Psychophysical Performance and Mandarin Tone Recognition in Noise by Cochlear Implant Users

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Objective: **The present study was aimed to examine the relationship between psychophysical performance in temporal and spectral resolution and Mandarin tone recognition in noise by cochlear-implant (CI) listeners.**

Design: **Seventeen Nucleus-24 implant users, 10 postlingually deafened and 7 prelingually deafened, participated in the experiments. A 3-interval, forced-choice procedure was used to measure gap detection and pure-tone frequency discrimination at 250 to 4,000 Hz in octave steps. A 4-alternative forced-choice procedure was used to measure Mandarin tone recognition in quiet and in noise. Signal-to-noise ratios (SNRs) varied from +10 to –10 dB. All stimuli were delivered to the clinical processor via a speaker in a sound free field. The obtained data were compared to data collected from normal-hearing control subjects, as well as cochlear-implant users who performed similar tasks using single-electrode stimulation via a research interface.**

Results: **Postlingually-deafened CI subjects generally performed better than prelingually-deafened subjects. The average gap detection threshold was 30 ms with a range from 4 to 128 ms. The average frequency difference limen was 100 Hz with a range from 12 to 192 Hz, regardless of the standard frequency. The average tone recognition was 80% correct in quiet, which dropped to 55% at +10 dB SNR and essentially chance performance at –5 dB SNR. In comparison, the normal-hearing control subjects maintained essentially perfect performance over this SNR range. Only frequency discrimination at 1,000 Hz was significantly correlated with tone recognition in quiet but all psychophysical measures were correlated to tone recognition in noise.**

Conclusions: **The present result suggests that the CI users can rely on either temporal or spectral cues to perform tone recognition in quiet, but need both cues for tone recognition in noise. Future CI processors need to extract and encode these acoustic cues to achieve better performance in tone perception and production.**

(Ear & Hearing 2007;28;62S–65S)

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The last decade has observed rapid development in cochlear implants in China, from essentially a nonexistence of multichannel cochlear-implant (CI) users to more than 1,000 users today (Cao, 2004; Han, 2004; Zeng, 1995). A unique opportunity has arisen with this development to understand the acoustic cues in tonal languages and to extract and encode these cues in CIs. In general, current CIs cannot deliver satisfactory performance in tone recognition (e.g., Huang, Wang, & Liu, 1995; Lee, van Hasselt, Chiu, et al., 2002; Wei, Cao, & Zeng, 2004). Poor tone perception, in turn, may have resulted in poor tone production, particularly in prelingually-deafened children with CIs (Xu, Li, Hao, et al., 2004).

The most salient cue for tone recognition is change in voice pitch, which is manifested acoustically by changes in fundamental frequency and its associated harmonics (Liang, 1963). Except for an obsolete version of the Nucleus device (Xu, Dowell, & Clark, 1987), current CIs do not explicitly extract and encode fundamental frequency information (Zeng, 1995). Current CIs rely on the less salient cue in the temporal envelope domain to encode tones (Fu, Zeng, Shannon, et al., 1998; Xu, Tsai, & Pfingst, 2002). To improve CI tone recognition, suggestions have been made to enhance the temporal envelope cue directly (Luo & Fu, 2004) as well as to encode the fundamental frequency explicitly (Lan, Nie, Gao, et al., 2004) or implicitly by frequency modulation (Nie, Stickney, & Zeng, 2005).

To achieve better performance in CI tone recognition, we need to have a better understanding of the limiting factors in CI users and in CI processing strategies. The present study systematically measured psychophysical performance in gap detection and frequency discrimination in a group of Mandarin-speaking CI users. We then measured tone recognition in quiet and in noise in the same group of CI users to examine the relationship between temporal and spectral resolution and tone recognition.

Methods

Subjects

Seventeen Nucleus-24 CI users participated in this study. There were 8 females and 9 males, with a mean age of 22 yr old (ranging from 10 to 49). Ten of them were postlingually deafened (>6 yr old) and 7 were prelingually deafened. They all used the ACE

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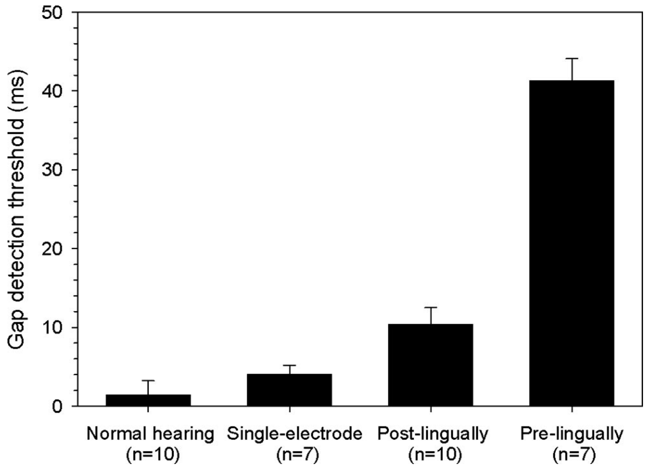

Fig. 1. Gap detection threshold in 10 normal-hearing subjects (Zeng, Kong, Michalewski, et al., 2005), 7 cochlear-implant users who performed gap detection with single-electrode stimulation using a research interface (Zeng, unpublished data), 10 postlingually deafened and 7 prelingually deafened who performed the same task using their clinical processors. Error bars = 1 standard error in all figures.

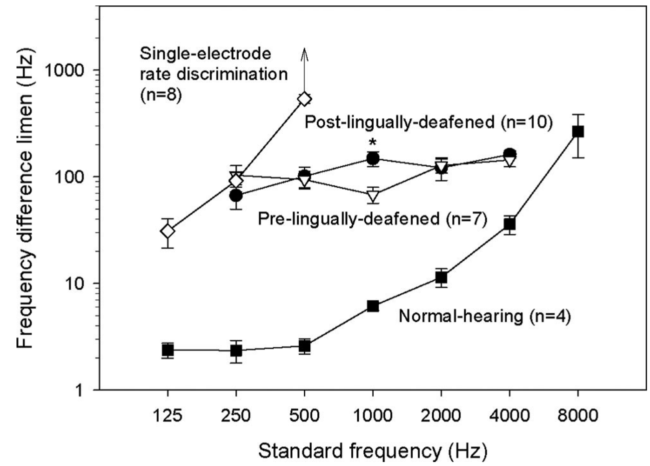

Fig. 2. Frequency discrimination as a function of standard frequency in 4 normal-hearing subjects (Zeng, Kong, Michalewski, et al., 2005), 8 cochlear-implant users who performed temporal rate discrimination on a single electrode (Zeng, 2002), 10 postlingually-deafened and 7 prelingually-deafened who performed pure-tone frequency discrimination using their clinical processors. Asterisks represent a significant difference between groups at the tested conditions.

processing strategy with MP1 +2 stimulation. The average CI use was 18 mo, ranging from 7 to 40.

Stimuli

Gap detection used a broad-band white noise, which had a 500-msec duration and a silent interval inserted in the temporal center of the noise (Zeng, Oba, Garde, et al., 1999). Frequency discrimination used 200-msec pure-tones with standard frequencies from 250 to 4,000 Hz in octave steps (Zeng, Kong, Michalewski, et al., 2005.). Mandarin tone recognition used the same 100-syllable tone list (25 CV combinations × 4 tones) as used in a previous study (Wei, Cao, & Zeng, 2004). The noise was spectrally-shaped to have the same long-term spectrum as the entire 100 syllables. All stimuli were presented at the most comfortable loudness level on an individual basis (Fig. 1, Fig. 2, Fig. 3).

Procedure

An adaptive, 3-interval, forced-choice procedure was used in gap detection and frequency discrimination. The 2-down, 1-up decision rule was used to produce a 70.7% correct criterion for the threshold measure. A 4-interval, forced-choice procedure was used in tone recognition.

Both mixed-subjects and within-subjects designs were used to analyze the obtained data. The mixed-subjects design was used to test whether there was a significant difference in performance between normal-hearing control and CI users, as well as between postlingually- and prelingually-deafened CI users. The within-subjects design was used to test whether there was a significant difference between different frequencies and signal-to-noise ratios in the same group of subjects. A p-value less than 0.05 was deemed to be significant different.

RESULTS

Gap Detection

Normal-hearing listeners could detect a 2-msec gap, but all CI users required a significantly longer

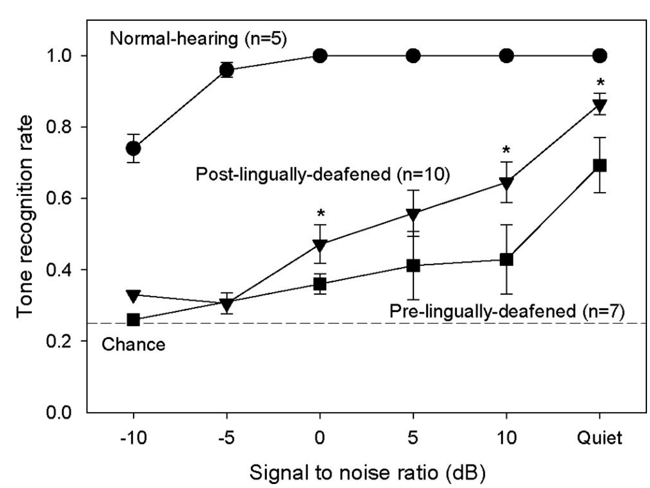

Fig. 3. Mandarin tone recognition as a function of signal to noise ratio in 5 normal-hearing subjects (Kong & Zeng, 2006), 10 postlingually-deafened and 7 prelingually-deafened cochlear-implant users. Chance performance is 0.25. Asterisks represent a significant difference between groups at the tested conditions.

gap for detection, including a 4-, 10- and 41-msec gap for CI users with single-electrode stimulation, postlingually- and prelingually-deafened CI users, respectively. An independent-sampled Student's *t*-test showed that all group differences were significant ($p < 0.05$).

Frequency Discrimination

Normal-hearing subjects required a 2–3 Hz difference for standard frequencies at or below 500 Hz and an increasingly greater difference for standard frequencies at or above 1,000 Hz. With single-electrode stimulation, the CI users required a frequency difference that was 1–2 orders of magnitude poorer than normal-hearing subjects at 500 Hz and could not perform the task at standard frequencies above 500 Hz. With the clinical processor, the CI users performed similarly to those with single-electrode stimulation at 250 Hz but were able to discriminate a 100-Hz difference for standard frequencies up to 4,000 Hz. There was no difference in performance between the post- and prelingually-deafened subjects [$F(1,15) = 1.4$, $p > 0.05$].

Tone Recognition

Normal-hearing subjects maintained nearly perfect performance, except for the 0.74 recognition rate at –10 dB SNR. In contrast, the 0.7 recognition rate was the best the CI users could perform in quiet condition. The postlingually-deafened CI users performed significantly better than the prelingually-deafened CI users [$F(1,15) = 5.2$, $p < 0.05$], but both groups produced basically chance performance at –10 and –5 dB SNRs.

DISCUSSION

Psychophysical Performance and Tone Recognition

Correlational analysis revealed several interesting findings. First, gap detection was significantly correlated with frequency discrimination at only 1,000 Hz ($r = 0.59$, $p < 0.05$) but was not correlated with tone recognition in noise. Second, only frequency discrimination at 1,000 Hz was significantly correlated with tone recognition in quiet ($r = 0.33$, $p < 0.05$). Third, as tone recognition became more difficult with noise, its performance was correlated with more psychophysical measures. For example, tone recognition at 10-dB SNR was significantly correlated with frequency discrimination at 500, 1,000, and 2,000 Hz ($r = 0.23$–0.35, $p < 0.05$); tone recognition at −5 dB SNR was significantly correlated with frequency discrimination at all frequencies from 250 Hz to 4,000 Hz, as well as with gap detection ($r = 0.21$–0.61, $p < 0.05$). The present result suggests that psychophysical measures are necessary but not sufficient to account for tone recognition. The present result also suggests that the cues for tone recognition are distributed: The CI users can choose to use any of them in relatively easy listening but have to rely on all available cues in difficult listening conditions.

Comparison with Previous Studies

Gap detection, rate discrimination, and electrode ranking of "place pitch" were measured extensively by single-electrode stimulation using a research interface in various CI populations (e.g., Nelson, Van Tasell, Schroder, et al., 1995; Shannon, 1989; Zeng, 2002). However, functional assessment of gap detection and frequency discrimination with the clinical processors was less often performed under controlled and comparable conditions. Typically, single-electrode stimulation measures patient variables, but functional assessment via clinical processors measures limitations posed by both electrical stimulation and the processing strategy.

For example, Shannon (1989) used single-electrode stimulation and found that there was generally <10 ms gap detection threshold in both Nucleus and Ineraid subjects. Tyler et al. (1989), on the other hand, used processors and found that many CI users had a gap detection threshold greater than 40 ms. On the contrary, many studies using single-electrode stimulation found the upper limit of frequency discrimination to be 300–500 Hz (e.g., Zeng, 2002), but studies using multichannel processors, including the present one, have found relatively good frequency discrimination at high frequencies (e.g., Dorman, Smith, Smith, et al., 1996).

Tone recognition in quiet in the present study was generally comparable to the previously reported results (e.g., Lee, van Hasselt, Chiu, et al., 2002; Wei, Cao, & Zeng, 2004). Similar to previous results in relating psychophysical performance to speech performance (Dorman, Smith, Smith, et al., 1996; Tyler, Moore, & Kuk, 1989), the present study showed that gap detection is weakly correlated, but frequency discrimination is significantly correlated with tone recognition. In addition, the present study showed that the more challenging the task (i.e., lower SNRs), the more frequencies at which frequency discrimination was correlated with tone recognition in noise.

Conclusion

The present study systematically measured gap detection, frequency discrimination, and tone recognition in quiet and noise in 17 CI users. CI gap detection was significantly poorer than the normal-hearing control but was not correlated with tone recognition in quiet. CI frequency discrimination was also significantly poorer than in the normal-hearing control and was correlated with tone recognition in quiet only at 1,000 Hz. Both gap detection and frequency discrimination at other frequencies (250–4,000 Hz) became correlated with tone recognition in noise. The present result suggests that multiple acoustic cues may be used for tone recognition, particularly in more difficult listening situations such as the presence of noise.

ACKNOWLEDGMENTS

We thank our cochlear-implant subjects for their time and dedication. This work was supported in part by Chinese NSF grant 39570756 (to K.C.) and NIH Grant 2 R01 DC02267 (F.-G.Z).

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Received December 13, 2005; accepted April 29, 2006.

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