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

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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.

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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 post-operative 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-Robin 1988; Lynch et al. 1988; Cowan et al. 1990; Bernstein et al. 1991; Waldsein & 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,

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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.

Testing Conditions

Participants were tested in melody recognition tasks under three testing conditions. In CI only (E) condition, melodies were presented through a speaker and participants listened with their CI turned on. In tactile only (T) condition, a low-pass filtered version of the melodies were presented through a tactile stimulator attached to the participant's fingertip while the participant wore a pair of earplugs to minimize possible residual low-frequency hearing and with their CI turned off. In the combined CI and tactile stimulation (ETS) condition, melodies were delivered through a speaker while participants listened with their CI turned on. Meanwhile, a low-pass filtered version of the presenting melody was delivered through a tactile stimulator (Huang et al. 2017; Huang et al. 2018).

Procedure and Stimuli

In the experiment, participants sat inside a sound-proof chamber, facing the midpoint between two speakers that were 1 m away. Stimuli were presented through a GSI 61 Clinical Audiometer (Grason-Stadler Inc.) and a GSI loud speaker (Fig. 1A). The sound materials were presented from a speaker on the same side of each participant's CI at an angle of 45º to the midline. Low-pass filtered versions of the stimuli (first-order low-pass filter with cutoff frequency at 500 Hz) were delivered via a tactile stimulator, TACTAID VBW32 (Audiological Engineering Co.), attached to the index fingertip of a participant's nondominant hand using electrical tape (Fig. 1B). For the calibration of tactile stimulation intensity, the voltage output of the tactile stimulation was adjusted to 2.5 volts induced from a sinusoidal vibration of 250 Hz as the 0 dB reference, which was provided by the manufacturer. For calibration of the synchrony between auditory and tactile stimulation, a series of pure tones with frequencies at 200, 250, and 500 Hz with duration of 1 sec were generated and delivered from the speakers and the tactile aid. The outputs of the auditory and tactile stimuli were stored and examined by off-line analysis. Results showed that phase offset between outputs of the two channels was within 0.2π.

TABLE 1. Biographical data of participants

Sub	Age	Gen	Age (R)	Age (L)	Yr music	Etiology	Yr (R)	Yr (L)	Device	Sent/Word (%)
S1	67	M	10	45	0	Unknown		18	N22	68/82
S2	85	M	47	47	0	Noise exposure	2		CI	85/96
S3	74	F	55	56	0	Autoimmune disease		3	N22	50/80
S4	67	M	1.5	1.5	0	Spinal meningitis	5		CI	88/96
S5	82	M	43	43	0	Unknown		6	N24	48/64
S6	48	F	15	15	6	Unknown		7	N22	85/96
S7	59	F	5	5	30	Unknown	7	1	CII	100/100
S8	81	F	38	38	6	Viral infection		5	N22	84/92
S9	51	M	35	35	0	Trauma	16		N22	100/100
S10	43	F	9	28	10	Ototoxicity	12		CI	75/92
S11	54	F	4	4	8	Unknown	7		N22	73/92
S12	70	F	5	5	5	Hereditary		7	CII	100/100
S13	71	F	45	45	25	Nerve		7	CI	55/74
S14	47	F	18	18	0	Unknown	2	12	N24	85/97
S15	35	M	28	28	20	Unknown	6	6	N22	100/100

"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.

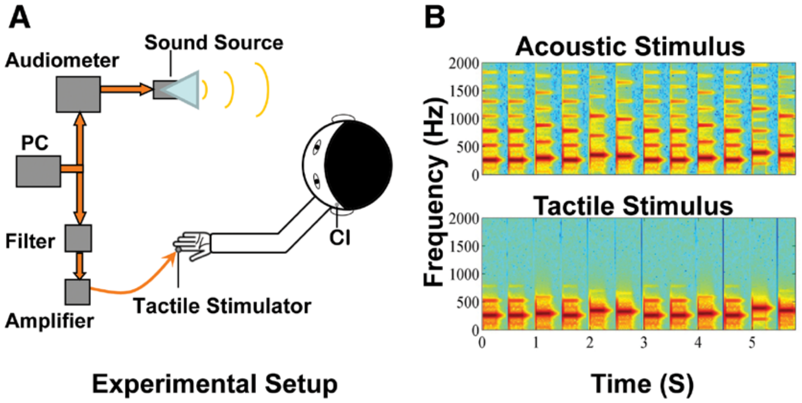

Fig. 1. Illustration of the experimental setup and stimuli. A, Acoustic and tactile stimuli were presented to participants from a speaker and a tactile stimulator, respectively. Acoustic signals were sent to a GSI 61 clinical audiometer and then through a GSI speaker to participants. Tactile signals were generated by sending the auditory signals through a low-pass filter (cut-off frequency 500 Hz), amplifier, and attenuator before being delivered to participants through a tactile stimulator. B, Spectrum of example stimuli. Upper panel: Stimuli presented from the acoustic channel, for example, original sound material. Lower panel: Stimuli presented from the tactile channel, for example, low-pass filtered signal. The melody piece in this example is "Happy Birthday" without rhythmic cues.

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. They were asked to circle out any of the melodies that 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 rationalized 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 2. The list of melody titles

No.	Melody Title
1	Old MacDonald had a farm
2	Twinkle, twinkle, little star
3	London bridge is falling down
4	Mary had a little lamb
5	This old man
6	Yankee Doodle
7	She'll be coming round the mountain
8	Happy birthday
9	Lullaby, and good night
10	Take me out to the ball game
11	Auld Lang Syne
12	Star spangled banner

"No.", number.

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

		Levene's Test for Equality of Variances		*t*-Test				
Test Condition		F	Sig.	*T*	Df	Sig. (Two-Tailed)	Mean Difference	Std. Error Difference
Rhythmic	E	0.63	0.44	2.50	13	0.03	16.5	6.61
	T	0.00	0.98	3.46	13	0.00	32.35	9.35
	ETS	0.52	0.48	2.54	13	0.03	20.96	8.27
Nonrhythmic	E	9.65	0.01	3.93	8.43 (corrected)	0.00	29.33	7.47
	T	1.30	0.28	1.34	13	0.20	6.94	5.17
	ETS	6.63	0.03	4.34	8.80 (corrected)	0.00	37.61	8.19

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

independent samples *t*-test by comparing musician and nonmusician 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: $[(\mathrm{ETS} - \mathrm{E})/\mathrm{E}] \times 100$. 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 [$F_{(1, 13)} = 18.6$, $p < 0.001$, $\eta_p^2 = 0.6$]. The main effects of stimulation mode [$F_{(1.2, 15.0)} = 57.0$, $p < 0.001$, $\eta_p^2 = 0.8$, with Greenhouse-Geisser correction] and rhythmic condition [$F_{(1, 13)} = 103.3$, $p < 0.001$, $\eta_p^2 = 0.9$] were significant. No interaction was found between stimulation mode and rhythmic condition [$F_{(2, 26)} = 0.44$, $p = 0.65$, $\eta_p^2 = 0.03$], stimulation mode and musical training [$F_{(2, 26)} = 1.7$, $p = 0.21$, $\eta_p^2 = 0.11$], or between rhythmic condition and musical training [$F_{(1, 13)} = 0.03$, $p = 0.86$, $\eta_p^2 = 0.00$].

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

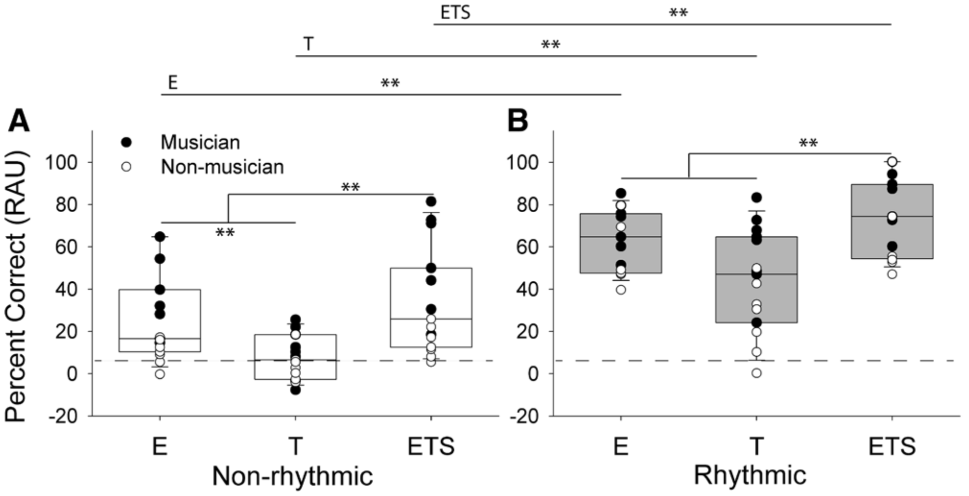

Fig. 2. A, The distribution of RAU values of melody recognition performance with nonrhythmic melodies as a function of tactile alone (T), cochlear implant alone (E), and combined cochlear implant and tactile (ETS) conditions (labeled position on the x axis). B, The distribution of RAU values of melody 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; ** $p < 0.01$.

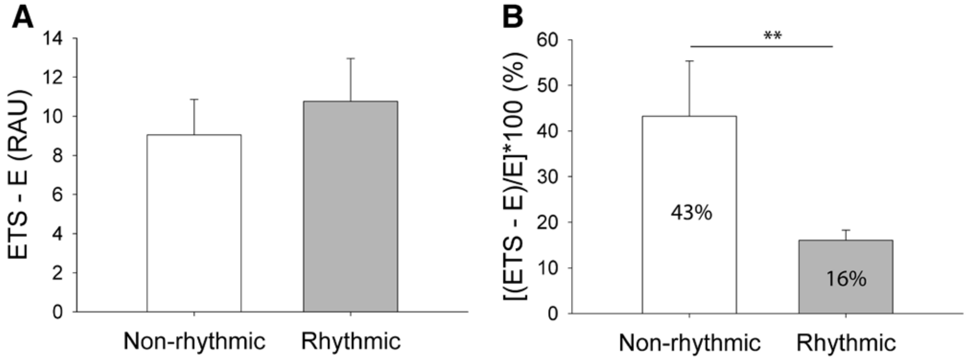

Fig. 3. A, Average absolute enhancement of melody recognition as a function of rhythmic conditions (labeled position on the x axis). B, Normalized relative enhancement. Open bar: nonrhythmic, Filled bar: rhythmic. Error bars are SE. Stars mark the significant difference; ** $p < 0.01$.

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 comparing 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 [$F_{(1, 29)} = 0.5$, 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 [$F_{(1, 29)} = 10.5$, 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 precochlear 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 [$F_{(1, 14)} = 9.6$, 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 [$F_{(1, 14)} = 2.0$, 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

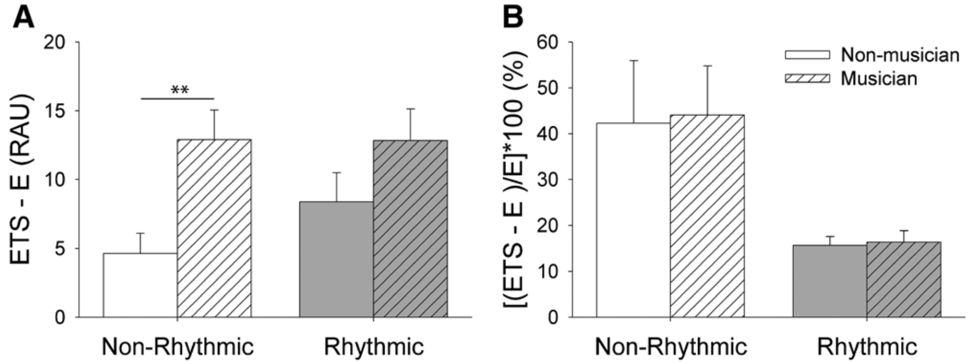

Fig. 4. A, Average absolute enhancement of melody recognition as a function of rhythmic conditions (labeled position on the x axis) and musical training. B, Normalized relative enhancement. Open bar: nonrhythmic; Filled bar: rhythmic; Blank bar: Nonmusician; Hashed bar: musician; Error bars are SE. Stars mark the significant difference; ** $p < 0.01$.

our experiment may not be extended to a broader frequency range or for the perception of more complex musical sounds. Future studies need to further examine the behavioral consequences of ETS in CI users to provide evidence of changes in the thresholds of frequency perception and discrimination, as well as in the perception of other complex sounds, for example, the perception of musical timbres or natural sound textures.

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 (Levanen et al. 1998; Foxe et al. 2000; Lee et al. 2001; Schulz et al. 2003; Ragert et al. 2004; Kayser et al. 2005; Caetano & Jousmaki 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 & Hamdorf 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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J.H. designed and performed experiments, analyzed data, and wrote the article. B.S. created the testing software, processed testing stimuli, and edited the article. T.L. processed testing stimuli and edited the article. F.G.Z. designed the experiments and provided critical revision. All authors discussed the results and implications and commented on the artcile at all states.

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REFERENCES

Bendor, D., & Wang, X. (2005). The neuronal representation of pitch in primate auditory cortex. *Nature, 436*, 1161–1165.

Bernstein, L. E., Demorest, M. E., Coulter, D. C., et al. (1991). Lipreading sentences with vibrotactile vocoders: Performance of normal-hearing and hearing-impaired subjects. *J Acoust Soc Am, 90*, 2971–2984.

Brooks, P. L., Frost, B. J., Mason, J. L., et al. (1985). Acquisition of a 250-word vocabulary through a tactile vocoder. *J Acoust Soc Am, 77*, 1576–1579.

Caetano, G., & Jousmäki, V. (2006). Evidence of vibrotactile input to human auditory cortex. *Neuroimage, 29*, 15–28.

Carroll, J., Tiaden, S., Zeng, F. G. (2011). Fundamental frequency is critical to speech perception in noise in combined acoustic and electric hearing. *J Acoust Soc Am, 130*, 2054–2062.

Chang, J. E., Bai, J. Y., Zeng, F. G. (2006). Unintelligible low-frequency sound enhances simulated cochlear-implant speech recognition in noise. *IEEE Trans Biomed Eng, 53*(12 Pt 2), 2598–2601.

Chen, J. K., Chuang, A. Y., McMahon, C., et al. (2010). Music training improves pitch perception in prelingually deafened children with cochlear implants. *Pediatrics, 125*, e793–e800.

Ching, T. Y., Incerti, P., Hill, M. (2004). Binaural benefits for adults who use hearing aids and cochlear implants in opposite ears. *Ear Hear, 25*, 9–21.

Clark, G. M. (2013). The multichannel cochlear implant for severe-to-profound hearing loss. *Nat Med, 19*, 1236–1239.

Cooper, W. B., Tobey, E., Loizou, P. C. (2008). Music perception by cochlear implant and normal hearing listeners as measured by the Montreal Battery for Evaluation of Amusia. *Ear Hear, 29*, 618–626.

Cowan, R. S., Blamey, P. J., Galvin, K. L., et al. (1990). Perception of sentences, words, and speech features by profoundly hearing-impaired children using a multichannel electrotactile speech processor. *J Acoust Soc Am, 88*, 1374–1384.

Crommett, L. E., Pérez-Bellido, A., Yau, J. M. (2017). Auditory adaptation improves tactile frequency perception. *J Neurophysiol, 117*, 1352–1362.

Dorman, M. F., Gifford, R. H., Spahr, A. J., et al. (2008). The benefits of combining acoustic and electric stimulation for the recognition of speech, voice and melodies. *Audiol Neurootol, 13*, 105–112.

Dorman, M. F., Gifford, R., Lewis, K., et al. (2009). Word recognition following implantation of conventional and 10-mm hybrid electrodes. *Audiol Neurootol, 14*, 181–189.

Drennan, W. R., & Rubinstein, J. T. (2008). Music perception in cochlear implant users and its relationship with psychophysical capabilities. *J Rehabil Res Dev, 45*, 779–789.

Elbert, T., Pantev, C., Wienbruch, C., et al. (1995). Increased cortical representation of the fingers of the left hand in string players. *Science, 270*, 305–307.

Fletcher, M. D., Mills, S. R., Goehring, T. (2018). Vibro-tactile enhancement of speech intelligibility in multi-talker noise for simulated cochlear implant listening. *Trends Hear, 22*, 2331216518797838.

Fowler, C. A., & Dekle, D. J. (1991). Listening with eye and hand: cross-modal contributions to speech perception. *J Exp Psychol Hum Percept Perform, 17*, 816–828.

Foxe, J. J. (2009). Multisensory integration: frequency tuning of audio-tactile integration. *Curr Biol, 19*, R373–R375.

Foxe, J. J., Morocz, I. A., Murray, M. M., et al. (2000). Multisensory auditory-somatosensory interactions in early cortical processing revealed by high-density electrical mapping. *Brain Res Cogn Brain Res, 10*, 77–83.

Galvin, J. J., 3rd, Fu, Q. J., Nogaki, G. (2007). Melodic contour identification by cochlear implant listeners. *Ear Hear, 28*, 302–319.

Galvin, J. J., 3rd, Fu, Q. J., Oba, S. (2008). Effect of instrument timbre on melodic contour identification by cochlear implant users. *J Acoust Soc Am, 124*, EL189–EL195.

Galvin, J. J., 3rd, Fu, Q. J., Oba, S. I. (2009). Effect of a competing instrument on melodic contour identification by cochlear implant users. *J Acoust Soc Am, 125*, EL98–E103.

Gantz, B. J., & Turner, C. W. (2003). Combining acoustic and electrical hearing. *Laryngoscope, 113*, 1726–1730.

Gfeller, K., & Lansing, C. R. (1991). Melodic, rhythmic, and timbral perception of adult cochlear implant users. *J Speech Hear Res, 34*, 916–920.

Gillmeister, H., & Eimer, M. (2007). Tactile enhancement of auditory detection and perceived loudness. *Brain Res, 1160*, 58–68.

Green, T., Faulkner, A., Rosen, S. (2002). Spectral and temporal cues to pitch in noise-excited vocoder simulations of continuous-interleaved-sampling cochlear implants. *J Acoust Soc Am, 112*(5 Pt 1), 2155–2164.

Hackett, T. A., Smiley, J. F., Ulbert, I., et al. (2007). Sources of somatosensory input to the caudal belt areas of auditory cortex. *Perception, 36*, 1419–1430.

Hanin, L., Boothroyd, A., Hnath-Chisolm, T. (1988). Tactile presentation of voice fundamental frequency as an aid to the speechreading of sentences. *Ear Hear, 9*, 335–341.

Hnath-Chisolm, T., & Kishon-Rabin, L. (1988). Tactile presentation of voice fundamental frequency as an aid to the perception of speech pattern contrasts. *Ear Hear, 9*, 329–334.

Hnath-Chisolm, T., & Medwetsky, L. (1988). Perception of frequency contours via temporal and spatial tactile transforms. *Ear Hear, 9*, 322–328.

Hu, Y., & Loizou, P. C. (2010). Effects of introducing low-frequency harmonics in the perception of vocoded telephone speech. *J Acoust Soc Am, 128*, 1280–1289.

Huang, J., Chang, J., Zeng, F. G. (2017). Electro-tactile stimulation (ETS) enhances cochlear-implant Mandarin tone recognition. *World J Otorhinolaryngol Head Neck Surg, 3*, 219–223.

Huang, J., Sheffield, B. M., Lin, P., et al. (2017) Electro-tactile stimulation enhances cochlear implant speech recognition in noise. *Scientific Reports*, doi:10,1038/s41598-017-02429-1.

Kayser, C., Petkov, C. I., Augath, M., et al. (2005). Integration of touch and sound in auditory cortex. *Neuron, 48*, 373–384.

Kong, Y. Y., Cruz, R., Jones, J. A., et al. (2004). Music perception with temporal cues in acoustic and electric hearing. *Ear Hear, 25*, 173–185.

Kong, Y. Y., Stickney, G. S., Zeng, F. G. (2005). Speech and melody recognition in binaurally combined acoustic and electric hearing. *J Acoust Soc Am, 117*(3 Pt 1), 1351–1361.

Lakatos, P., Chen, C. M., O'Connell, M. N., et al. (2007). Neuronal oscillations and multisensory interaction in primary auditory cortex. *Neuron, 53*, 279–292.

Landry, S. P., Guillemot, J. P., Champoux, F. (2014). Audiotactile interaction can change over time in cochlear implant users. *Front Hum Neurosci, 8*, 316.

Lappe, C., Herholz, S. C., Trainor, L. J., et al. (2008). Cortical plasticity induced by short-term unimodal and multimodal musical training. *J Neurosci, 28*, 9632–9639.

Lee, D. S., Lee, J. S., Oh, S. H., et al. (2001). Cross-modal plasticity and cochlear implants. *Nature, 409*, 149–150.

Lemus, L., Hernández, A., Luna, R., et al. (2010). Do sensory cortices process more than one sensory modality during perceptual judgments? *Neuron, 67*, 335–348.

Levänen, S., Jousmäki, V., Hari, R. (1998). Vibration-induced auditory-cortex activation in a congenitally deaf adult. *Curr Biol, 8*, 869–872.

Levänen, S., & Hamdorf, D. (2001). Feeling vibrations: enhanced tactile sensitivity in congenitally deaf humans. *Neurosci Lett, 301*, 75–77.

Looi, V., Sucher, C., McDermott, H. J. (2003) Melodies familiar to the Australian population across a range of hearing abilities. *Austr NZ J Audiol*, *25*, 75–83.

Lynch, M. P., Eilers, R. E., Oller, D. K., et al. (1988). Speech perception by congenitally deaf subjects using an electrocutaneous vocoder. *J Rehabil Res Dev, 25*, 41–50.

Magne, C., Schön, D., Besson, M. (2006). Musician children detect pitch violations in both music and language better than nonmusician children: Behavioral and electrophysiological approaches. *J Cogn Neurosci, 18*, 199–211.

McDermott, H. J. (2004) Music perception with cochlear implants: A review. *Trends in Hearing*, *8*, 49–82.

Middlebrooks, J. C., & Snyder, R. L. (2010). Selective electrical stimulation of the auditory nerve activates a pathway specialized for high temporal acuity. *J Neurosci, 30*, 1937–1946.

Nimmons, G. L., Kang, R. S., Drennan, W. R., et al. (2008). Clinical assessment of music perception in cochlear implant listeners. *Otol Neurotol, 29*, 149–155.

Pantev, C., Lappe, C., Herholz, S. C., et al. (2009). Auditory-somatosensory integration and cortical plasticity in musical training. *Ann N Y Acad Sci, 1169*, 143–150.

Pantev, C., Ross, B., Fujioka, T., et al. (2003). Music and learning-induced cortical plasticity. *Ann N Y Acad Sci, 999*, 438–450.

Ragert, P., Schmidt, A., Altenmüller, E., et al. (2004). Superior tactile performance and learning in professional pianists: evidence for meta-plasticity in musicians. *Eur J Neurosci, 19*, 473–478.

Röder, B., Teder-Sälejävi, W., Sterr, A., et al. (2014) Improved auditory spatial tuning in blind humans. *Nature*, *400*, 162–166.

Rothenberg, M., & Molitor, R. D. (1979). Encoding voice fundamental frequency into vibrotactile frequency. *J Acoust Soc Am, 66*, 1029–1038.

Rouger, J., Lagleyre, S., Fraysse, B., et al. (2007). Evidence that cochlear-implanted deaf patients are better multisensory integrators. *Proc Natl Acad Sci U S A, 104*, 7295–7300.

Sharma, A., Gilley, P. M., Dorman, M. F., et al. (2007). Deprivation-induced cortical reorganization in children with cochlear implants. *Int J Audiol, 46*, 494–499.

Schulz, M., Ross, B., Pantev, C. (2003). Evidence for training-induced crossmodal reorganization of cortical functions in trumpet players. *Neuroreport, 14*, 157–161.

Singh, S., Kong, Y. Y., Zeng, F. G. (2009). Cochlear implant melody recognition as a function of melody frequency range, harmonicity, and number of electrodes. *Ear Hear, 30*, 160–168.

Sokal, R. R., & Rohlf, J. F. (1981). *Biometry: The Principles and Practice of Statistics in Biological Research* (2nd ed.) (859p). San Francisco: W.H. Freeman and Company.

Studebaker, G. A. (1985). A “rationalized” arcsine transform. *J Speech Hear Res, 28*, 455–462.

Tang, Q., Benítez, R., Zeng, F. G. (2011). Spatial channel interactions in cochlear implants. *J Neural Eng, 8*, 046029.

Tervaniemi, M., Just, V., Koelsch, S., et al. (2005). Pitch discrimination accuracy in musicians vs nonmusicians: An event-related potential and behavioral study. *Exp Brain Res, 161*, 1–10.

Turner, C. W., Gantz, B. J., Vidal, C., et al. (2004). Speech recognition in noise for cochlear implant listeners: benefits of residual acoustic hearing. *J Acoust Soc Am, 115*, 1729–1735.

Verrillo, R. (1963). Effect of contactor area on the vibrotactile threshold. *J Acoust Soc Am*, *81*, 1906–1916.

Verschuur, C., Hellier, W., Teo, C. (2016). An evaluation of hearing preservation outcomes in routine cochlear implant care: Implications for candidacy. *Cochlear Implants Int, 17(Suppl 1)*, 62–65.

von Ilberg, C., Kiefer, J., Tillein, J., et al. (1999). Electric-acoustic stimulation of the auditory system. New technology for severe hearing loss. *ORL J Otorhinolaryngol Relat Spec, 61*, 334–340.

Waldstein, R. S., & Boothroyd, A. (1995). Comparison of two multichannel tactile devices as supplements to speechreading in a postlingually deafened adult. *Ear Hear, 16*, 198–208.

Waldstein, R. S., & Boothroyd, A. (1995). Speechreading supplemented by single-channel and multichannel tactile displays of voice fundamental frequency. *J Speech Hear Res, 38*, 690–705.

Weisenberger, J. M. (1989). Evaluation of the Siemens Minifonator vibrotactile aid. *J Speech Hear Res, 32*, 24–32.

Weisenberger, J. M., Heidbreder, A. F., Miller, J. D. (1987). Development and preliminary evaluation of an earmold sound-to-tactile aid for the hearing-impaired. *J Rehabil Res Dev, 24*, 51–66.

Weisenberger, J. M., & Miller, J. D. (1987). The role of tactile aids in providing information about acoustic stimuli. *J Acoust Soc Am, 82*, 906–916.

Wilson, B. S., Finley, C. C., Lawson, D. T., et al. (1991). Better speech recognition with cochlear implants. *Nature, 352*, 236–238.

Wu, C., Stefanescu, R. A., Martel, D. T., et al. (2015). Listening to another sense: somatosensory integration in the auditory system. *Cell Tissue Res, 361*, 233–250.

Yao, W. N., Turner, C. W., Gantz, B. J. (2006). Stability of low-frequency residual hearing in patients who are candidates for combined acoustic plus electric hearing. *J Speech Lang Hear Res, 49*, 1085–1090.

Yau, J. M., Olenczak, J. B., Dammann, J. F., et al. (2009). Temporal frequency channels are linked across audition and touch. *Curr Biol, 19*, 561–566.

Yau, J. M., Weber, A. I., Bensmaia, S. J. (2010). Separate mechanisms for audio-tactile pitch and loudness interactions. *Front Psychol, 1*, 160.

Zeng, F. G., Rebscher, S., Harrison, W., et al. (2008). Cochlear implants: system design, integration, and evaluation. *IEEE Rev Biomed Eng, 1*, 115–142.

Zhang, T., Dorman, M. F., Gifford, R., et al. (2014). Cochlear dead regions constrain the benefit of combining acoustic stimulation with electric stimulation. *Ear Hear, 35*, 410–417.