F0 on individual electrodes (e.g., Geurts and Wouters, 2001; Green et al., 2002). Despite this, CI users' sensitivity to temporal pitch cues is greatly reduced as the F0 increases (e.g., Zeng, 2002). Although amplitude envelope and vowel duration cues may partially compensate for the limited pitch cues to Mandarin tones (e.g., Fu et al., 1998; Luo and Fu, 2004), Mandarin tone recognition is still much more challenging in CI users than in NH listeners (e.g., Luo et al., 2008; Han et al., 2009; Zhou et al., 2013).

With the CI candidacy criteria expanded nowadays, an increased percentage of the CI population has some residual low-frequency acoustic hearing and chooses to wear a hearing aid (HA) in the non-implanted ear. In the binaural bimodal fitting (i.e., CI + HA) condition, acoustic hearing from the HA may be integrated with electric hearing from the CI to yield improved speech recognition in noise as compared to the CI or HA alone condition (e.g., Kong et al., 2005; Dorman et al., 2008). The bimodal benefits in noise may be associated with a mechanism in which residual low-frequency acoustic hearing provides fine-grained pitch cues for CI users to better segregate speech from noise based on the pitch differences between target talkers and the background noise (e.g., Turner et al., 2004; Kong et al., 2005). The contribution of the pitch cues from residual low-frequency acoustic hearing to improved Mandarin tone recognition with CIs was verified in a simulation study (Luo and Fu, 2006). It is however previously unexamined whether there are bimodal benefits to tone recognition in real Mandarin-speaking CI users.

Previous studies with CI users (e.g., Luo et al., 2008; Han et al., 2009; Zhou et al., 2013) have only tested isolated Mandarin tone recognition without context. It is unclear whether CI users are able to use context pitch cues to handle talker variability in voice pitch and achieve tone normalization in everyday situations with continuous speech. We hypothesized that the central pitch contrast processing for tone normalization (Huang and Holt, 2011) may not be effective with CI alone due to the inadequate pitch cues. With bimodal fitting or CI + HA, the pitch cues from residual acoustic hearing may not only improve tone recognition without context but also elicit stronger context effects on tone recognition. To test these hypotheses, a similar design as Huang and Holt (2009) was adopted to test tone recognition with or without context in prelingually deafened native Mandarin CI users (ranging in age from preteens to young adults) with either CI alone or CI + HA. CI users were also compared with native Mandarin NH listeners (young adults) to examine whether a similar contrastive context effect in NH listeners' tone recognition (e.g., Huang and Holt, 2009) will also be observed in CI users' tone recognition, even though the CI group was younger than the NH group. Studies have shown that the general auditory mechanism for context effects in phoneme recognition is available even in NH infants or children with limited cognitive capacity, memory resources, and language experience (Fowler et al., 1990; Hufnagle et al., 2013).

2. Methods

2.1. Subjects

Ten native Mandarin NH listeners (five females and five males aged between 22 and 33 years with an average age of 26 years) were recruited from the Purdue University community as the control group. All NH subjects had hearing thresholds below 25 dB HL at octaves between 0.25 and 8 kHz in both ears. Fifteen native Mandarin CI users (seven females and eight males aged between 10 and 20 years with an average age of 15 years) were recruited from the patient population of the Children's Hearing Foundation in Taiwan. CI subject demographics including their CI and HA details are listed in Table 1. These CI subjects were all prelingually deafened and have been using their implant for more than one year. Before implantation, all CI subjects except S6 wore bilateral HAs and received auditory-verbal therapy from the Children's Hearing Foundation. After implantation, most CI subjects continued to wear an HA in the non-implanted ear (i.e., bimodal users) except S3, S4, S6, S7, and S13. Among those who used CI alone, S7 had hearing fluctuation due to enlarged vestibular aqueduct (EVA), while the others had no usable residual hearing in the non-implanted ear. Table 2 lists the unaided and aided hearing thresholds for each CI subject's non-implanted ear. The unaided audiograms mostly showed a moderately severe sloping to profound hearing loss, while the aided thresholds were mostly within the range of mild to moderate hearing loss for frequencies up to 2 kHz. This study was reviewed and approved by the local IRB committees. Informed consent was obtained from all subjects and the parents of CI subjects who were under 18 years old. All subjects were compensated for their participation in this study.