Electro-Tactile Stimulation Enhances Cochlear-Implant Melody Recognition: Effects of Rhythm and Musical Training

Juan Huang,¹ Thomas Lu,² Benjamin Sheffield,³,⁴ and Fan-Gang Zeng²

Objectives: Electro-acoustic stimulation (EAS) enhances speech and music perception in cochlear-implant (CI) users who have residual low-frequency acoustic hearing. For CI users who do not have low-frequency acoustic hearing, tactile stimulation may be used in a similar fashion as residual low-frequency acoustic hearing to enhance CI performance. Previous studies showed that electro-tactile stimulation (ETS) enhanced speech recognition in noise and tonal language perception for CI listeners. Here, we examined the effect of ETS on melody recognition in both musician and nonmusician CI users.

Design: Nine musician and eight nonmusician CI users were tested in a melody recognition task with or without rhythmic cues in three testing conditions: CI only (E), tactile only (T), and combined CI and tactile stimulation (ETS).

Results: Overall, the combined electrical and tactile stimulation enhanced the melody recognition performance in CI users by 9% points. Two additional findings were observed. First, musician CI users outperformed nonmusicians CI users in melody recognition, but the size of the enhancement effect was similar between the two groups. Second, the ETS enhancement was significantly higher with nonrhythmic melodies than rhythmic melodies in both groups.

Conclusions: These findings suggest that, independent of musical experience, the size of the ETS enhancement depends on integration efficiency between tactile and auditory stimulation, and that the mechanism of the ETS enhancement is improved electric pitch perception. The present study supports the hypothesis that tactile stimulation can be used to improve pitch perception in CI users.

Key words: Cochlear implant, Electro-acoustic stimulation (EAS), Electro-tactile stimulation (ETS), Melody, Multisensory integration, Tactile aid.

Introduction

Cochlear implants (CI) have proven to be successful in restoring speech perception in people with profound hearing loss. Currently, commercially available CI devices transform sound envelope information into electrical pulses, but do not explicitly extract and deliver fundamental frequency (<500 Hz) that is crucial for pitch perception (e.g., Green et al. 2002). In addition, the intracochlear electrode array does not likely activate the low-frequency spiral ganglion neurons (Middlebrooks & Snyder 2010). Furthermore, the wide spread of electric current and the abnormal electrode-to-neuron interface results in much poorer than normal spatial selectivity (Tang et al. 2011). These limitations lead to poor performance in pitch-related tasks by CI users, such as music perception and speech perception in noise (Wilson et al. 1991; Zeng et al. 2008; Clark 2013). Studies have shown that electro-acoustic stimulation (EAS) can enhance performance in pitch-related tasks in CI users with residual low-frequency acoustic hearing (Turner et al. 2004; Kong et al. 2005; Chang et al. 2006; Yao et al. 2006; Dorman et al. 2009; Singh et al. 2009; Hu & Loizou 2010; Zhang et al. 2014; Carroll et al. 2011). The combination of low-frequency acoustic hearing and CI stimulation has also produced a super-additive effect, in which the EAS performance is larger than the sum of the CI and acoustic stimulation alone performance (von Ilberg et al. 1999; Gantz & Turner 2003; Ching et al. 2004; Dorman et al. 2008). Since only about 9% of CI users have sufficient postoperative residual hearing, the EAS benefits are not available to the majority of present CI users (Verschuur et al. 2016). Tactile sensation, however, operates in the low-frequency range and may potentially replace the role of residual low-frequency acoustic hearing in CI users (Verrillo 1963). Indeed, tactile aids have been used in auditory rehabilitation for those with profound hearing loss (Weisenberger et al. 1987; Weisenberger & Miller 1987; Hanin et al. 1988; Hnath-Chisolm & Kishon-Rabin 1988; Hnath-Chisolm & Medwetsky 1988; Weisenberger 1989; Fowler & Dekle 1991). For example, integrated tactile stimulation can improve detection threshold or increase perceived loudness (Foxe et al. 2000; Lakatos et al. 2007). Tactile stimulation also enhances speech perception, lipreading, and even word acquisition in participants with hearing loss (Rothenberg & Molitor 1979; Brooks et al. 1985; Hnath-Chisolm & Kishon-Rabin 1988; Lynch et al. 1988; Cowan et al. 1990; Bernstein et al. 1991; Waldstein & Boothroyd 1995a, 1995b). Recently, we have applied tactile stimulation to enhance CI performance, showing that electro-tactile stimulation (ETS) enhances speech perception in noise and mandarin tone recognition (Huang et al. 2017; Huang et al. 2018). Researchers have also found that vibro-tactile stimulation improves the intelligibility of speech in multi-talker noise for simulated cochlear implanted listening (Fletcher et al. 2018). The main goal of the present study was to extend the ETS result to music perception.

CI music perception has been extensively studied. First, CI users perform normally in temporal-based tests such as rhythmic or metric patterns, but poorly in melody and timbre perception (Gfeller & Lansing 1991; Kong et al. 2004; McDermott 2004; Cooper et al. 2008; Drennan & Rubinstein 2008). We hypothesize that the ETS is more beneficial for CI melody perception without any rhythmic cues than with the rhythmic cues. Second, musical training enhances CI pitch discrimination and melody recognition (Galvin et al. 2007; Galvin et al. 2008; Galvin et al. 2009; Chen et al. 2010). Additionally,
musical training facilitates cross-modal plasticity since playing a musical instrument involves multimodal processing (Pantev et al. 2003; Lappe et al. 2008). We also hypothesize that the ETS benefits music perception more in CI users with music training than those without.

MATERIALS AND METHODS

Participants

Seventeen CI participants were recruited to participate in the study. The participants were divided into two groups: musicians and nonmusicians. Participants in the musician group (n = 9, one left-handed) had more than 5 years of professional musical training (7.4 ± 2.0 years) and more than 5 years of active experience playing a musical instrument (14.5 ± 9.4 years) prior cochlear implantation. The performance under the CI only condition by one participant reached ceiling (100% correct), so this participant was excluded from the data analysis. The nonmusician group (n = 8, two left-handed) consisted of CI users who did not have professional musical training and did not play a musical instrument. For the three bilateral CI users, only one CI of their own choice was tested. They were asked to pick the side that they relied on more in daily use: S7 was tested on the left side, S14 was tested on the right side, and S15 was tested on the right side. For the four CI and hearing aid (HA) users (S3, S5, S11, and S12), tests were conducted without their HAs. One nonmusician participant could not perform above the chance level in any of the tasks and was excluded from the data analysis. Therefore, the results reported here were based on the data from 15 participants (eight musicians and seven nonmusicians). Both groups achieved a similarly high level of sentence recognition in quiet (musician: 84% ± 16% versus nonmusician: 75% ± 20%, t(13) = 0.96, p > 0.35) and word recognition in quiet (musician: 93% ± 9% versus nonmusician: 88% ± 13%, t(13) = 0.96, p > 0.36). Table 1 shows the detailed participant information and the baseline speech perception of each participant. Air conduction hearing-level thresholds were greater than 80 dB HL for all participants across frequencies from 125 Hz to 8000 Hz when tested without their CI.

TABLE 1. Biographical data of participants

<table>
<thead>
<tr>
<th>Sub</th>
<th>Age</th>
<th>Gen</th>
<th>Age (R)</th>
<th>Age (L)</th>
<th>Yr music</th>
<th>Etiology</th>
<th>Yr (R)</th>
<th>Yr (L)</th>
<th>Device</th>
<th>Sent/Word (%)</th>
</tr>
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<tbody>
<tr>
<td>S1</td>
<td>67</td>
<td>M</td>
<td>10</td>
<td>45</td>
<td>0</td>
<td>Unknown</td>
<td>18</td>
<td>N22</td>
<td>68/82</td>
<td></td>
</tr>
<tr>
<td>S2</td>
<td>85</td>
<td>M</td>
<td>47</td>
<td>47</td>
<td>0</td>
<td>Noise exposure</td>
<td>2</td>
<td>CI</td>
<td>85/96</td>
<td></td>
</tr>
<tr>
<td>S3</td>
<td>74</td>
<td>F</td>
<td>55</td>
<td>56</td>
<td>0</td>
<td>Autoimmune disease</td>
<td>3</td>
<td>N22</td>
<td>50/80</td>
<td></td>
</tr>
<tr>
<td>S4</td>
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<td>M</td>
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<td>1.5</td>
<td>0</td>
<td>Spinal meningitis</td>
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<td>CI</td>
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</tr>
<tr>
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<td>N24</td>
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<td></td>
</tr>
<tr>
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<td>15</td>
<td>15</td>
<td>6</td>
<td>Unknown</td>
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<td>N22</td>
<td>85/96</td>
<td></td>
</tr>
<tr>
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<td>59</td>
<td>F</td>
<td>5</td>
<td>5</td>
<td>30</td>
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<td>1</td>
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<tr>
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<td>38</td>
<td>38</td>
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<td>S9</td>
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<td>35</td>
<td>0</td>
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<td>16</td>
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<td>S10</td>
<td>43</td>
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<td>9</td>
<td>28</td>
<td>10</td>
<td>Ototoxicity</td>
<td>12</td>
<td>CI</td>
<td>75/82</td>
<td></td>
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<tr>
<td>S11</td>
<td>54</td>
<td>F</td>
<td>4</td>
<td>4</td>
<td>8</td>
<td>Unknown</td>
<td>4</td>
<td>N22</td>
<td>73/92</td>
<td></td>
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<tr>
<td>S12</td>
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<td>CI</td>
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<td>45</td>
<td>45</td>
<td>25</td>
<td>Nerve</td>
<td>7</td>
<td>CI</td>
<td>55/74</td>
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</tr>
<tr>
<td>S14</td>
<td>47</td>
<td>F</td>
<td>18</td>
<td>18</td>
<td>0</td>
<td>Unknown</td>
<td>2</td>
<td>N24</td>
<td>85/97</td>
<td></td>
</tr>
<tr>
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<td>Unknown</td>
<td>6</td>
<td>6</td>
<td>N22</td>
<td>100/100</td>
</tr>
</tbody>
</table>

Sub, subject; Gen, gender; Age (R), age of hearing loss onset in right ear; Age (L), age of hearing loss onset in left ear; Yr music, years of musical training; Yr (R), years of using CI in right ear; Yr (L), years of using CI in left ear; Sent/Word (%), correct percentages of sentence and word recognition.
Participants were tested in the melody recognition task under E, T, and ETS conditions. Before the test, a sinusoidal waveform with a frequency of 250 Hz and duration of one minute was used as a calibration tone for both the acoustic and tactile stimulation for each participant. The most comfortable levels (MCLs) of both CI and tactile stimulation were used for each participant. The MCL of tactile stimulation ranged between −20 dB and −10 dB relative to the maximum output of the transducer and the acoustic MCL ranged from 65 to 75 dB SPL across participants. There were no significant differences between musicians and nonmusicians for either auditory or tactile MCL.

Twelve isochronous melodies were used as testing materials (Singh et al. 2009), generated using a software synthesizer (ReBirth RB-338, version 2.1.1). The 12 common melodies were used as testing materials for their general familiarity through discussions among hearing and music professionals, and from earlier studies, which demonstrated that these melodies were familiar for normal-hearing and CI users (Looi et al. 2003; Kong et al. 2005; Nimmons et al. 2008). One set of the melodies contained both melodic and rhythmic information (rhythmic condition), whereas the other set contained only melodic information (nonrhythmic condition) with notes of the same duration (quarter notes with 350 msec in duration) and a silent gap of 150 msec between notes. Each song consisted of 12 to 14 notes of its initial phrase spanning a frequency range from 207 Hz (G3) to 523 Hz (C5) and was presented five times in a pseudorandom order for each stimulation condition, making a total of six testing blocks for each participant. Each block lasted about 10 min. The order of presentation of six conditions (E, T, and ETS with rhythmic and nonrhythmic melody) was randomized, with a total of 60 presentations per condition (12 songs × 5 repetitions). It is a closed-set task. After each trial, participants were asked to click 1 of 12 buttons that contained the title of the song that they heard on the experiment interface. No feedback was provided. The percentage of correct responses was recorded. Participants took at least 15 min of rest between test blocks. Before the tests, participants were provided the list of the titles of the 12 melodies that they were not familiar to him/her. All participants were familiar with the 12 melodies. Table 2 shows the titles of the 12 familiar melodies that were used in the experiment.

Data Analysis

The percentage of correct responses of melody recognition under each condition was calculated as follows: number of correct responses/[12(songs) x 5(repetitions)]. The percentage correct scores were transformed to arc-sine values to equate variance (Sokal & Rohlf 1981; Studebaker 1985), so that ratio- nalized arcsine unit (RAU) scores were used in further statistical analyses. The main effects of stimulation modality (E, T, or ETS), rhythmic condition (rhythmic versus nonrhythmic), and musical training (musician versus nonmusician) were examined using a mixed-model analysis of variance (ANOVA), with stimulation modality and rhythm condition as within-subject factors and musical training as the between-subject factor. For the repeated measures of the within-subject factors, the Greehouse-Geisser correction was used to adjust the freedom of the F-distribution if Sphericity was violated. A follow-up post-hoc pairwise comparison with the Tukey HSD procedure was conducted to examine how testing conditions differ from one another. The effects of rhythmic condition in each stimulation modality conditions were further analyzed using paired sample t-test, and musical training was further analyzed using

<table>
<thead>
<tr>
<th>Table 2. The list of melody titles</th>
</tr>
</thead>
<tbody>
<tr>
<td>No.</td>
</tr>
<tr>
<td>1</td>
</tr>
<tr>
<td>2</td>
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<tr>
<td>3</td>
</tr>
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<td>8</td>
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<td>9</td>
</tr>
<tr>
<td>10</td>
</tr>
<tr>
<td>11</td>
</tr>
<tr>
<td>12</td>
</tr>
</tbody>
</table>

"No.", number.
independent samples t-test by comparing musician and non-musician data in each stimulation modality conditions with rhythmic and nonrhythmic melody recognition separately (results shown in Table 3).

The absolute enhancement produced by ETS was quantified by subtracting the CI only condition from the ETS condition, and then was normalized to the baseline: [(ETS − E)/E] x 100. A mix-model ANOVA was conducted to examine the effects of stimulation modality, rhythmic, and musical training on the absolute and relative ETS enhancement, respectively.

**RESULTS**

Participants’ performance was analyzed using a mixed-model ANOVA with two within-subject factors, stimulation mode (E, T, or ETS) and rhythm condition (rhythmic versus nonrhythmic), and a between-subject factor musical training (musician versus nonmusician). The main effect of musical training was significant [F(1, 13) = 18.6, p < 0.001, \( \eta^2_p = 0.6 \)]. The main effects of stimulation mode [F(1.2, 15.0) = 57.0, p < 0.001, \( \eta^2_p = 0.8 \), with Greenhouse-Geisser correction] and rhythm condition [F(1) = 103.3, p < 0.001, \( \eta^2_p = 0.9 \)] were significant. No interaction was found between stimulation mode and rhythmic condition [F(2, 26) = 0.44, p = 0.65, \( \eta^2_p = 0.03 \)], stimulation mode and musical training [F(1, 13) = 1.7, p = 0.21, \( \eta^2_p = 0.11 \)], or between rhythm condition and musical training [F(1, 13) = 0.03, p = 0.86, \( \eta^2_p = 0.00 \)].

**The ETS Enhancement**

Figure 2 shows boxplots of individual melody recognition performance as a function of stimulation modes (T, E, and ETS) in nonrhythmic (left panel) and rhythmic (right panel) conditions. The correct percentage RAU values of rhythmic melody recognition are 63% ± 15% (E), 44% ± 24% (T), 74% ± 19% (ETS), and of nonrhythmic melody recognition 26% ± 10% (E), 8% ± 10% (T), 35% ± 25% (ETS). All test conditions resulted in significant melody recognition with performance better than 8% (the chance level of RAU performance), except for tactile alone stimulation in the nonrhythmic condition.

The main effect of stimulation mode was further examined with a post-hoc pairwise multiple comparisons of the estimated marginal means among E, T, and ETS conditions, with the Tukey HSD procedure. Each of the pairwise comparisons yielded

**TABLE 3.** The results of the independent samples t-test between musicians and nonmusicians

<table>
<thead>
<tr>
<th>Test Condition</th>
<th>Levene’s Test for Equality of Variances</th>
<th>t-Test</th>
</tr>
</thead>
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<tr>
<td></td>
<td>F</td>
<td>Sig.</td>
</tr>
<tr>
<td>Rhythmic</td>
<td></td>
<td></td>
</tr>
<tr>
<td>E</td>
<td>0.63</td>
<td>0.44</td>
</tr>
<tr>
<td>T</td>
<td>0.00</td>
<td>0.98</td>
</tr>
<tr>
<td>ETS</td>
<td>0.52</td>
<td>0.48</td>
</tr>
<tr>
<td>Nonrhythmic</td>
<td></td>
<td></td>
</tr>
<tr>
<td>E</td>
<td>9.65</td>
<td>0.01</td>
</tr>
<tr>
<td>T</td>
<td>1.30</td>
<td>0.28</td>
</tr>
<tr>
<td>ETS</td>
<td>6.63</td>
<td>0.03</td>
</tr>
</tbody>
</table>

*Sig.*, significance level; *Std.*, standard deviation; E, CI stimulation; T, tactile stimulation; ETS, combined CI and tactile stimulation.

Fig. 2. A, The distribution of RAU values of melody recognition performance with nonrhythmic melodies as a function of tactile alone (T), cochlear implant alone (E), and combined cochlear implant and tactile (ETS) conditions (labeled position on the x axis). B, The distribution of RAU values of melody recognition performance with rhythmic melodies. The boxes represent the data distribution between the first and the third quartiles. The short lines in the boxes are the medians. The upper bars are the maximums and the lower bars are the minimums. Data points beyond the upper and lower bars are outliers. Individual data points are plotted together with boxes. Filled circle: musicians; Open circle: nonmusicians. The upper lines illustrate the comparisons between nonrhythmic and rhythmic conditions for specified stimulation mode. Stars mark the significant difference. Dash lines are chance level; **p < 0.01.
significant mean differences: ETS versus E (mean difference = 9.7, SE = 1.2, \( p < 0.01 \)), ETS versus T (mean difference = 28.3, SE = 3.5, \( p < 0.01 \)), and E versus T (mean difference = 18.6, SE = 2.9, \( p < 0.01 \)).

When rhythmic cues were presented, the average performance in the combined CI and tactile stimulation condition was 10.8% points higher (\( t_{(14)} = 6.7, p < 0.01 \)) than the CI alone condition (Fig. 2B). The addition of low-frequency tactile stimulation significantly enhanced the melody recognition performance. More interestingly, when rhythmic cues were excluded and only pitch cues were available for participants to recognize the melodies, correct percentage with CI stimulation alone was about 26% on average. Although the performance with tactile stimulation alone was at chance level, when combined with CI stimulation in the ETS condition, the additional low-frequency tactile stimulation still produced enhancement as high as 9% points on average compared with condition E (\( t_{(14)} = 5.3, p < 0.01 \)) (Fig. 2A). These data suggest that the tactile improvement is not dependent on rhythmic cue but directly affects the pitch processing.

**Effects of Rhythm**

A pairwise comparison revealed that the estimated marginal means across the three stimulation modalities between the rhythmic and nonrhythmic conditions was significantly different (mean difference = 37.6, SE = 3.7, \( p < 0.01 \)). The rhythmic cue increased melody recognition performance in E (\( t_{(14)} = 8.9, p < 0.01 \)), T (\( t_{(14)} = 6.3, p < 0.01 \)), and ETS (\( t_{(14)} = 7.9, p < 0.01 \)) conditions, respectively, as shown in the comparisons of corresponding stimulation modes between the nonrhythmic (Fig. 2A) and rhythmic (Fig. 2B) results (upper lines and significance levels in Fig. 2). These results suggest that CI users relied much on rhythmic cues in recognizing the familiar melodies.

We quantified the effect of tactile stimulation in the ETS condition by extracting data of the CI only (E) condition from the ETS condition and normalizing to the CI baseline performance \([\text{ETS} - \text{E}] / \text{E} \times 100\). Figure 3A shows the absolute performance differences between ETS and E conditions with nonrhythmic and rhythmic melody recognition performance. The ANOVA indicated no significant difference in absolute enhancement between the nonrhythmic and rhythmic conditions \([F_{(1, 29)} = 0.5, \text{MS} = 22.2, p = 0.5]\). The normalized enhancements produced by ETS with respect to baseline performance in the E condition are shown in Figure 3B, with 43% for nonrhythmic and 16% for rhythmic melody recognition. The ANOVA indicated significant difference in the normalized enhancement produced by ETS between rhythmic and nonrhythmic melody conditions \([F_{(1, 29)} = 10.5, \text{MS} = 5541.7, p < 0.01]\).

**Effects of Musical Training**

As indicated in the comparison between musicians (black circles) and nonmusicians (open circles) in Figure 2, the pre-cochlear implant musical training produced an overall enhancement independent of stimulation modalities and rhythm conditions. Musicians’ melody recognition performance was significantly better than that of nonmusicians in all rhythmic melody tests and in nonrhythmic melody tests for E and ETS conditions, but not for the T condition (Table 3).

Figure 4B shows the absolute performance differences between ETS and E conditions as a function of rhythm and musical training, the corresponding relative difference is shown in Figure 4B. ANOVA indicated that the absolute enhancement effect produced by the tactile stimulation in musicians was significantly higher than that of nonmusicians in nonrhythmic condition \([F_{(1, 14)} = 9.6, \text{MS} = 255.7, p < 0.01]\) (Fig. 4A, left bars). The average performance for musicians was higher than nonmusicians in the rhythmic condition (Fig. 4A, right bars), although the difference was not statistically significant \([F_{(1, 14)} = 2.0, \text{MS} = 74.1, p = 0.2]\), the relative percentage difference was no longer significant between the two participant groups after normalizing the ETS enhancement with respect to the CI only performance for each participant (Fig. 4B).

**DISCUSSION**

The Effect of Rhythmic Cue on the ETS Enhancement

The rhythmic cue produced no significant difference in absolute ETS enhancement (Fig. 3A), but it generated 27% points significant difference in relative ETS enhancement (the absolute ETS enhancement as the percentage of the baseline performance in CI only condition) (Fig. 3B). Since the duration and amplitude of all notes in the melodies were identical, rhythmic melody involves both rhythmic and pitch cues whereas nonrhythmic melody contains only pitch cues for participants to use in perceiving familiar melodies. Our findings indicate that the ETS significantly improved pitch perception in CI users regardless of musical training experience.

We have to point out that the tactile stimulation used in the study contains only low-passed frequency components below 500 Hz, within the frequency range where the tactile sensation functions. The benefit of low-frequency tactile stimulation in
The Effects of Musical Training on ETS Enhancement

Our data show that pre-CI music training produced significantly better post-CI melody recognition in musician users than nonmusician users. The overall better melody recognition performance observed in musicians may result from their superior pitch-processing and rhythmic pattern recognition. Musical training has been shown to enhance auditory-somatosensory integration and neural responses to pitch information in musicians (Pantev et al. 2003; Pantev et al. 2009), and thus produce corresponding behavioral benefits (Tervaniemi et al. 2005; Magne et al. 2006). Results reported in the present study have confirmed that precochlear implant musical training produces superior music perception. Such superiority in music perception remains even after the deprivation of acoustic inputs. The effect of musical training is not sensory modality specific, which presents in the electrical hearing and extends to tactile-mediated and ETS-mediated music perception in CI users.

One interesting observation from the present study is that musicians can recognize familiar melody through the low-frequency information presented via tactile stimulation alone, suggesting that musical training also enhances tactile processing. Such an effect may be caused by improved auditory-tactile integration in processing music information. Cross-modal plasticity has been observed from musicians who have gone through auditory-tactile musical training (Elbert et al. 1995; Pantev et al. 2003; Ragert et al. 2004; Pantev et al. 2009), and tactile sensory perception was thus modified by musical training.

Musicians had a greater absolute ETS enhancement than nonmusicians. However, pre-CI music training did not produce more relative ETS enhancement in the musician CI users. When the ETS enhancement is normalized by the electrical stimulation baseline, the relative ETS enhancement is similar between musicians and nonmusicians. In other words, the size of enhancement of melody recognition relative to the baseline CI performance induced by additional tactile presentation of low-frequency information was similar between musicians and nonmusicians for both rhythmic and nonrhythmic melody conditions, suggesting that the ETS-produced benefit in music processing is independent of musical training.

Mechanisms of the ETS Enhancement

It has long been reported that the integration between auditory and tactile stimulation and perception occurs at various neural levels from the cochlear nucleus to the primary and secondary auditory cortex (Levänen et al. 1998; Foxe et al. 2000; Lee et al. 2001; Schulz et al. 2003; Ragert et al. 2004; Kayser et al. 2005; Caetano & Jousmäki 2006; Hackett et al. 2007; for a recent review, see Wu et al. 2015). With the deprivation of auditory stimulation in people with hearing loss, enlarged auditory cortical responses have been observed for auditory and tactile stimulation, as well as for combined stimulation (Elbert et al. 1995; Levänen et al. 1998; Lee et al. 2001; Sharma et al. 2007). As a consequence, the sensation of vibration and auditory events is enhanced (Levänen & Hamdord 2001; Gillmeister & Eimer 2007; Rouger et al. 2007).

As shown in a previous study, the auditory and tactile interaction in spectral processing becomes greater following the cochlear implantation in CI users (Landry et al. 2014). The enhanced performance by the combined electrical and tactile stimulation in the present study might be related to the greater recruitment of auditory pathway in response to vibrotactile stimulation.

In the nonrhythm condition, pitch is the only cue for participants to use in recognizing the melodies. The large enhancement induced by the ETS relative to CI alone baseline (Fig. 3B) indicates that the auditory-tactile integration facilitated electrical pitch perception in CI users. The exact underlying neural mechanisms remain unclear, but are likely related to frequency processing in auditory-tactile integration at various neural levels from the cochlear nucleus to the primary and secondary auditory cortex (Yau et al. 2009; Foxe 2009; Yau et al. 2010; Lemus et al. 2010; Crommett et al. 2017). The additional low-frequency tactile stimulation may activate the multisensory-responsive neurons along the auditory pathway and facilitate the neural response to the electrical stimulation, refine or strengthen pitch coding by neurons along the auditory pathway or in auditory and tactile convergence areas (Röder et al. 2014; Bendor & Wang 2005; Lappe et al. 2008; Lemus et al. 2010), thus enhancing pitch processing in CI users.

CONCLUSION

The present study found that tactile stimulation significantly enhanced CI melody recognition by 9% points (Fig. 2).
The ETS benefit depended on both rhythmic cue and music training. Consistent with our first hypothesis, the ETS benefited melody recognition more without rhythmic cues than with the rhythmic cue (43% versus 16% increase from the baseline, Fig. 3B). However, our second hypothesis on music training was only partially consistent with the results: Musician CI users derived more ETS benefits than nonmusician CI users but their relative size of the benefit was equal. The partially consistent results indicate that music training boosts the overall baseline CI performance, but is not required for the ETS enhancement. Our findings suggest that a tactile aid can be used in combination with a CI to improve music perception in CI users.

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