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Impact of Auditory-Motor Musical Training on Melodic Pattern Recognition in Cochlear Implant Users

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Objective: Cochlear implant (CI) users struggle with tasks of pitch-based prosody perception. Pitch pattern recognition is vital for both music comprehension and understanding the prosody of speech, which signals emotion and intent. Research in normal-hearing individuals shows that auditory-motor training, in which participants produce the auditory pattern they are learning, is more effective than passive auditory training. We investigated whether auditory-motor training of CI users improves complex sound perception, such as vocal emotion recognition and pitch pattern recognition, compared with purely auditory training.

Study Design: Prospective cohort study.

Setting: Tertiary academic center.

Patients: Fifteen postlingually deafened adults with CIs.

Intervention(s): Participants were divided into 3 one-month training groups: auditory-motor (intervention), auditory-only (active control), and no training (control). Auditory-motor training was conducted with the “Contours” software program and auditory-only training was completed with the “AngelSound” software program.

Main Outcome Measure: Pre and posttest examinations included tests of speech perception (consonant–nucleus–consonant, hearing-in-noise test sentence recognition), speech prosody perception, pitch discrimination, and melodic contour identification.

Results: Participants in the auditory-motor training group performed better than those in the auditory-only and no-training ($p < 0.05$) for the melodic contour identification task. No significant training effect was noted on tasks of speech perception, speech prosody perception, or pitch discrimination.

Conclusions: These data suggest that short-term auditory-motor music training of CI users impacts pitch pattern recognition. This study offers approaches for enriching the world of complex sound in the CI user. **Key Words:** Auditory-motor training—Cochlear implants—Music—Music training—Pitch-based speech prosody—Vocal emotion.

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Cochlear implants are remarkable in their ability to restore hearing and improve quality of life for many profoundly deaf individuals. Cochlear implant (CI) users perform well in tasks of speech discrimination, but have difficulty in tasks of complex sound perception, such as hearing in noise and music perception (1,2). Despite tremendous improvement in processing strategies and electrode design, CI devices continue to provide only

coarse spectral information, resulting in poor frequency resolution. Thus, current CI devices remain limited in their ability to encode fine structure information, which is critical for pitch perception (3,4). Poor pitch perception leads to worse performance in perception of speech-in-noise, tonal language, and music (5–7). Not surprisingly, CI users underperform relative to age-matched normal-hearing (NH) listeners on a wide array of music perception and complex sound processing tasks (8–10).

Music training in NH individuals is a promising strategy for improving a variety of auditory and cognitive skills. In NH individuals, music perception abilities have been linked to perception of pitch-based speech prosody (i.e. perception of sentence intonation contours) and speech-in-noise (11–13). A comparison of the performance between highly trained musicians and nonmusician controls showed that musicians outperformed nonmusicians in tasks of hearing in noise, particularly when presented with simultaneous auditory stimuli from

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different spatial locations (14). In NH individuals, intensive music training improves complex auditory skills not exclusively related to music, such as speech, language, recognition of emotion, and other auditory processing tasks (15–18). Moreover, longitudinal studies suggest that improved performance in these tasks is more likely a result of training than of genetic predispositions (19–21).

There is emerging evidence that music training in CI users may confer benefits in other areas of complex auditory processing as is seen in NH listeners (28–30). Music training in CI users has been shown to have a mixed effect on short- and long-term music perception, with some studies demonstrating a substantial improvement in pitch perception, timbre identification, and melody recognition, whereas others show only a modest effect following training (22–26). Galvin et al (27) found that those who underwent music training exercises identified melodic contours (i.e. pitch patterns) more accurately. Although relatively sparse literature exists on this subject, it is predicted that auditory-motor training (i.e. playing an instrument or producing pitch patterns) may be superior to auditory-only, or purely perceptual, training. The process of playing an instrument is thought to create an “action-perception link” between the motor and auditory systems of the brain, which could strengthen the effect of training (31–33).

If music training can improve auditory perception, and this leads to performing complex speech processing tasks well, then it follows that music training may improve speech perception in CI users. Although several authors have investigated the effect of music training on speech perception, these studies have produced mixed results. Lo et al (34) investigated the effects of melodic contour identification training using purely perceptual music training on speech perception in CI users. Although consonant recognition and speech prosody perception improved in CI users after training, there was no perceived benefit for sentence recognition in noise. Fuller et al (35) studied the effects of individual and group music training approaches in CI users on speech and music perception. Participants in the individual training approach completed melodic contour identification (MCI) exercises on a computer, whereas those in the group training approach engaged in group exercises of music perception, singing, vocal emotion identification, and music improvisation. Although posttraining MCI performance improved for those in the individual training program and vocal emotion identification scores improved in the music therapy group, no cross-over benefit was noted.

A pilot study by Patel (36), in which 2 CI users underwent short-term keyboard training, showed moderate improvements in speech perception in noise and pitch-based prosody perception (36). These early data suggested that simple music training of CI users may have an impact on music perception (melodic contour identification, pitch perception) as well as complex speech tasks (emotion-based speech prosody identification and speech perception in noise). Here, we examined

the effect of short-term auditory-motor training of melodic contour processing on tasks of music perception (pitch ranking and melodic contour identification) and speech perception (speech-in-quiet, speech-in-noise, and emotion-based prosody identification) compared with auditory-only melodic contour training in CI users. Music training that includes multimodal interactions (i.e. combined auditory and motor processes) has been associated with improved outcomes compared with purely perception training (37,38). Thus, we hypothesized that auditory-motor training would result in improved outcomes compared with auditory-only training in music and speech perception.

METHODS

Participants

Participants were postlingually deafened unilateral or bilateral CI users, adults ages 18 or older, with at least 1 year of CI experience. Only 1 ear was tested for each individual, typically the participant’s “better-performing ear,” as determined by subjective preference. Participants with residual or bimodal hearing were asked to replace their hearing aid with an earplug. All participants were English speakers without vision problems or cognitive or learning disorders. Exclusion criteria included failure to comply with the study requirements of music training. We enrolled 20 CI users for this study. Two participants were eliminated from analysis because of inability to complete the training protocols. Thus, 18 CI users (8 female, 10 male) ranging in age from 28 to 70 ($M = 61.6$, $SD = 10.5$) and CI experience from 1 to 18 years ($M = 8.3$, $SD = 5.4$) were included in the study analysis. All 3 CI manufacturers were represented in this study (Advanced Bionics [6 patients], Cochlear [9 patients], and Med El [3 patients]). Relevant patient demographics are summarized in Table 1. The UCSF Office of Ethics and Compliance approved the protocol. Written informed consent was obtained from all participants.

Study Design

Participants were randomly assigned to 1 of 3 groups: intervention (7 patients), active control (7 patients), and passive control (4 patients). All participants completed baseline and posttraining speech and music performance evaluations that included testing of speech-in-quiet, speech-in-noise, emotion-based speech prosody, pitch discrimination, and melodic contour identification. Baseline and posttraining examinations were performed 4 weeks apart. Participants in the intervention and active control arms completed music training exercises as specified below for 30 min/day, 5 days/week for 1 month, for a total of 10 training hours. All training exercises were completed at home. Patients in the passive control (no intervention) arm did not undergo any training exercises.

Patients in the intervention arm completed auditory-motor training exercises that consisted of melodic contour patterns performed on a keyboard, using the freely available Contours software application as described in Colgrove and Patel (39). This software application provides simple musical keyboard training targeted to individuals with no prior music experience. The keyboard setup and Contours program are shown in Figure 1A. Training consisted of visual cues (matching the colored keys of the piano keyboard to the notes), auditory cues (listening to the pitch presented), and motor cues (correctly playing the pattern of notes). The melodic contours varied in

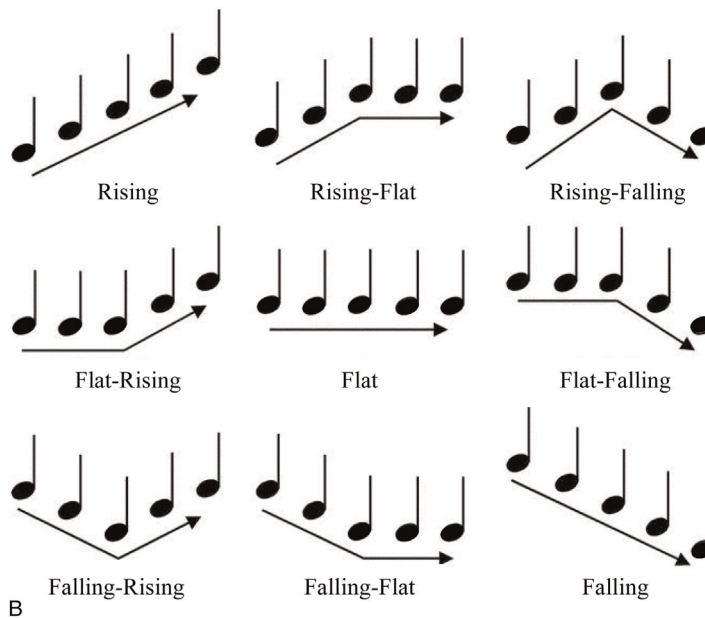
TABLE 1. Patient demographics

Patient	Age	HL Cause	Pre or Postlingually Deafened	Age at Onset of HL	Age at Profound HL	DPD (yrs)	Age at implantation	Length of CI Use (yrs)	Unilateral/Bilateral/Bimodal	CI Device
Int_1	67	Idiopathic	Post	28	39	26	65	1	Unilateral (R)	AB HiRes Ultra Naida Q90
Int_2	55	Congenital	Pre	0	16	23	39 (R); 41 (L)	16 (R); 14 (L)	Bilateral (Pref: R)	Cochlear N24 Contour CP810 (R, L)
Int_3	57	EVAS	Pre	3	45	3	54 (R); 48 (L)	3 (R); 9 (L)	Bilateral (Pref: R)	AB HiRes Advantage Naida Q90 (R, L)
Int_4	57	Idiopathic	Post	12	35	20	55	2	Unilateral (L)	Cochlear N5
Int_5	67	Autoimmune	Post	12	43	21	64	3	Unilateral (R)	AB HiRes Ultra Naida Q90
Int_6	54	Trauma	Post	7	18	31	52 (R); 49 (L)	2 (R); 5 (L)	Bilateral (Pref: L)	Med-El Rondo (R, L)
Int_7	70	Idiopathic	Post	48	60	0	62 (R); 60 (L)	8 (R); 10 (L)	Bilateral (Pref: L)	AB HiRes 90K Helix Naida Q90 (R, L)
AC_1	60	Idiopathic	Post	6	53	1	58 (R); 54 (L)	2 (R); 6 (L)	Bilateral (Pref: L)	AB HiRes 90K UltraNaida Q90 (R); AB HiRes 90K Advantage Neptune (L)
AC_2	58	Autoimmune	Post	23	40	0	40	18	Unilateral (R)	AB CII HiFocus II Naida
AC_3	65	Idiopathic	Post	28	43	13	56	9	Unilateral (R)	Cochlear N6
AC_4	67	Idiopathic	Post	39	49	2	51 (R); 62 (L)	16 (R); 5 (L)	Bilateral (R)	Cochlear N6 (R, L)
AC_5	68	Idiopathic	Post	5	40	12	52	16	Unilateral (L)	Cochlear N24 Contour CP910
AC_6	28	Congenital	Post	0	15	1	16	12	Unilateral (R)	Cochlear N6 CI24RE
AC_7	80	Idiopathic	Post	68	71	7	72	8	Unilateral (R)	Med-El Rondo
PC_1	61	Cochlear otosclerosis	Post	18	40	14	55	6	Unilateral (R)	Cochlear Freedom Contour Advance
PC_2	66	Idiopathic	Post	40	61	3	64	2	Unilateral (L)	Med-El Rondo
PC_3	66	Idiopathic	Post	10	50	6	56	10	Bilateral (Pref: R)	Cochlear Freedom Contour Advance (R); Cochlear CI512 (L)
PC_4	64	Idiopathic	Post	12	58	5	55 (R); 57 (L)	9 (R); 7 (L)	Bilateral (Pref: L)	Cochlear N5 (R); Cochlear N6 (L)

AB indicates advanced bionics; AC, active control; DPD, duration of profound deafness; EVAS, enlarged vestibular aqueduct syndrome; HL, hearing loss; Int, intervention arm; L, left ear; PC, passive control; Pref, preferred; R, right ear.



A



B

FIG. 1. (A) Keyboard setup for the intervention group, depicted with the Contours program, designed by Colgrove and Patel (39). (B) Nine melodic patterns, or contours, were used in MCI baseline and posttraining tests using the methods of Galvin et al (27).

difficulty (0–5 semitone interval), length (5–7 notes within a pattern), and timbre (pure tones, piano, and violin). Patients were provided with a piano keyboard (CME Xkey 37-key ultraslim controller keyboard, Sweetwater Sound, Fort Wayne, IN), an Android tablet (Google Nexus 9 tablet [8.9-in]) with the Contours software application, and speakers (Sony XB10 portable Bluetooth connectivity). Patients were instructed to spend 1 week on the “Easy” and “Medium” levels and 2 weeks on the “Hard” level, where level varied based on semitone interval and contour length. If the participant felt that the “Medium” or “Hard” levels were too challenging, they could continue with the “Easy” level during their training. Participants completed all training

exercises at home. Compliance to training exercises was recorded in the application and monitored remotely by research staff.

Patients in the active control arm completed auditory-only, or purely perceptual, training that consisted of performing MCI exercises with varying levels of difficulty, from 0–5 semitone interval, and with different instrument timbre (pure tones, piano, and violin). Custom software was used for training (AngelSound™; Emily Shannon Fu Foundation, <http://angel-sound.tigerspeech.com>). Participants were provided with a laptop (Lenovo N3350 Idea Pad [11.6-in]) and speakers (Sony XB10 portable Bluetooth connectivity) and completed training exercises at home. Compliance to training exercises was

recorded on the laptop and monitored remotely by research staff.

Study Settings

The study took place at the University of California, San Francisco between January 2018 and January 2019. Patients were recruited through flyers posted on bulletin boards, at audiology outpatient clinics, and at hearing loss support group locations.

Testing was performed inside a soundproof booth. Speech and music stimuli were presented using a single loudspeaker (Sony SS-MB150H), calibrated to an average level of 65-dB SPL. Verbal responses for the open-set word and speech-in-noise testing were scored by the experimenter in an adjacent room. Responses for the closed-set tasks were collected via touch-screen on a Windows surface tablet (ClearType HD Display [10.6-in]) located inside a sound booth.

Experimental Design

Word Discrimination in Quiet

Monosyllabic word recognition testing was performed using standard consonant–nucleus–consonant word lists (40). Different word lists were used for each individual's baseline and posttraining testing to prevent potential bias.

Speech-in-Noise

Sentence recognition in noise was assessed using the Bamford–Kowal–Bench speech-in-noise (BKB-SIN) test (41). Participants were presented with a paired list, each composed of 10 sentences spoken by a male voice in the presence of a 4-talker babble with an extended speech-to-noise ratio (SNR) range (+21 to –6 dB). In this study, the target sentence level is fixed for the first 8 sentences and attenuated for sentences 9 and 10 by 3 and 6 dB, respectively. The babble level increases in 5-dB steps for the first 7 sentences and is fixed for sentences 8–10. Lists are scored on the basis of the number of correctly identified keywords. Performance is reported as SNR-50, in dB, calculated on the basis of the SNR at which a listener correctly recognizes 50% of the keywords.

Vocal Emotion Recognition

Emotion-based speech prosody was evaluated with voice-recordings, as described in Chatterjee et al (42). Twelve sentences were selected from the hearing-in-noise test, and spoken by 1 male and 1 female speaker with 5 emotions (angry, happy, neutral, sad, and scared). Participant underwent a training session before testing to become familiarized with the emotion-based prosody of the sentences using the same target emotions and male/female voices, but with different sentences that were not used during testing. Patients were exposed to 60 stimuli with a male voice and 60 stimuli with a female voice.

Pitch Discrimination

The pitch ranking task protocol was similar to that described in Deroche et al (43) and Jiam et al (26). Participants were presented with 2 sound stimuli and asked to choose the higher-pitched of the 2 tones. Pitch changes occurred at reference F_0 of 100–150 Hz. The target signals were sinusoidally modulated at 0, 2, 4, 6, 8, 10, and 12 semitones above the reference frequencies. Each tone lasted 300-ms, with a silent interval of 300-ms between stimuli. Each complex was equalized at 65-dB SPL before the start of the study and presented with a ± 3 dB rove to discourage listeners from relying on loudness cues.

Melodic Contour Identification

MCI was measured using stimuli as in Galvin (44) adapted to be used on AngelSound custom software. Stimuli consisted of 9 melodic contours with 5 notes each that varied in pitch pattern: “Rising,” “Flat,” “Falling,” “Flat-Rising,” “Falling-Rising,” “Rising-Flat,” “Falling-Flat,” “Rising-Falling,” and “Flat-Falling,” as shown in Figure 1B. The spacing between successive notes in the contours was between 0 to 5 semitones. The lowest note in a contour was A3 (220 Hz). Each note lasted 300-ms, with a silent interval of 50-ms between notes. Participants were presented with different timbre (pure tones and piano). Scores were reported in terms of percentage correct, calculated by the testing software.

Statistical Methods

Statistical analyses were performed using STATA (Stata-Corp; College Station, TX) and statistical significance was assessed at an α level of 0.05. For music and speech perception tasks, baseline and posttraining scores were compared and a delta score was obtained for each individual. To examine differences in performance among training groups, a 1-way analysis of variance with training group factors (intervention, active control, and passive control) was used. A Tukey–Kramer correction for multiple comparisons was used to examine *post hoc* pairwise differences between training groups. The degree of freedom between-groups and within-groups was 2 and 15, respectively.

Multiple regression analyses were used to assess the effect of duration of profound deafness, age of onset of hearing loss, and age of profound hearing loss on performance across the 3 training groups.

RESULTS

Demographics

The mean age of participants in the 3 groups was similar (intervention: $M = 61$; active control: $M = 60.8$; passive control: $M = 64.2$). No significant difference was noted in patient age among groups [$F(2, 15) = 0.14$, $p > 0.05$]. Similarly, age of implantation was not found to be significantly different among groups [$F(2, 15) = 0.83$, $p > 0.05$]. However, the length of CI use varied significantly among the groups [$F(2, 15) = 3.72$, $p = 0.04$]. Additionally, although all 3 CI manufacturers were represented in this study, there was not equal representation of each manufacturer in each training group.

Word Discrimination in Quiet

Figure 2 shows the mean scores (percent correct) for baseline and posttraining for consonant discrimination in quiet. Analyses were conducted to determine whether auditory-motor training and/or auditory-only training correlated to improvement in posttraining scores compared with the no-training group. No significant training effect was noted [$F(2, 15) = 0.60$, $p = 0.56$].

Speech-in-Noise

Mean performance on the speech-in-noise task is shown in Figure 3A. Performance is measured as a function of SNR, in dB, for 50% correct speech recognition. Performance was better with lower babble levels

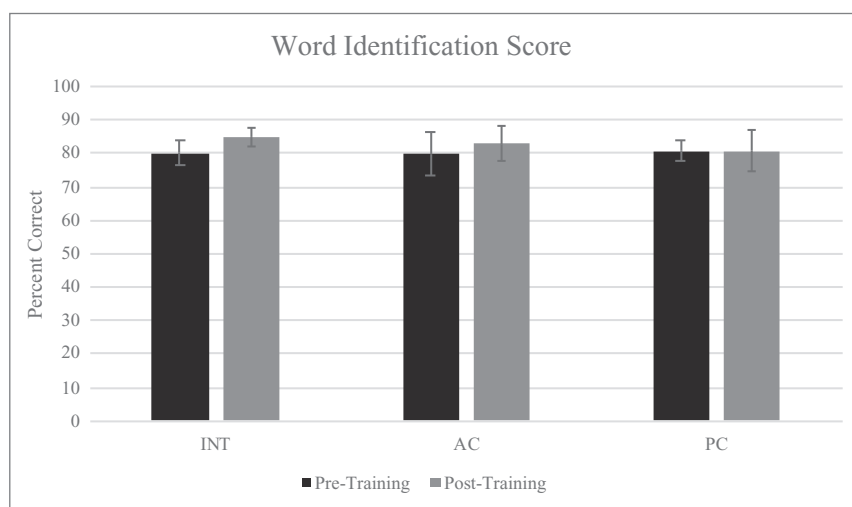


FIG. 2. Mean word identification scores (percent correct) in quiet before and after training, for the 3 participant groups. (B) The intervention, active control, and passive control training groups are abbreviated here as INT, AC, and PC, respectively.

and declined as the babble level increased, as expected. No significant training effect was noted [$F(2, 15) = 0.31$, $p = 0.73$]. Figure 3B shows individual “delta” scores, or the difference in performance on BKB-SIN in the baseline and posttraining conditions for each patient. A negative score indicates an improvement in performance. Within the active control group, the mean posttraining score was better than the baseline performance, though without statistical significance ($t = 0.86$, $p > 0.05$).

Vocal Emotion Recognition

Figure 4 shows the vocal emotion identification scores before and after training for the 3 participant groups. Although individuals in the intervention and active control training groups demonstrated a general trend toward improvement in this task, these results were not statistically significant [$F(2, 15) = 0.34$, $p = 0.72$] and [$F(2, 15) = 1.37$, $p = 0.28$], for the male and female voices, respectively.

Pitch Discrimination

Mean performance for the pitch discrimination task before and after training for the 3 participant groups is shown in Figure 5. Pitch discrimination scores were subdivided on the basis of the semitone interval between the 2 notes presented. Patients tended to perform more poorly when presented with smaller semitone intervals. Music training had no perceived effect on performance.

Melodic Contour Identification

Mean baseline and posttraining MCI scores for each training group in the pure tones and piano conditions are shown in Figure 6. The mean baseline performance level varied among the training groups, though these differences were not statistically significant; [$F(2, 15) = 0.09$, $p = 0.91$] and [$F(2, 15) = 0.35$, $p = 0.71$] for the pure tones and piano conditions, respectively.

In the pure tones condition, no significant training effect was noted [$F(2, 15) = 0.64$, $p = 0.54$]. The mean improvement scores for intervention, active control, and passive control training groups were 8.74%, 11.47%, and 3.1%. In the piano condition, however, participants in the intervention group significantly improved following training compared with patients in the active control and passive control groups [$F(2, 15) = 6.59$, $p = 0.01$] with posthoc Tukey–Kramer correction ($\alpha < 0.05$). Individuals in the intervention group in the piano condition demonstrated the greatest degree of improvement, with an average increase of 17.8% following training. Participants in the active control group improved posttraining MCI scores only modestly (mean improvement of 4%), whereas those in the passive control group demonstrated a slightly poorer performance following training, with an average decline of 1.1% posttraining.

Multiple regression analyses showed that factors such as age of onset of hearing loss (HL), age at profound hearing loss (PHL), and duration of profound deafness (DPD) did not affect performance even after controlled for differences in performance across the 3 training groups (HL: $\beta = 0.03$, $p = 0.82$; PHL: $\beta = 0.01$, $p = 0.92$; DPD: $\beta = 0.36$, $p = 0.16$).

DISCUSSION

In this study, we investigated the following research questions: Does music training improve both music perception and complex speech perception in cochlear implant users, and if so, which aspects of complex speech are improved? Does auditory-motor training have a greater effect on performance on music and speech perception tasks compared with auditory-only training? Our results show that music training may be beneficial for some, though not all, aspects of music and speech perception in CI users. Specifically, we found that for

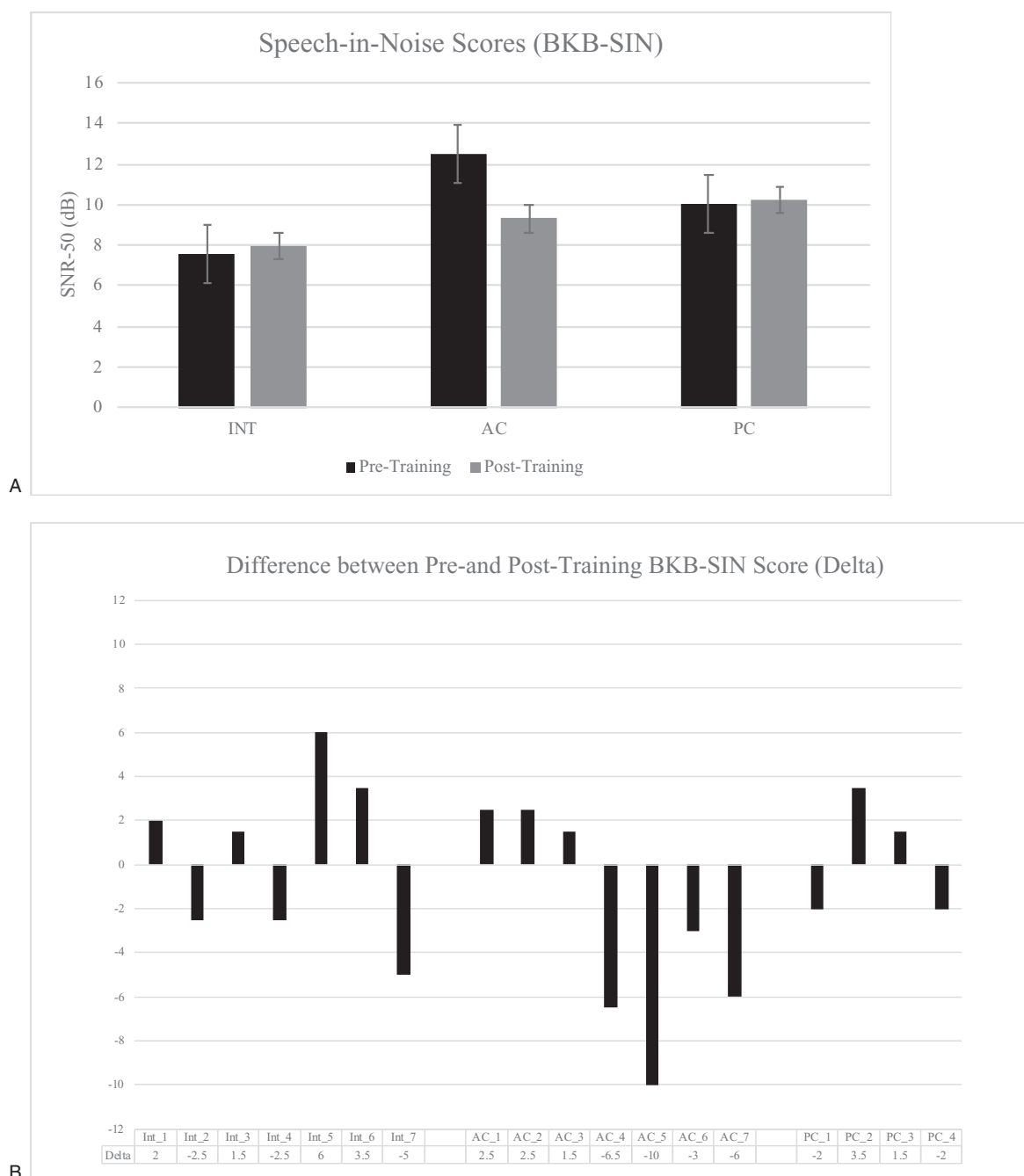


FIG. 3. (A) Performance on the speech-in-noise task before and after training, for the 3 participant groups. Performance is reported as SNR-50, in dB, calculated on the basis of the SNR at which a listener correctly recognizes 50% of the keywords. A lower score indicates better performance. (B) Difference between baseline and posttraining BKB-SIN scores. Delta denotes the difference in score, where a negative delta indicates improvement in performance. Abbreviations for training groups as in Figure 2.

complex, musical tones, auditory-motor training may be superior to auditory-only training.

Our results show no significant improvement for perception of sentences in noise regardless of training group. By contrast, preliminary data from Patel (36) showed enhanced perception of speech-in-noise in 1 patient and improvement in a speech prosody task in another patient. Four patients (Int_7, AC_4, AC_5, and AC_7) showed a

robust improvement in speech reception thresholds. Interestingly, 2 of the 4 patients were bimodal listeners with a contralateral hearing aid. Lo et al (34) also noted a large improvement in speech reception thresholds of certain individuals without a significant group effect. As these individuals were also bimodal listeners, the authors postulated that hearing aid users, with more access to acoustic and fine-structure cues, may find melodic contour training

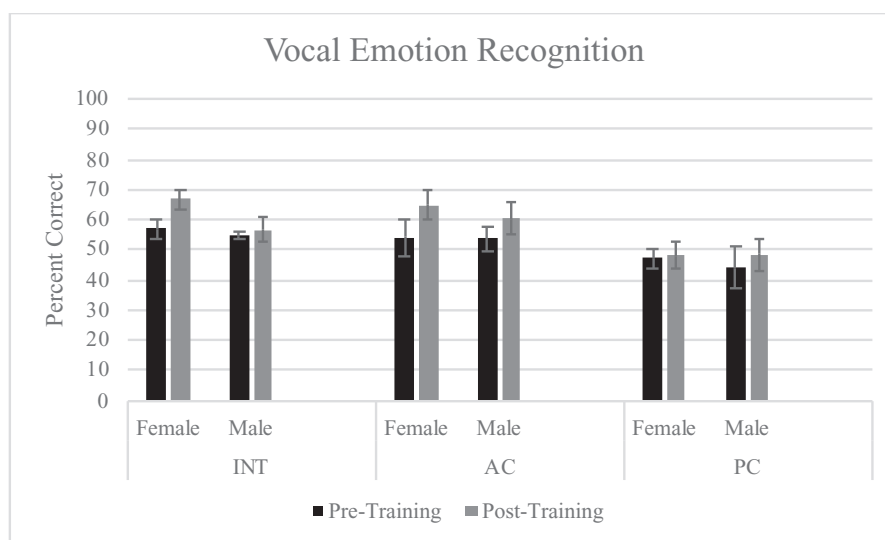


FIG. 4. Performance on vocal emotion identification task before and after training, for the 3 participant groups. Abbreviations for training groups as in Figure 2.

particularly effective for perceiving speech in noise. Our findings suggest that musical training may provide meaningful auditory processing benefits to certain types of CI users, such as those with bimodal hearing.

Certain aspects of complex speech perception were enhanced following training. In particular, vocal emotion recognition of female voice excerpts showed a trend toward improvement in the auditory-motor and auditory-only groups. Fuller et al (35) found that when individuals are exposed to specific training for emotion identification, they demonstrate improvement in vocal emotion identification scores. However, the authors

found that other types of perceptual music training (i.e. pitch/timbre) did not have the same effect on emotion-based speech prosody perception. In our study, we hypothesize that the training paradigm may have led to improved fundamental frequency, F0, tracking, resulting in enhanced performance in vocal emotion identification. However, further studies are needed to determine the relationship between training and speaker-specific differences (i.e. frequency, intonation, prosody, and so on) on vocal emotion recognition.

Previous studies have investigated the effect of short-term training on pitch perception in CI users and found

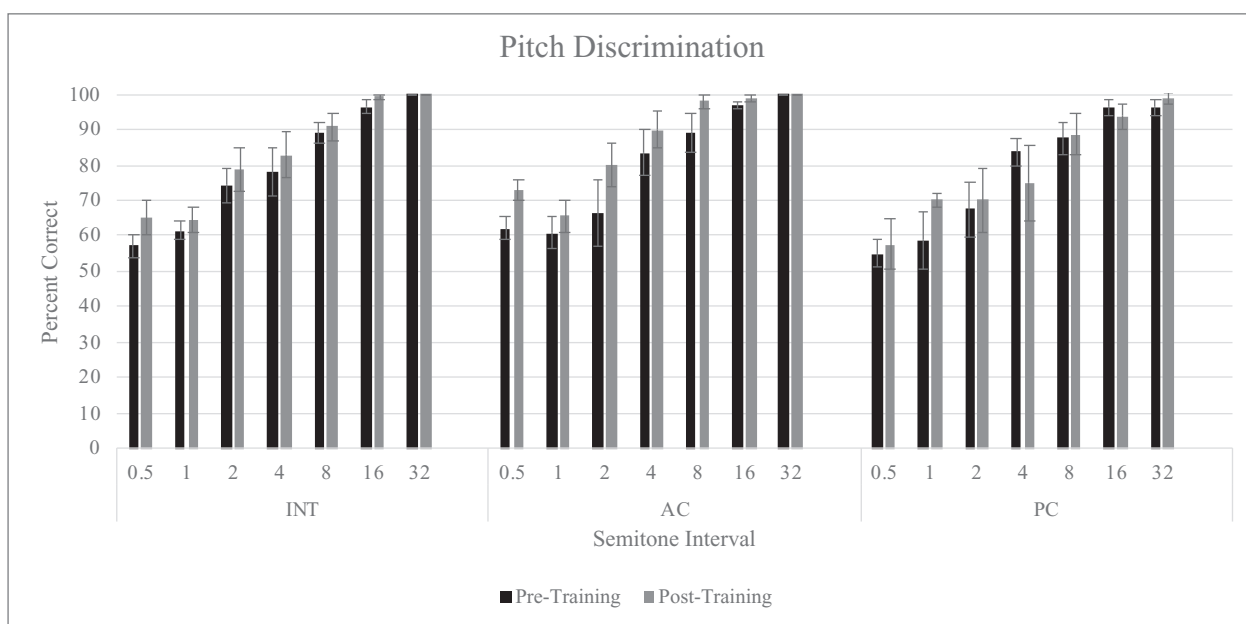


FIG. 5. Performance on pitch discrimination task before and after training, for the 3 participant groups. Abbreviations for training groups as in Figure 2.

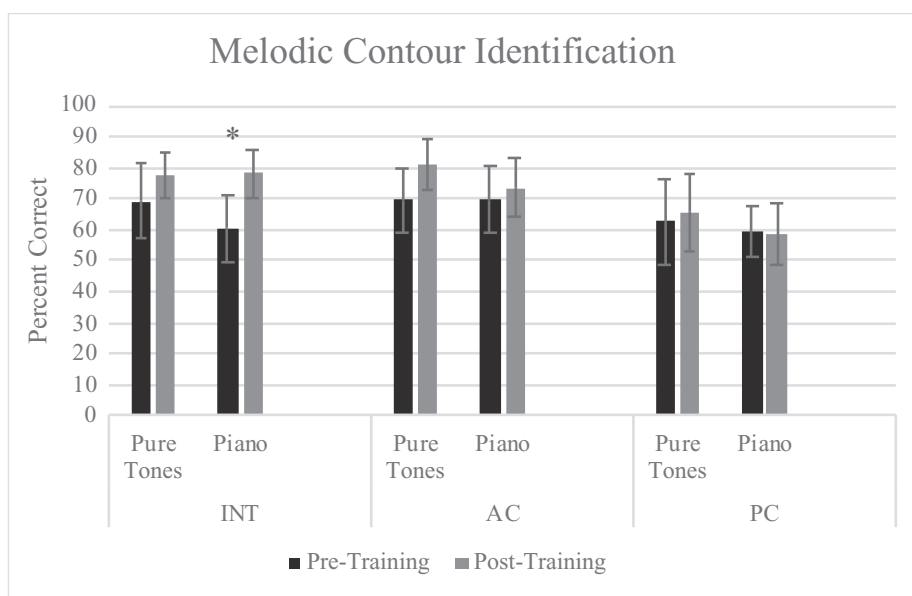


FIG. 6. Performance on melodic contour identification task before and after training, for the 3 participant groups.

mixed results (26,30). In our study, we found no significant difference in performance in the pitch discrimination task between training groups. Several of the participants reached a ceiling effect with this task before training, which may explain why no significant training effect was noted.

In general, melodic contour training, whether auditory-motor or auditory-only, improved MCI performance. Post-training MCI scores improved most dramatically in the auditory-motor training group in the piano condition compared with the auditory-only training group and the no-training group. However, in the pure tones condition, a roughly equivalent increase in posttraining MCI scores was noted in both the auditory-motor and auditory-only training groups. We suspect that auditory-motor training may be better than auditory-only training for certain types of musical timbre, such as piano, which have rich spectral complexity. However, when the target sound is simpler, such as in the pure tones condition, music training of any type (i.e. auditory-motor or auditory-only) may be beneficial.

There are several limitations to the present study. First, there was a relatively small sample size of participants within each training group. Second, there is considerable variability in average length of CI use, type of CI device among groups, and programming strategy which could impact complex sound perception. Further, duration of deafness and use of hearing aid amplification varied among patients. We were unable to control for these variables in our study. Third, the average age of participants is high ($M = 61.6$) and the length of training was fairly short. Future studies may be useful to determine whether our results could be replicated with a younger, and perhaps more recently

implanted, cohort, and whether the benefit in sound perception is enhanced by increasing the length of training.

In summary, a short, 4-week training course has the ability to improve music perception in CI users. Specifically, we found that auditory-motor training results in a robust improvement of MCI scores in the piano condition compared with auditory-only training. We suspect that the auditory-motor training may be beneficial for certain types of music perception, but further training studies involving variations in instrument and timbre are needed to better characterize the relationship between auditory-motor training and complex sound perception.

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