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Melodic Contour Identification by Cochlear Implant Listeners

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Abstract

Objective—While the cochlear implant provides many deaf patients with good speech understanding in quiet, music perception and appreciation with the cochlear implant remains a major challenge for most cochlear implant users. The present study investigated whether a closed-set melodic contour identification (MCI) task could be used to quantify cochlear implant users' ability to recognize musical melodies and whether MCI performance could be improved with moderate auditory training. The present study also compared MCI performance with familiar melody identification (FMI) performance, with and without MCI training.

Methods—For the MCI task, test stimuli were melodic contours composed of 5 notes of equal duration whose frequencies corresponded to musical intervals. The interval between successive notes in each contour was varied between 1 and 5 semitones; the "root note" of the contours was also varied (A3, A4, and A5). Nine distinct musical patterns were generated for each interval and root note condition, resulting in a total of 135 musical contours. The identification of these melodic contours was measured in 11 cochlear implant users. FMI was also evaluated in the same subjects; recognition of 12 familiar melodies was tested with and without rhythm cues. MCI was also trained in 6 subjects, using custom software and melodic contours presented in a different frequency range from that used for testing.

Results—Results showed that MCI recognition performance was highly variable among cochlear implant users, ranging from 14% to 91% correct. For most subjects, MCI performance improved as the number of semitones between successive notes was increased; performance was slightly lower for the A3 root note condition. Mean FMI performance was 58% correct when rhythm cues were preserved and 29% correct when rhythm cues were removed. Statistical analyses revealed no significant correlation between MCI performance and FMI performance (with or without rhythmic cues). However, MCI performance was significantly correlated with vowel recognition performance; FMI performance was not correlated with cochlear implant subjects' phoneme recognition performance. Preliminary results also showed that the MCI training improved all subjects' MCI performance; the improved MCI performance also generalized to improved FMI performance.

Conclusions—Preliminary data indicate that the closed-set MCI task is a viable approach toward quantifying an important component of cochlear implant users' music perception. The improvement in MCI performance and generalization to FMI performance with training suggests that MCI training may be useful for improving cochlear implant users' music perception and appreciation; such training may be necessary to properly evaluate patient performance, as acute measures may underestimate the amount of musical information transmitted by the cochlear implant device and received by cochlear implant listeners.

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INTRODUCTION

With advances in cochlear implant technology, cochlear implant users' speech recognition in quiet listening conditions has generally improved. However, music perception and appreciation remains a major challenge for cochlear implant users. Most current cochlear implant devices provide only 16 to 22 electrodes with which to represent the entire spectrum of sound. Although this coarse spectral resolution may be adequate for speech recognition, it is not sufficient to code musical pitch information (e.g., Gfeller et al., 2000; Kong et al., 2004; McDermott & McKay, 1997; Oxenham et al., 2004; Shannon et al., 2004; Smith et al., 2002). The limited spectral resolution in cochlear implants also precludes resolving of harmonics, which is important for pitch perception, timbre perception and segregating instruments. For complex sounds, resolved low-order harmonics generally yield stronger pitch percepts than higher-order harmonic components (e.g., Houtsma & Smurzynski, 1990); given that the cochlear implant does not provide enough spectral resolution to support resolving of harmonic components, the pitch of complex tones is less salient than for normal hearing (NH) listeners, and timbre percepts may be quite distorted relative to normal. Besides the relatively poor spectral resolution, cochlear implant listeners receive limited temporal information, which reduces the ability to track melodies according to the fundamental frequency (F0) of musical notes. Cochlear implant listeners are able to detect amplitude modulation over a limited frequency range (up to _300 Hz), further limiting access to temporal cues (Shannon, 1992).

Pitch perception is an important underlying component of music perception, as melody recognition strongly depends on perceiving exact intervals between successive notes. In normal and electric hearing, the pitch of a sound is thought be extracted from the place of stimulation in the cochlea (place code), by resolving frequency components in the neural firing pattern (temporal code), or possibly by analyzing phase components across the signal spectrum at different cochlear locations (e.g., Loeb, 2005; McKay et al., 2000; Tong et al., 1982). With NH listeners, it is difficult to disentangle the relative contributions of the place code and temporal code to pitch perception. Several studies have examined "nonspectral" pitch perception for sinusoidal amplitude modulated (SAM) noise (e.g., Burns & Viemeister, 1976, 1981) and have found that temporal pitch cues are generally weak above 300 Hz. In cochlear implant research, it is possible to separate the place and rate of stimulation and theoretically examine their relative contributions to pitch perception. Although there is great intersubject variability in cochlear implant users' electrode pitch range and resolution, temporal pitch becomes weaker above 300 Hz, similar to NH listeners (e.g., Shannon, 1983). Intersubject variability may be due to the location of the implanted electrodes and their proximity to healthy neural populations (which may be affected by the duration of deafness and etiology of hearing loss before implantation). Single- and multi-electrode place pitch sensitivity has been somewhat correlated with cochlear implant users' speech performance (e.g., Henry et al., 2000; Nelson et al., 1995). It is also possible that place and/or rate pitch percepts are not comparable to pitch percepts by NH listeners; while interpreted as pitch cues due to testing constraints (e.g., forced-choice tests, pitch scaling, and so on), cochlear implant users may actually be perceiving "timbre" cues, which, while ordered along a pitch continuum, may not support pitch-intensive listening tasks such as melody recognition or musical interval identification. Speech perception (e.g., phoneme, word, or sentence recognition in quiet) may rely less strongly on pitch cues and more strongly on spectral profile cues. Music perception, on the other hand, much more strongly depends on pitch cues. It is unclear how single-channel pitch discrimination, as typically measured in cochlear implant psychophysical studies, may contribute to multichannel music perception.

Several studies have tested cochlear implant listeners' music perception by directly stimulating the implanted electrodes with varying stimulation rate and electrode place (e.g.,

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McDermott & McKay, 1997; Pijl & Schwarz, 1995a; 1995b). Pijl & Schwarz (1995a) measured familiar melody recognition (without rhythmic cues) in cochlear implant users by varying the stimulation rate delivered to a single electrode. Several frequency ranges were used to code familiar melodies. Results showed that melody recognition was significantly better at the lower frequency ranges, reflecting the limits of patients' temporal processing above 300 Hz. Pijl & Schwarz (1995b) also tested the ability of non–musically trained cochlear implant subjects to reproduce musical pitch intervals by adjusting the stimulation rate delivered to a single electrode pair. Results showed that subjects were able to reproduce intervals within 1.5 semitones, using only temporal cues. McDermott & McKay (1997) similarly measured musical pitch perception in a musically trained cochlear implant user; both the electrode place and the rate of stimulation were varied. Results showed that although low-frequency rate cues (_500 Hz) provided some musical pitch information, electrode place provided the dominant pitch cue. Given the limits of temporal and spectral resolution measured directly in cochlear implant users, the cochlear implant can provide only a limited representation of musical melody.

Familiar melody recognition has been used to directly assess cochlear implant listeners' music perception abilities (e.g., Fujita & Ito, 1999; Kong et al., 2004; Pijl & Schwarz, 1995a, 1995b). In general, cochlear implant users' familiar melody recognition performance is much worse than that of NH listeners. Recently,Kong et al. (2004) investigated the relative contribution of temporal and spectral cues to familiar melody recognition in both cochlear implant listeners and NH subjects listening to acoustic cochlear implant simulations (in which the spectral resolution was varied between 1 and 64 channels). Melody identification was evaluated with two sets of 12 familiar melodies. One set contained both rhythm and melody information, whereas the other set contained only melody information. For NH subjects, high levels of performance were possible when both rhythm and melody cues were available, regardless of the spectral resolution. Interestingly, mean cochlear implant performance was lower than that of NH subjects listening to a single-channel acoustic cochlear implant simulation, suggesting that cochlear implant users were not able to access the rhythm cues contained in the melodies as well as NH listeners. When the rhythm cues were removed, 32 or more frequency channels were required for NH listeners to obtain a high level of performance. Without rhythm cues, cochlear implant listeners' melody recognition performance was most comparable to that of NH subjects listening to 1 to 2 spectral channels. Given that cochlear implant users typically can access 4 to 8 spectral channels provided by the cochlear implant device for speech recognition (e.g., Fishman et al., 1997; Friesen et al., 1999; Fu et al., 1998; Fu & Nogaki, 2005), it is unclear why cochlear implant users cannot utilize a similar number of spectral cues for melody recognition. It is probable that perception of exact pitch intervals is more important to melody recognition than to speech recognition. Although music listening experience (before and after implantation) may have contributed to differences in cochlear implant and NH performance, familiar melody identification performance is quite similar between musician and nonmusician NH listeners (e.g., Bigand, 2003; Madsen & Staum, 1983). It is unclear whether musical experience may benefit recognition of spectrally distorted, isochronously presented familiar melodies. For example,Lynch et al. (1991) found that music experience/education and cultural background greatly influenced melody recognition performance when notes within a melody were mistuned, similar to the sort of mistuned pitch effects cochlear implant listeners may experience.Gfeller et al. (2000) described the listening habits and music appreciation of a large number of subjects (65 cochlear implant users). Music appreciation with the cochlear implant tended to vary according to the listening environment, prior familiarity with a musical piece, and structural components (type of instrument, type of rhythm, and so forth). It is also possible that the pitch quantization and pitch distortion associated with the implant device affected cochlear implant users more strongly than NH subjects listening to cochlear implant simulations (which may have more

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to do with the veracity of the simulations than perceptual differences between the two subject groups).

One shortcoming of testing familiar melody recognition is that the limits of the cochlear implant device to represent melody cannot be accurately quantified, and in turn cannot be used to guide any speech processor optimization for music perception. Presently, there are no music perception tests that can provide this sort of information, whether because of limited number of stimuli, or constraints imposed by the task. For example, Gfeller et al. (1991, 1997) measured cochlear implant users' melody and rhythm discrimination using the Primary Measures of Musical Audition (PMMA) test (Gordon, 1979). In the PMMA test, cochlear implant subjects were asked whether a pair of melodies or rhythms were the same or different; melodies had between 2 and 5 notes, and one or more of the notes was varied. Results showed that cochlear implant listeners were more sensitive to changes in rhythm than in melody. However, because a two-alternative discrimination task was used to measure performance, the high chance level (50% correct) as well as the limited number of stimuli (40 items) did not allow the limits of melody recognition performance to be quantified precisely.

In developing an appropriate and meaningful test of cochlear implant users' music perception, it is important to consider the perceptual processes targeted by the listening task. For example, familiar melody identification may require closer attention to the exact intervals presented in the melody, whereas perception of novel melodies may involve attention to the "pitch contour" of the melody (e.g., Dowling, 1994). As such, deviations from the expected intervals for a familiar melody may strongly affect identification performance. For novel melodies, perceiving the structural elements may depend less on the exact intervals, and more on the general contour of changes in pitch, rhythm and timbre. Because cochlear implant users' perception of these structures will be limited by the amount of information transmitted by the device, it is important to quantify these limits in a systematic way. Currently, there is not a repeatable metric with which to compare music perception for different speech processor settings within individual patients. Such a metric would be very beneficial for evaluating novel speech processing strategies in terms of the amount of melodic information transmitted and received. In the present study, we developed the melodic contour identification (MCI) test as a metric to assess cochlear implant users' music perception. In the MCI test, cochlear implant users were asked to identify one of nine 5-note melodic contours. The interval between successive notes in each contour was systematically varied between 1 and 5 semitones to test the musical pitch resolution provided by the cochlear implant device. The "root note" (i.e., the lowest note in the contour) was also varied (A3, A4, and A5) to test whether there was optimal sensitivity to musical pitch in different frequency ranges. Three-harmonic complexes were used to represent the musical notes to test cochlear implant user performance in a multichannel context. For comparison purposes, familiar melody recognition was also evaluated with two sets of 12 familiar melodies, in which the rhythm cues were either preserved or removed.

EXPERIMENT 1: MELODIC CONTOUR IDENTIFICATION AND FAMILIAR MELODY IDENTIFICATION

Methods

Subjects—Eleven cochlear implant users participated in the present experiment. None were musicians before becoming deaf. All subjects were paid for their participation, and all provided informed consent before participating in the experiment (in compliance with the local Institutional Review Board protocol). There was a wide range in speech recognition performance and in music appreciation among the cochlear implant subjects. Relevant

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demographic details are shown in Table 1. For comparison, multitalker vowel and consonant recognition were also measured in these subjects. Detailed description of testing materials and procedures for phoneme recognition can be found inFu et al. (2005). The recognition scores for each individual cochlear implant users are listed in Table 1. Nine NH subjects were also tested to compare performance between cochlear implant and NH listeners in the melodic contour identification task.

Stimuli—Melodic contour identification performance was tested by using nine five-note melodic patterns. The nine patterns represented simple pitch contours (e.g., “Rising,” “Flat,” “Falling”) and changes in pitch contour (e.g., “Flat-Rising,” “Falling-Rising,” “Rising-Flat,” “Falling-Flat,” “Rising-Falling,” “Flat-Falling”). Figure 1 shows the melodic patterns and response screen used in the MCI test. The melodic contours were generated in relation to a “root note,” (i.e., the lowest note in the melody); the shaded notes in Figure 1 represent the root note in each contour. To test whether contours were better represented for different frequency ranges, three root notes were selected: A3 (220 Hz), A4 (440 Hz), and A5 (880 Hz). All notes in the contours were generated according to: $f=2^{\frac{x}{12}}f_{ref}$, where f is the frequency of the target note, x is the number of semitones relative to the root note and f_{ref} is the frequency of the root note. The interval between successive notes in the melodic contour was varied between 1 and 5 semitones. For example, for the “Rising” contour, when successive notes were separated by 5 semitones, the contour spanned almost 2 octaves; when successive notes were separated by 1 semitone, the contour spanned less than half an octave. Thus, for the MCI test, a total of 135 melodic contours were generated (9 melodic patterns × 3 root notes × 5 semitone distances). The fundamental frequency range covered by the entire stimulus set was 220 to 2794 Hz. Each note was generated as a harmonic complex: fundamental frequency [F0] + first harmonic (2*F0; −3 dB) + second harmonic (3*F0; −6 dB). Harmonic complexes (rather than pure tones) were used to better approximate some of the spectral components found in natural production of musical notes, and thereby better approximate cochlear implant subjects’ “real-world” music perception. Each note was 250 msec in duration; the onset was ramped (10 msec) and the offset was damped (10 msec) to reduce any transient spectral splatter. The interval between notes was 50 msec.

Figure 2 shows two examples of the “Rising” melodic contour, with root note A5 (880 Hz). The left contour has 5 semitones between successive notes; the right contour has 1 semitone between notes. The right y-axis shows frequency in Hz. The left axis shows the frequency channels assigned by Frequency Allocation Table 9, which is used by many Nucleus-22 patients. The horizontal lines show the cutoff frequencies of the analysis bands for Table 9. When there are 5 semitones between successive notes, each change in F0 is coded by a different channel (electrode). Because of the wide range of frequency components, the contour is represented using 15 of the available 22 electrodes. For this contour, cochlear implant listeners may attend to changes across frequency channels. When there is only 1 semitone between successive notes, changes in F0 are coded by, at most (depending on the root note), only 3 electrodes; the entire contour may activate, at most, 9 of the available 22 electrodes. For this contour, cochlear implant listeners may attend to changes within and across frequency channels. For within-channel pitch percepts, cochlear implant listeners may attend to temporal periodicity cues found in the modulated envelope, although these pitch cues are generally weaker than electrode place cues. Also, cochlear implant listeners may detect small changes in amplitude across adjacent electrodes, as the slope of the analysis filters is fairly broad, allowing some stimulation on nearby electrodes even for a tone centered within the analysis band. Small changes in these local spectral envelopes might provide some additional pitch information for the 1-semitone contours.

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Familiar melody identification (FMI) was also measured for 12 familiar melodies used by Kong et al. (2004, 2005), with and without rhythm cues. Three-harmonic complexes were generated for each note, using the same methods as for melodic contours. The F0 range covered by all melodies was 415 to 1047 Hz. Similar to the familiar melody analyses shown inKong et al. (2004) and Pijl & Schwartz (1995a), we analyzed the familiar melodies used in the present study. However, we have added more components to the analysis, including: the total number of notes, the number of novel notes (i.e., new notes within the contour), the number of changes in note, the semitone range, the number of novel beats (i.e., new beats within the contour), the number of changes in beat, the range of rhythm (in beats). These components were used to derive a “melodic index” and “rhythmic index” for each melody, thereby describing, to some extent, differences in melodic and rhythmic complexities among the test melodies. The melodic index was defined as the mean of the number of novel notes, the number of changes in note, and the semitone range, each divided by the total number of notes. Similarly, the rhythmic index was defined as the mean of the number of novel beats, the number of changes in beat, and the beat range, each divided by the total number of notes. The results of the analysis can be seen in Appendix 1. There are marked differences in the melodic and rhythmic indices between melodies.

For example, “Mary Had a Little Lamb” has a melodic index of 0.36, reflecting the limited number of novel notes and relatively small semitone range. “The Star Spangled Banner” has a melodic index of 0.94, reflecting the comparatively larger semitone range and number of novel notes. Note that while the melodic index may indicate differences in complexity between melodies, it does not indicate whether one melody might be easier to identify than another. For cochlear implant listeners, melodies with a large semitone range may be easier to identify than those with a small range. In many previous studies (e.g., Kong et al., 2004, 2005; Pijl & Schwartz, 1995a, 1995b), rhythm cues were removed from familiar songs to test the ability of the cochlear implant device to represent melody. However, the variability in the rhythmic index suggests that many melodies are not equally weighted in terms of rhythmic cues. For example, “Yankee Doodle Dandy” has a rhythmic index of 0.12, reflecting that the rhythm changes very little during the melody; removing the rhythmic information would not significantly affect the rhythm cues. “Happy Birthday” has a rhythmic index of 0.53, reflecting a wider range of beats and more changes in rhythm; thus, removing rhythmic information would more strongly affect the rhythm cues associated with this melody. Because both melody and rhythm cues are essential for melody recognition, simply removing the rhythm cues may not be the best approach to measure the ability of the cochlear implant device to represent melody.

We conducted similar analyses for the MCI stimuli; the results can be found in Appendix 2. The mean melodic index is 0.98 for the contours, somewhat higher than that of the familiar melodies (0.62). This difference is mainly due to the greater number of stimuli (45 contours versus 12 melodies) as well as the greater semitone range (1 to 20 for contours versus 4 to 16 for melodies) and the number of total notes (5 for contours versus 11 to 15 for melodies). Note that the rhythmic index is constant for all contours (0.07). Given the range of contours, the range of notes in each contour, and the three frequency ranges tested for each contour (A3, A4, A5), these melodic contours seem well suited for measuring the ability of the cochlear implant device to convey musical melody.

Procedures—Cochlear implant users were tested using their clinically assigned speech processors. Patients were asked to set their sensitivity and volume settings as they would for comfortably loud speech; once set, subjects were asked to not change these settings. Testing was conducted in free field in a sound-treated booth (IAC). Stimuli were delivered via a single loudspeaker (Tannoy Reveal) at 70 dBA; subjects sat directly facing the loudspeaker. For the MCI task, a stimulus was randomly selected (without replacement) from among the

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135 melodic contours in the stimulus set. Nine response choices were shown onscreen (see Fig. 1) and the subject clicked on the response choice he/she thought was correct. Subjects were allowed to repeat each stimulus up to three times; no trial-by-trial feedback was provided. Subjects were told to guess if they were unsure of the answer, but cautioned against choosing the same response for every stimulus. Performance with the MCI task was measured a minimum of 2 times, and usually 5 or more times to obtain a stable measurement. Depending on whether learning effects were observed from test to test, MCI performance was measured in a single session or over two to four sessions. If significant learning effects were observed between test runs, only asymptotic performance was used to calculate mean MCI scores. Each run of the MCI test took 10 to 15 minutes to complete. To give some idea of procedural learning effects during MCI testing, the number of total tests is listed for each subject in Table 2. For the FMI task, melody recognition was first tested with rhythm cues. The stimulus set contained 2 presentations of each of the 12 melodies, with the rhythm cues preserved (24 stimuli in total). A stimulus was randomly selected from the set (without replacement) and presented to the subject. The subject responded by clicking on one of the 12 response choices shown onscreen; response choices were labeled with the melody titles. Subjects were allowed to repeat each stimulus up to three times; no immediate feedback was provided. After testing with melody recognition with rhythm cues, FMI was measured without rhythm cues. Similarly, the stimulus set contained 2 presentations of each of the 12 melodies, but with no rhythm cues (24 stimuli in total). A stimulus was randomly selected from the set (without replacement) and presented to the subject. The subject responded by clicking on one of the 12 response choices shown onscreen; response choices were labeled with the melody titles. FMI with and without rhythm cues was tested in a single 10- to 15-minute session.

Results—Figure 3 shows MCI performance for individual cochlear implant users. Note that subjects are ordered according to performance, from best to worst. For each subject, mean performance was calculated across all three frequency ranges and all internote semitone distances. The differently shaded bars represent the different cochlear implant devices. The limited number of subjects per type of device precludes any statistical analysis; however, no clear advantage was observed for any particular device. The dashed line shows mean performance from nine NH subjects; mean performance was 94.8% correct, with scores ranging from 88.1% to 100% correct. There was great intersubject variability in cochlear implant performance, as MCI scores ranged from 14.1% to 90.7% correct.

Table 2 shows mean cochlear implant performance for the MCI task; mean performance was also calculated for the 3 root note and 5 semitone-distance conditions. In terms of cochlear implant users' sensitivity to root note, performance was generally lower for root note A3. Performance was only slightly (but significantly) affected by the root note [one-way repeated-measures ANOVA: $F(2,20) = 3.66$, $p = 0.044$]. Cochlear implant users' performance generally declined as the semitone distance between successive notes was reduced. A one-way repeated-measures ANOVA showed that performance was significantly affected by the semitone distance [$F(4,40) = 27.56$, $p < 0.001$]. Post hoc Bonferroni *t*-tests revealed that performance with 1 semitone between notes was significantly worse than that with any of the other semitone distances ($p < 0.05$), and that performance with 2 semitones between notes was significantly worse than that with 5 semitones between notes ($p < 0.05$); there was no significant difference between the remaining semitone distances.

In terms of cochlear implant listeners' sensitivity to the nine melodic contours, the "Flat" contour was generally easiest to identify. Table 3 shows the mean percent correct and percent of total responses for each of the nine melodic contours. The column total means for a cumulative confusion matrix (across all test runs and subjects) were used to analyze response bias. Mean recognition performance was highest for the "Flat" contour and lowest

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for the “Falling” contour. Analysis of the distribution of responses revealed that, on average, subjects responded with “Flat” most frequently and “Falling” least frequently; note that chance level was 11.1%.

Figure 4 shows FMI performance for individual cochlear implant users, with and without rhythm cues. Note that subjects are ordered according to performance in the MCI task (Figure 3), from best to complete the FMI task, due to time restrictions. As with the MCI data, there was great intersubject variability. When rhythm cues were available, FMI scores ranged from 16.7% to 95.8% correct; when rhythm cues were removed, scores ranged from 4.2% to 58.5% correct. Mean FMI performance (across all subjects) is shown in Table 2. A one-way repeated measures ANOVA showed that FMI performance was significantly better when rhythm cues were available [F(1,8) = 49.30, $p < 0.001$].

Cochlear implant listeners’ phoneme recognition performance was compared with their MCI and FMI performance. Linear regressions were fit between MCI and vowel recognition performance, and between MCI and consonant recognition performance. Linear regressions were also fit between FMI (no rhythm cues) and vowel recognition performance, and between FMI (no rhythm cues) and consonant recognition performance. Table 4 shows r^2 values and levels of significance for each of the regressions. Only the regression between cochlear implant users’ MCI and vowel recognition performance was statistically significant ($p < 0.01$). There was no significant correlation between cochlear implant subjects’ FMI and phoneme recognition performance, or between MCI and FMI performance.

EXPERIMENT 2: MELODIC CONTOUR IDENTIFICATION TRAINING

The results of Experiment 1 demonstrated a large intersubject variability in music perception. Interestingly, cochlear implant subjects’ MCI performance was correlated with vowel recognition performance, suggesting that the large intersubject variability was common to both music and speech perception. Previous studies have shown that moderate auditory training may improve cochlear implant users’ speech performance, thereby reducing the variability in patient performance. The improvement in performance may occur over the short term (e.g., Rosen et al., 1999) or long term (e.g., Fu et al., 2002). Daily training that targets phonemic contrasts has been shown to be especially effective in improving cochlear implant users’ phoneme recognition (Fu et al., 2005). Structured training using musical materials has also been shown to improve cochlear implant listeners’ musical timbre perception (Gfeller et al., 2002). In Experiment 2, we trained 6 of the 11 subjects who participated in Experiment 1 on the MCI task. Subjects trained for approximately 1 hour per day, using alternate frequency ranges that were not used in the MCI test stimulus set. The purpose of Experiment 2 was to test whether moderate auditory training with simple musical contours would improve cochlear implant users’ performance in the MCI and FMI tests, thereby reducing the variability in cochlear implant users’ music perception performance.

Methods

Subjects—Six of the 11 cochlear implant users who participated in experiment 1 participated in the present experiment.

Stimuli—MCI training stimuli were similar to those used in Experiment 1, except that different root notes were used for the training contours. The root note for the training contours was shifted from that of the test contours to avoid any direct training of the test contours. For subjects S3, S5, and S9, the root note for each melodic contour was randomly selected to be between A3 (220 Hz) and A5 (880 Hz), without including A3, A4, and A5 as root notes; for subjects S4, S7, and S10, the root note was C4 (262 Hz).

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Procedures—MCI training was conducted at home for most subjects on a laptop computer, using custom training software (see Fu et al., 2005, for a general description of the training software). Subjects listened to audio playback during the training via Cochlear's TV cable connected to the headphone jack of the laptop computer. Subjects S3, S4, S7, S9, and S10 trained for a half-hour per day, every day. The time course for training varied among subjects, ranging from 1 week to nearly 2 months (the time course for each subject can be seen in Figure 6). Subject S5 was trained in the lab for 3 hours per day, over a 5-day period; training was conducted in free field in a sound-treated booth at comfortable listening levels, similar to the test environment. The training was conducted using trial-by-trial audio and visual feedback, with repeated playback comparison between the subject's (incorrect) response and the correct response. Each training exercise consisted of 25 melodic contours; note that the 9 melodic contours were distributed randomly within the stimulus set. A contour was selected (randomly, without replacement) from the stimulus set. The subject clicked on one of the response choices shown onscreen. The number of response choices ranged from 2 to 9, depending on the level of difficulty. If the subject answered correctly, visual feedback was provided and a new contour was presented. If the subject answered incorrectly, audio and visual feedback was provided, in which the correct response and the subject's (incorrect) response were repeatedly played back, allowing the subject to compare the melodic contours. When the subject's performance achieved a criterion level of performance (80% correct), the software automatically increased the level of difficulty by increasing the number of response choices and/or reducing the number of semitones between successive notes in the contour. The computer automatically logged subjects' training performance. Subjects who trained at home returned to the lab regularly for retesting. For retesting, MCI performance was measured for the same root notes used in Experiment 1 (A3, A4, A5). At the end of the training period, subjects' FMI performance was also remeasured. Follow-up measures of MCI performance were obtained one month after training was stopped to see if any performance gains with training had been retained.

Results—Figure 5 shows baseline and post-training MCI results for 6 cochlear implant users. For all subjects, performance significantly improved with training. The amount of improvement ranged from 15.5 to 45.4 percentage points. Table 5 shows mean cochlear implant performance for the MCI task, before and after training; mean performance was also calculated for the 3 root note and 5 semitone-distance conditions. Mean results show that not only was MCI performance improved with training, but the intersubject variability was reduced (as evidenced by the lower standard deviation in mean performance after training). A one-way repeated-measures ANOVA showed that MCI performance was significantly improved with training [F(1,5) =26.69, $p = 0.004$]. In terms of sensitivity to root note, although performance improved for all root notes, one-way repeated-measures ANOVAs showed that the root note had no significant effect on MCI performance for baseline [F(2,10) = 2.24, $p = 0.157$] or post-training measures [F(2,10) = 0.66, $p = 0.538$]; note that for the 11 cochlear implant subjects in Experiment 1, performance was slightly but significantly worse with root note A3. In terms of sensitivity to the semitone distance between successive notes in a contour, a one-way repeated-measures ANOVA showed that both baseline performance [F(4,20) = 21.65, $p < 0.001$] and post-training performance [F(4,20) = 37.09, $p < 0.001$] was significantly affected by the semitone distance between notes. A two-way repeated-measures ANOVA showed that training significantly improved performance for all semitone distances [F(4,20) = 28.09, $p = 0.003$].

Although the time course of training was not explicitly controlled as an experimental parameter (subjects were allowed to continue training as long as they liked), performance was periodically tested during the training experiment. Figure 6 shows the time course of training for 6 cochlear implant users. Subjects S3 and S5 only trained for 1 week, whereas subjects S4, S7, S8, and S10 trained for 1 month or more. For most subjects, performance

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continued to improve during the training period. For three subjects (S3, S9, and S10), performance was retested after training was stopped. For subjects S3 and S10, follow-up measures were only slightly lower than post-training levels 1 month after training was stopped. For subject S9, follow-up measures were reduced from post-training levels, although they remained much higher than pretraining baseline levels.

FMI performance was also remeasured at the end of the training period. The same melodies were used for testing as in the baseline measures. Unfortunately, because baseline FMI performance was not measured with subjects S5 and S10, post-training FMI results could only be measured for subjects S3, S4, S7, and S9. Figure 7 shows baseline and posttraining FMI performance for these four subjects. Note that for subject S9, FMI retesting was conducted 1 week after training was begun; for subjects S3, S4, and S7, FMI retesting was conducted at the end of the training period. Results showed that FMI performance (with and without rhythm cues) was improved with the MCI training. Table 5 shows mean cochlear implant performance for the FMI task (with and without rhythm cues), before and after training. When rhythm cues were provided, mean performance improved by 9.1 percentage points; MCI training improved FMI performance while reducing intersubject variability (reduced standard deviation in mean performance after training). However, a one-way repeated-measures ANOVA showed that the improvement was not significant [F(1,3) = 1.09, $p = 0.373$]. Note that for subject S7, FMI performance with rhythm cues declined after training, whereas performance improved for the remaining 3 subjects. When rhythm cues were removed, mean performance improved by 20.8 percentage points. Although MCI training improved FMI performance, intersubject variability was not reduced (slightly higher standard deviation in mean performance after training), most likely because of the floor effects associated with the baseline FMI performance. A one-way repeated-measures ANOVA showed that the improvement in FMI performance (without rhythm cues) was significant [F(1,3) = 20.54, $p = 0.020$].

GENERAL DISCUSSION

The MCI task used in the present study showed that cochlear implant users were capable of only limited melodic contour recognition. Overall, even the best cochlear implant performance was substantially poorer than mean NH performance. In general, when there were 2 or fewer semitones between successive notes in the melodic contour, cochlear implant users had greater difficulty. However, subjects were able to significantly improve MCI performance with training, suggesting that cochlear implant users' music perception may be greatly improved with training and music listening experience. Moreover, the MCI training generalized to improved FMI performance, emphasizing the importance of training to develop better music perception skills. We will discuss the results of the present study in greater detail in the sections below.

MCI Performance of Cochlear Implant Users

The most striking result from the present study (and common to much cochlear implant research) is the large intersubject variability. There was no clear advantage in cochlear implant device, suggesting that the frequency allocations, electrode configurations and stimulation rates used in cochlear implant users' clinically assigned speech processors were not the limiting factors in MCI performance. More likely, differences in subjects' functional spectral resolution (i.e., the distribution of healthy neural populations and their proximity to the implanted electrodes) may have contributed to differences in patient performance. However, these patient differences will also interact with critical speech processor parameters (e.g., frequency allocation, electrode configuration), suggesting that for the top-performing patients, processor parameters may have been better optimized to the functional spectral resolution. For poorer-performing patients, these parameter settings may be

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suboptimal and some adjustment may be required to provide the maximum functional spectral resolution that can be supported by the remaining auditory neural populations. In terms of optimal frequency ranges for MCI, performance with A4 and A5 root notes was slightly better than that with the A3 root note. This may be due to poorer frequency selectivity in the apical channels (due to the frequency allocation or electrode selectivity) or to the spectral shift associated with the limited insertion of the electrode array. For cochlear implant users, the mismatch would be greatest in the apical end of the array. However, the difference in MCI performance between the three root notes was relatively small (_5 percentage points), suggesting that the different input frequency ranges and frequency allocations used in different cochlear implant devices were able to support similar MCI performance for a wide range of acoustic frequencies. In terms of cochlear implant listeners' musical frequency resolution, even the top performers were unable to identify all melodic contours when there was only 1 semitone between successive notes in a contour. With 1 semitone between notes, subjects S1 and S2 were able to correctly identify only ~63% of the contours. If identification of the "Rising," "Falling," and "Flat" contours are not considered, MCI performance was even lower. When there were 2 semitones between notes, subjects S1 and S2 were able to correctly identify more than 90% of the contours. These results suggest that top performers were capable of good MCI performance when there were 1 to 2 semitones between successive notes in melodic contours (or, ~0.13 octave resolution; for reference, 1 semitone between notes corresponds to ~0.08 octave resolution). In contrast, poorer-performing subjects (subjects S8, S9, S10, and S11) could correctly identify only ~34% of the contours when there were 5 semitones between successive notes. For these subjects, musical frequency resolution was greater than 0.40 octaves. Given that the frequency allocation in cochlear implant speech processors generally corresponds to relatively coarse resolution (for example, 1.2 octaves, on average, for each frequency channel in the default Nucleus 24 frequency allocation), top performers were able to hear out cross-channel differences in the spectral envelope (because all notes were three-harmonic complexes) or within-channel differences in the temporal envelope, whereas poor performers could not attend to these spectral or temporal cues. There was a significant correlation between MCI and vowel recognition performance, one of few examples of any correlation between speech and music perception in cochlear implant users. Because listeners most likely attended to spectral envelope cues in both tests, it is not surprising that performance would be correlated between these tests. Previous studies that compared FMI to speech recognition performance found no correlation between these measures. However, the FMI performance may have relied more strongly on perception of exact intervals, while the MCI and vowel recognition tests may not require such exact pitch perception. The FMI test also may depend more strongly on perception of rhythm cues, listeners' musical experience, and so forth, factors that do not affect MCI performance.

FMI Performance of Cochlear Implant Users

Consistent with previous studies (Kong et al., 2004), FMI performance depended greatly on rhythm cues. Mean performance (across subjects) was more than 30 percentage points better when rhythm cues were provided than when rhythm cues were removed. While showing the limited capability of the cochlear implant device to represent melody, these results most strongly point to the importance of rhythm cues to familiar melody recognition. FMI performance without rhythm cues shed little light on the limits of the cochlear implant device to convey melody (e.g., semitone resolution); hence, the impetus for the MCI test used in the present study. FMI performance was not significantly correlated with MCI performance or with phoneme recognition performance. Again, differences in cochlear implant users' musical experience (both before and after implantation), "distortions" to the familiar melodies by removing rhythm cues, and differences in the perceptual tasks (i.e., interval perception in FMI and contour perception in MCI) may have contributed to the

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“unpredictability” of the FMI results. For example, subject S11 performed very poorly in the MCI test (14% correct), but moderately well in the vowel recognition test (50.0% correct) and the FMI test without rhythm cues (29.2% correct); she reported great familiarity with the melodies used in the FMI test because she regularly sang them to her young daughter. In contrast, subject S3 performed much better in the MCI (72.3% correct) and vowel recognition (73% correct) tests, but much poorer in the FMI test (4.2% correct). Because prior experience with the test stimuli is not a factor in the MCI test, melodic contours may be preferable for assessing cochlear implant users’ music perception.

MCI Training in Cochlear Implant Users

Moderate, regular training with the MCI task significantly improved all subjects’ MCI performance. All subjects were trained with melodic contours that differed from the test contours in terms of the root note. Thus, to some degree, training with alternate frequency ranges generalized to the test frequency ranges. This result, along with most subjects’ continued improvement over the training period, suggests that some “perceptual learning” rather than simply “procedural learning” or memorization of the test stimuli occurred during the MCI training (Wright et al., 2001). The targeted, progressive method used in the MCI training was similar to that used in previous speech training studies (e.g., Fu et al., 2005). In these training studies, the opportunity to carefully listen to auditory-only stimuli (i.e., without lipreading) may have strongly contributed to the improved performance. Top-performing cochlear implant users may regularly listen to auditory-only stimuli (i.e., talking on the telephone); for these patients, auditory-only speech tests may be less difficult. Poorer-performing patients may rely more strongly on lipreading; for these patients, auditory-only speech tests are usually very difficult. For poor performing patients, acute auditory-only tests may underestimate the potential of the cochlear implant device to represent speech patterns, as targeted speech training has been shown to significantly improve performance. Similarly, with the MCI task, training significantly improved performance, and initial baseline testing underestimated the capability of the cochlear implant device to represent melody. The MCI training results also showed that most patients continued to improve throughout the training period (see Fig. 6). Follow-up measures in three subjects showed that MCI performance remained near post-training levels 1 month (or more) after training was stopped. For subjects S9 and S10, follow-up performance was slightly worse than at the end of training, yet remained much higher than baseline performance. These results suggest that subjects were able to retain the benefits of MCI training. Interestingly, for 4 of the training subjects, FMI performance (without rhythm cues) significantly improved after MCI training. Note that FMI was not directly trained. Thus, besides generalizing to improved MCI performance for different frequency ranges, MCI training generalized to improved FMI performance. Anecdotal reports also suggest that cochlear implant subjects’ music perception outside laboratory test conditions had generally improved. For example, some subjects reported that they were better able to separate the singer’s voice from the background music while listening to music in the car. While it is difficult to know exactly how MCI training may contribute to improved “real-world” music perception and appreciation, careful listening to melodic contours most likely improves cochlear implant listeners’ overall attention to the limited details provided by the cochlear implant device.

Comparison of Single-Electrode Pitch Discrimination and Modulation Detection to MCI/FMI Performance

In the present study, both MCI and FMI performance were measured with multichannel (i.e., 3-harmonic tone complexes) stimuli delivered to cochlear implant users’ speech processors. While the frequency allocation used in the speech processors may be a primary limitation in performance, cochlear implant users’ electrode pitch range and resolution may also be a limiting factor. Indeed, the frequency allocation may be manipulated to try to encode more

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fundamental frequency information (e.g., Laneau et al., 2004), but cochlear implant users will ultimately be limited by the spectro-temporal resolution of the implanted ear (i.e., limitations in electrode discrimination, modulation detection, rate discrimination, and so forth). It is not clear that single-electrode pitch range and resolution well reflects multichannel performance; for example, single-electrode pitch perception has been only modestly correlated with multichannel speech perception (e.g., Nelson et al., 1995). Although not directly measured in the present experiment, we previously measured single electrode pitch discrimination for a variety of stimulation modes and rates for five of the subjects (S2, S3, S5, S7, and S9) who participated in the present experiment (Galvin & Fu, 2004a, 2004b). Pitch discrimination performance was measured for a set of six adjacent electrodes located in the middle of the electrode array; stimuli were presented at loudness balanced, comfortably loud listening levels. Each electrode pair was compared to every other electrode pair in the stimulus set a minimum of 10 times. During testing, subjects were asked to choose which of two electrode pairs was higher in pitch. The results were transformed into units of discriminability (or d'; from Hacker & Ratcliffe, 1979). As with the MCI and FMI data, there was great variability in subjects' accumulated d' values across the stimulus set (ranging from 0.05 to 7.85 for a set of 6 adjacent electrodes). There was no correlation between accumulated d' and MCI baseline performance (linear regression: $r^2 = 0.441$, $p = 0.229$), accumulated d' and FMI (no rhythm cues) baseline performance ($r^2 = 0.816$, $p = 0.096$), accumulated d' and MCI post-training performance ($r^2 = 0.263$, $p = 0.377$), or accumulated d' and FMI (no rhythm cues) posttraining performance ($r^2 = 0.262$, $p = 0.489$). Interestingly, subject S3 had a relatively low accumulated d' value (0.46), yet was one of the better performers in the MCI task (and one of the poorest performers in the FMI task). Conversely, subject S5 had a relatively high accumulated d' value (6.705), but was only a moderate performer in the MCI task. Single-electrode pitch discrimination data might not provide the ideal comparison to the music perception data in the present study. First, the MCI and FMI stimuli used three-tone complexes, in which the harmonics were increasingly attenuated relative to the fundamental frequency. While the fundamental frequency may have contained the most energy, the other components may have contributed inconsistently, due to interactions with the frequency allocation and the electrode pitch. This spectral profile would undoubtedly be quite different from the single-electrode profile measured in the pitch discrimination task. Moreover, cochlear implant users lack the spectro-temporal fine structure details to resolve harmonic components, which may give rise to pitch uncertainty for multichannel stimuli. When the energy of harmonic components is nonlinearly distributed (as can be the case with many musical instruments), this pitch uncertainty may increase. Second, the MCI and FMI tasks may require different perceptual processes than the single-electrode pitch discrimination task. For the electrode pitch discrimination experiment, perception may be relatively more peripherally based (i.e., simple discrimination between two channels). The MCI task may require attention to pitch only to support a broad profile analysis of the melodic pattern, whereas the FMI task may require careful attention to the exact intervals supported by the electrode pitch. Both the MCI and FMI tasks involve higher processes, which while supported by the pitch cues at the periphery, may make use of these cues in different ways. Also, although not directly measured in the present study, modulation detection thresholds were measured for the same 5 subjects (S2, S3, S5, S7, and S9) as in the electrode pitch discrimination experiment; some of these data were previously presented in Galvin & Fu (2005). Modulation detection thresholds (MDTs) were measured for a variety of loudness-balanced stimulation levels that spanned the electrode DR, a range of stimulation rates (250 to 2000 pps), and a range of modulation frequencies (5 to 100 Hz). There were no correlations between mean MDTs (across each subject's DR) and MCI or FMI performance, for any of the stimulation rate/modulation frequency conditions. Note that there was not adequate power for these analyses, due to the limited number of subjects. However, similar to the electrode pitch discrimination data, good modulation sensitivity did not always produce the best MCI performance. For

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example, the mean MDT for a 1000-pps carrier (across all stimulation levels and modulation frequencies) for subject S5 was –34.79 dB, whereas MCI performance was 64.6% correct. For subject S2, the mean MDT was –23.52 dB, while MCI performance was 89.0% correct. Although it is difficult to know whether a larger number of subjects may produce better correlations between simple, single-channel psychophysical measures and multichannel MCI performance, it is probable that large intersubject variability will persist in all measures. As yet, the relative contributions of single-channel electrode pitch and rate pitch to multichannel melody perception are unclear.

Viability of the MCI Testing and Training

The present results suggest that the MCI test may be a viable approach towards measuring the limits of the cochlear implant to convey melodic information. The MCI test may hold some advantages over simple electrode pitch discrimination or FMI tests, in terms of assessing and quantifying cochlear implant users' melody perception. First, the test requires no previous familiarity with the stimuli. FMI testing depends strongly on listeners' familiarity with the test melodies, and may not generalize to perception of new, unfamiliar melodies. Second, the MCI test can be repeated as necessary over the short term, allowing changes in speech processing to be evaluated for music perception; this test repeatability may reduce potential learning effects associated with repeated FMI testing over the short term. Third, the MCI test directly tests melody perception, without the confounding factors of rhythm cues (or their removal) associated with FMI testing. Fourth, preliminary data shows high levels of performance for NH listeners in the MCI test, comparable to NH performance in FMI tests. Fifth, the MCI test is flexible in terms of the melodic contours, frequency ranges, and instrument stimuli used for evaluation. Multichannel stimuli may also better reflect "real world" melody perception capabilities than singlechannel pitch discrimination (whether pitch is encoded by electrode place or stimulation rate).

The MCI test may also be appropriate for prelingually deafened subjects, who may more easily learn and understand the melodic contours shown onscreen than phoneme/word labels used in a speech test. For prelingually deafened patients, the MCI test may be more accessible, as these patients may have little or no experience with the familiar melodies typically used for testing. Unfamiliarity with these familiar melodies may also extend to cochlear implant users from other cultures, for whom the MCI test may be more appropriate. Also, for pediatric cochlear implant users who have yet to develop robust central speech pattern templates, the MCI test may be useful for quantifying the ability of the implant device to convey meaningful, complex auditory information. Once quantified, adjustments could be made to the speech processor to provide better auditory resolution, which might benefit speech perception, especially during stages of language development. However, such an application of the MCI test would need to consider issues of child development, both in terms of cognition and hearing. Conceivably, the test could be made appropriate for young children who may not understand differences between pitch and loudness. Further studies may guide the development of an MCI test that is appropriate for pediatric implant users.

Preliminary results also suggest that MCI training may significantly benefit cochlear implant users' overall music perception and appreciation. Because the melodic contour stimuli differ in terms of quantifiable acoustic features, the training protocol can easily target difficult contrasts for individual patients, whether in terms of frequency range, intonation, or contour. Because the preliminary results generalized to improved FMI performance, MCI may be useful for developing cochlear implant users' music perception skills that require greater attention to pitch cues, which may be only weakly represented by their device. MCI training may also provide some momentum in developing music appreciation via the cochlear implant. For postlingually deafened cochlear implant users, speech recognition and speech quality is often initially poor through the implant. As listeners gain experience with their

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device, speech recognition and speech quality tend to dramatically improve. Cochlear implant listeners may not have equivalent meaningful listening opportunities for music as they do for speech, and thus may never experience similar adaptation for music. Certainly, the listening demands are quite different for speech and music, and cochlear implant processing degrades music information more severely than speech information. While robust central speech pattern templates may allow for easier adaptation to spectrally degraded speech signals, music perception requires greater attention to comparably weak cues. Regular training may help in the adaptation process, allowing melodic pattern recognition to grow stronger with experience.

It should be noted that although “musical,” the melodic contours used in the MCI test are not “music” per se. Music involves a complexity of rhythm, melody, harmony, and dynamics that are not represented by the melodic contours used in the present study. As such, cochlear implant subjects may have only identified “nonspeech” patterns (whose components arbitrarily correspond to frequencies of the Western musical scale); the same might be said for FMI melodies without rhythm cues. However, in the present study, we were most interested in quantifying the ability of the cochlear implant device to represent melody. Simple, single-channel psychophysical measures (e.g., electrode pitch discrimination, stimulation rate discrimination, etc.) may overestimate or underestimate cochlear implant users’ music perception performance. Similarly, the simple contours and notes used in the MCI test may not predict other aspects of cochlear implant users’ music perception. Subjective ratings may best reflect the quality of music perception via the cochlear implant. However, the MCI test provides some quantification of the implant’s ability to represent an important component of music (melodic contour), and to measure any benefits with alternative cochlear implant sound processing to music perception.

SUMMARY AND CONCLUSIONS

In the present study, MCI and FMI with three harmonic complexes were measured in cochlear implant users while listening to their clinically assigned speech processors. MCI training was also conducted in some of these cochlear implant users. Although the subject pool was somewhat limited (11 cochlear implant users), preliminary data show:

1. There was great intersubject variability in MCI and FMI performance. Despite differences in manufacturers’ devices and speech processors, there was no clear advantage for any particular cochlear implant device or processor. FMI performance depended greatly on the availability of rhythm cues; without rhythm cues, FMI performance was generally poor.
2. Top performers were able to correctly identify most melodic contours when there were 2 or more semitones between successive notes in the contour. Poor performers identified 40% or less of the melodic contours, even when there were 5 semitones between successive notes. These limitations in performance are most likely due to the limited spectral resolution (in both transmission and reception) provided by the cochlear implant device.
3. There was a significant correlation between cochlear implant subjects’ MCI and vowel recognition performance. There was no significant correlation between MCI and FMI, or between FMI and phoneme recognition.
4. Moderate MCI training with alternate frequency ranges from those used in testing significantly improved cochlear implant users’ MCI test performance. This improvement was largely retained even a month after training had been stopped. MCI training also generalized to improved FMI performance.

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APPENDIX 1

Analysis of melodic and rhythm components for melodies used in the FMI task. Categories of analysis included the total number of notes in the melody, the number of novel notes (i.e., notes that were not repeated), the number of times the note changed, the range of notes (in semitones); the frequency range of F0 (in Hz); the number of novel beats (e.g., quarternotes, half-notes, and so forth), the number of times the beat changed, and the total range of beats. The melodic index was calculated as the mean of novel notes, note changes and semitone range, each divided by the total number of notes in the melody. The rhythm index was calculated as the mean of novel beats, beat changes and beat range, each divided by the total number of notes in the melody Table A1.

APPENDIX 2

Analysis of melodic and rhythmic components for melodies used in the MCI task are shown in Table A2. Categories are similar to those described in Appendix 1.

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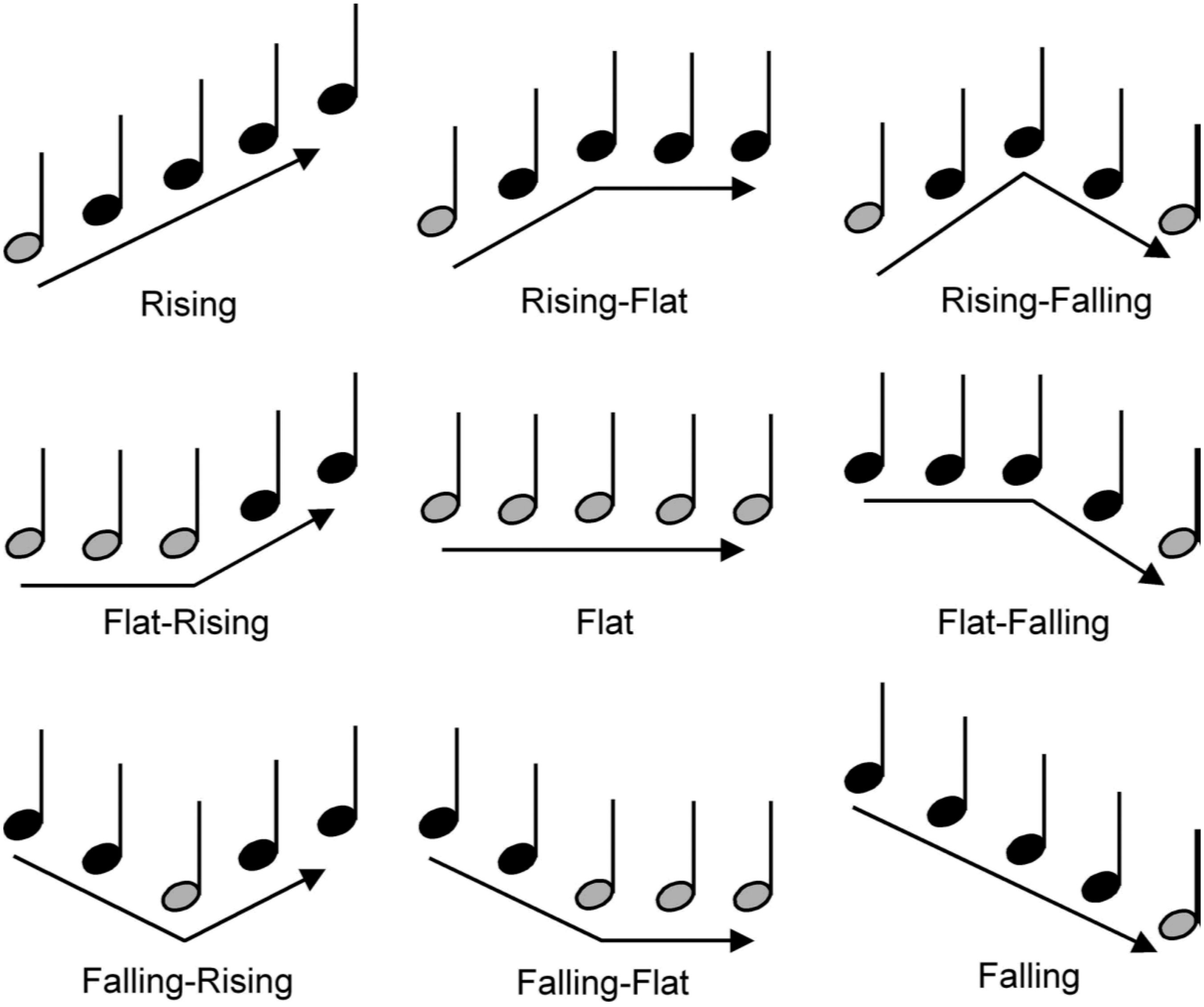

Fig. 1.

Melodic contours and response screen for the melodic contour identification (MCI) test. The shaded notes represent the root note (A3, A4, or A5) in each contour.

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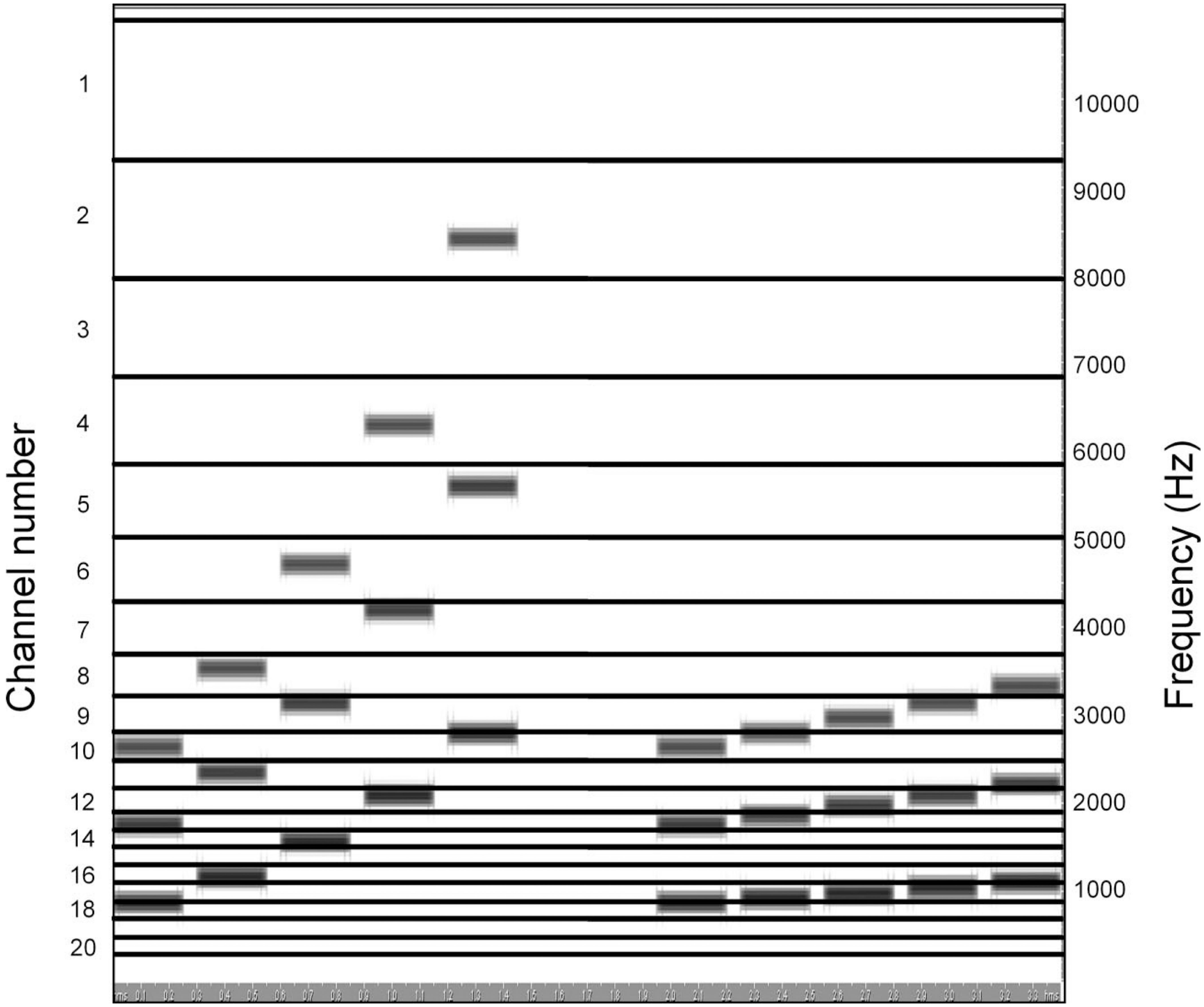

Fig. 2.

Spectrogram for “Rising” contour (root note: A5). In the left contour, there are five semitones between successive notes. In the right contour, there is one semitone between each note. The x-axis shows time. The right y-axis shows frequency (in Hz). The left y-axis shows the electrode assignment for subjects S3, S7, and S9 (Nucleus-22 frequency allocation Table 9). The horizontal lines show the cutoff frequencies for each frequency analysis channel.

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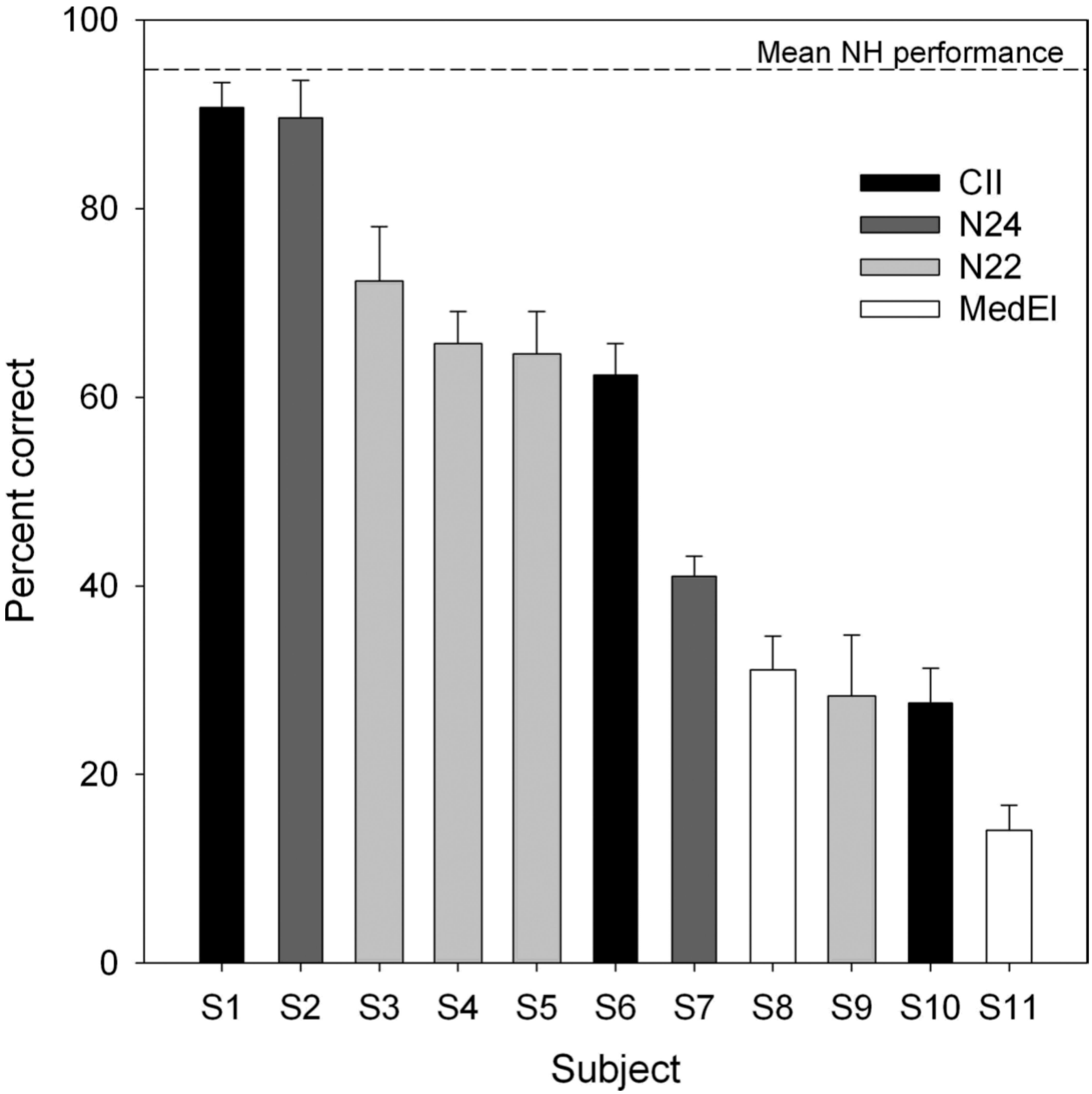

Fig. 3.

Melodic contour identification (MCI) performance for 11 cochlear implant users. Subjects are ordered according to mean performance. Error bars show 1 standard deviation.

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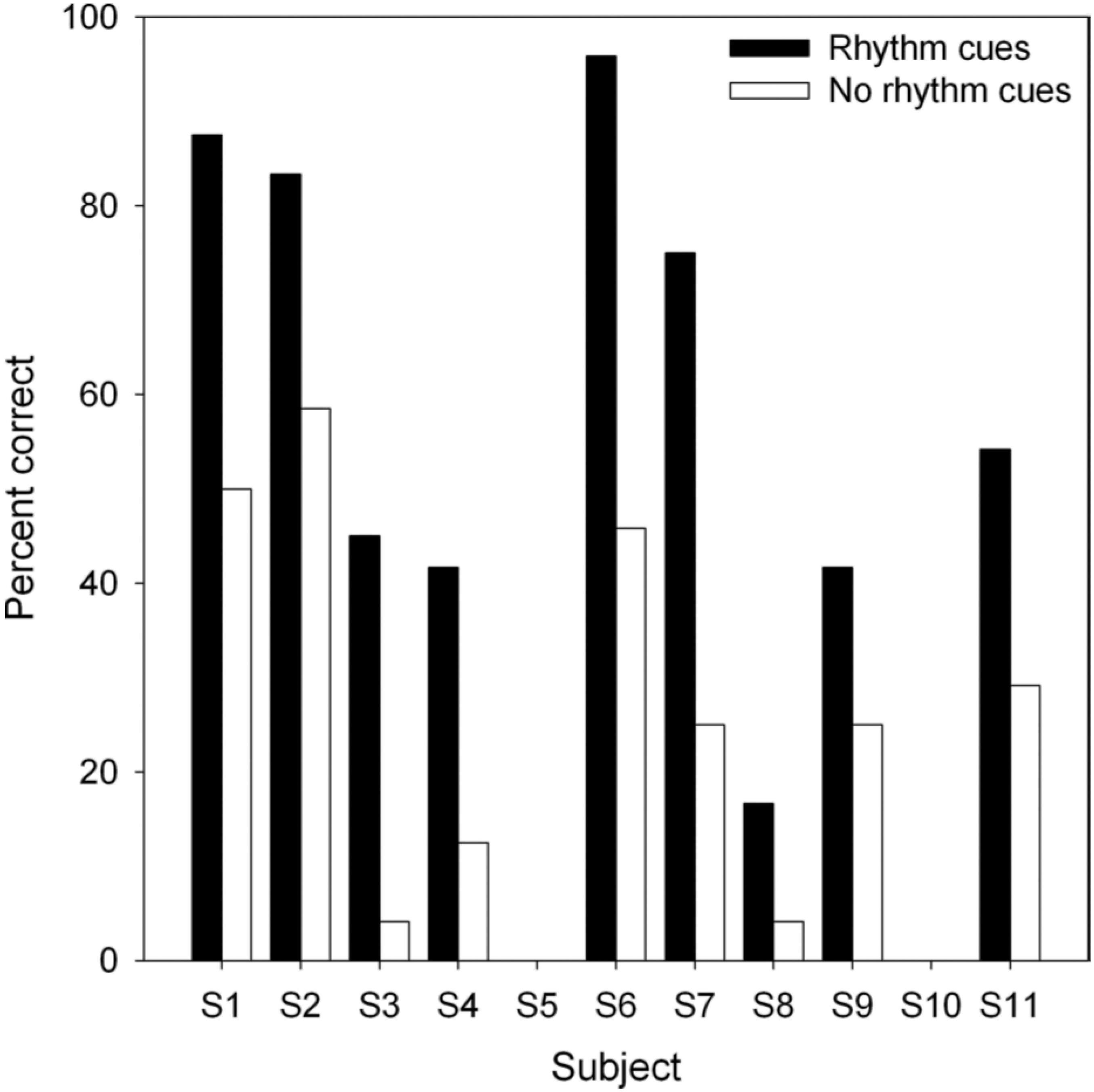

Fig. 4.

Familiar melody identification (FMI), with and without rhythm cues.

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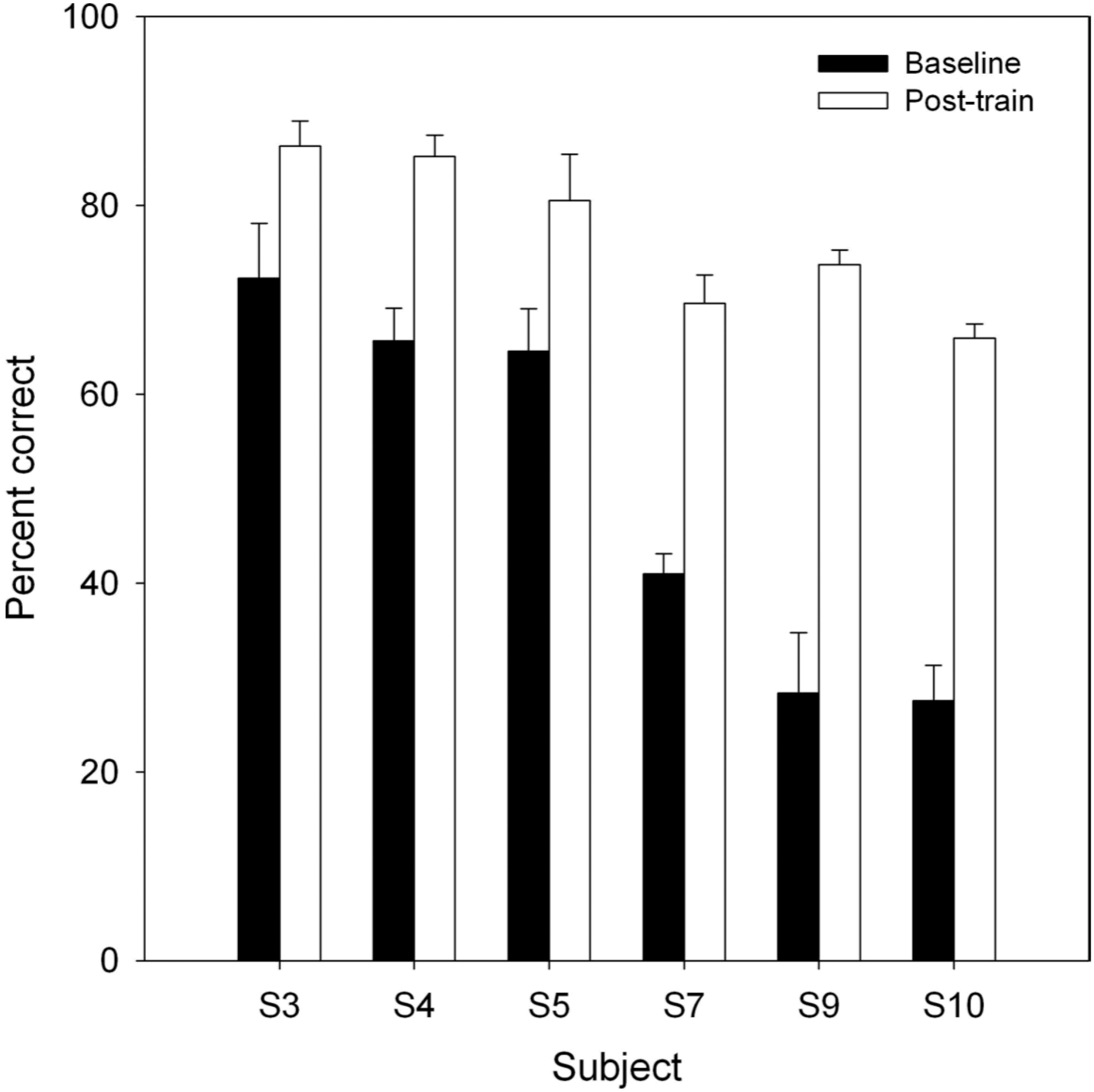

Fig. 5.

Baseline and post-training MCI performance for individual cochlear implant users. Baseline performance is the same as in Figure 3. Error bars show 1 standard deviation.

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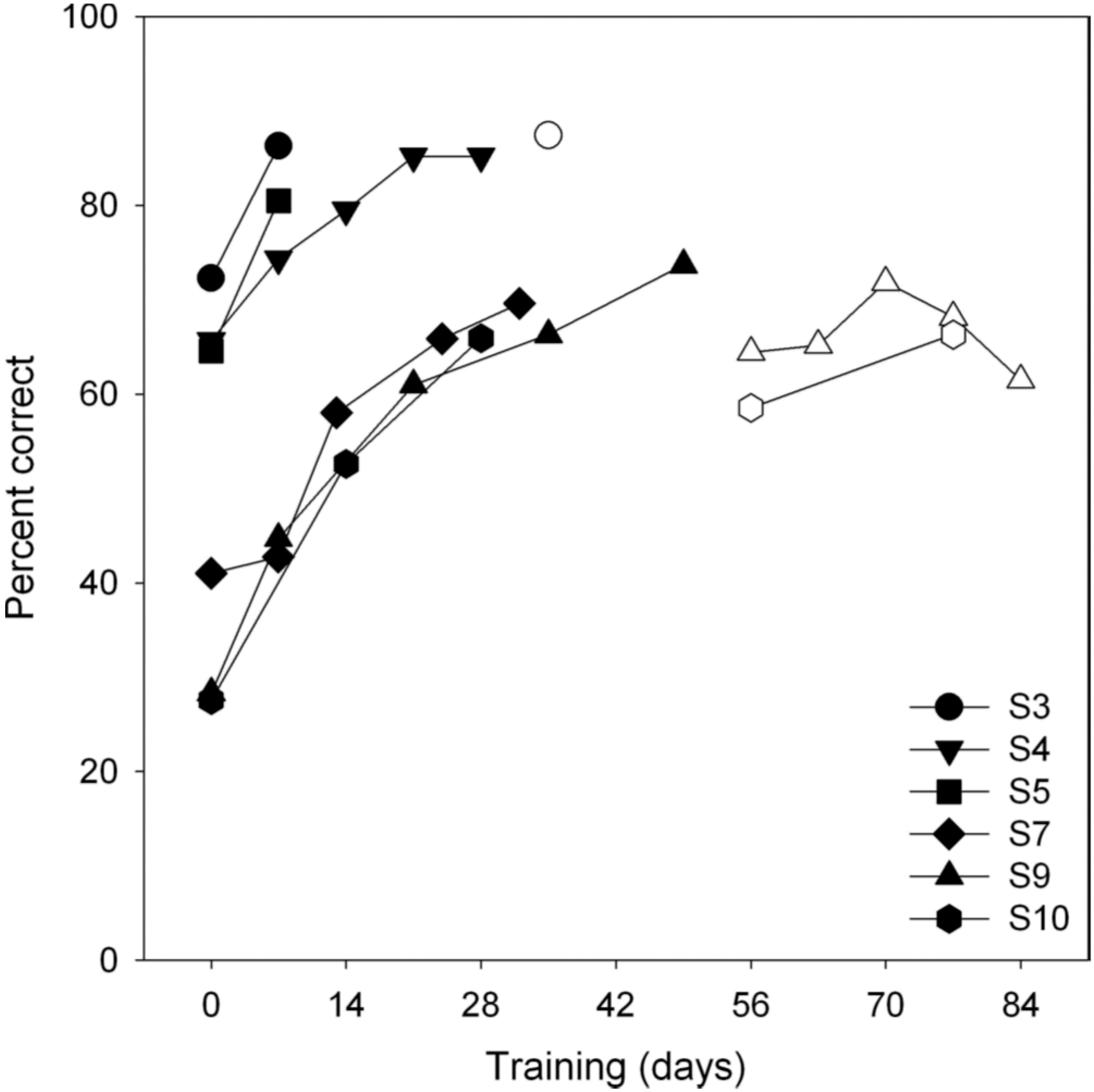

Fig. 6.
MCI test performance over time during the training experiment. Filled symbols show MCI performance that was retested during the training period. Open symbols show follow-up testing after training had been stopped.

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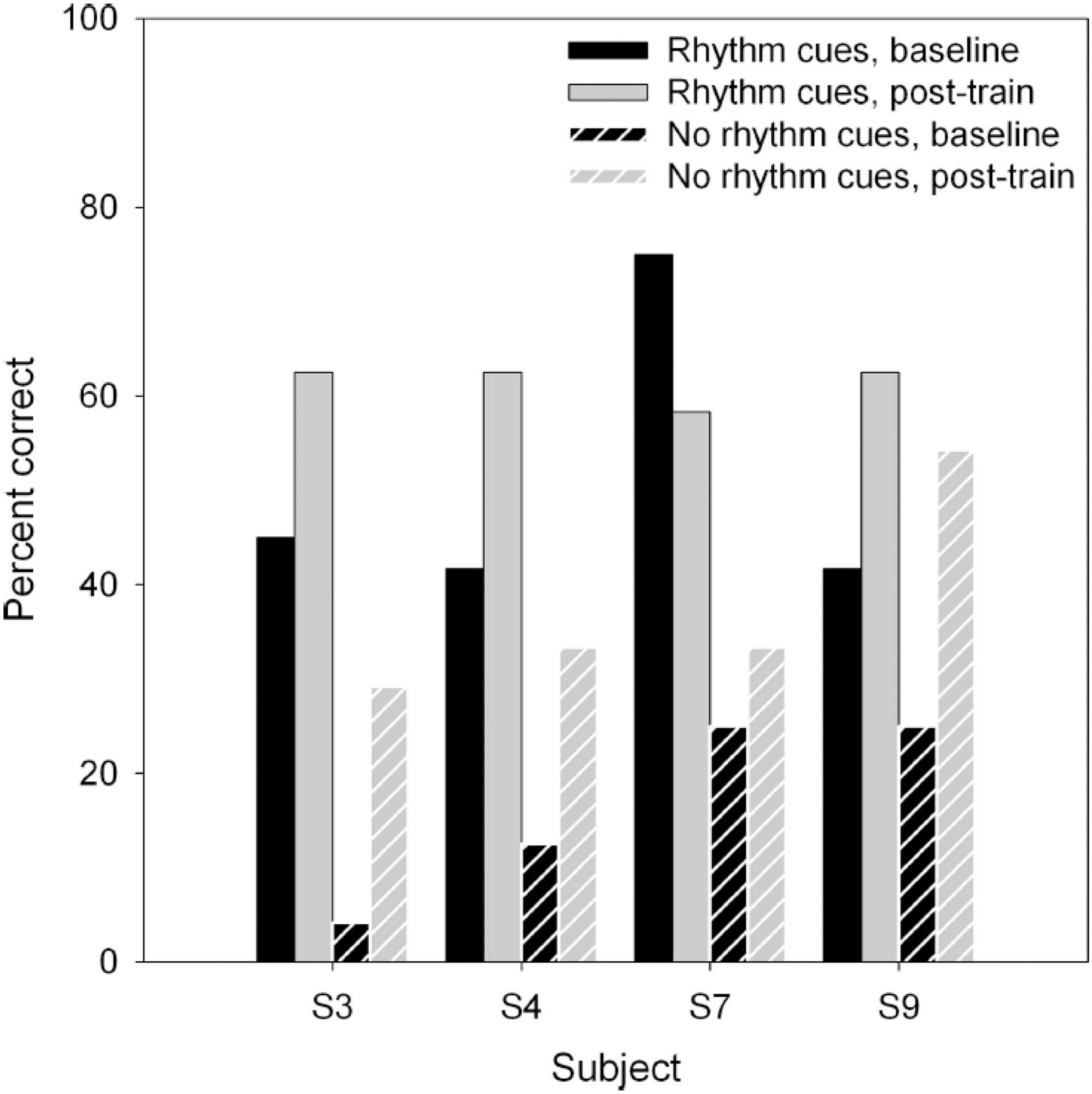

Fig. 7.
Baseline and post-training FMI performance for 4 subjects. Filled bars show FMI performance with rhythm cues; hatched bars show performance without rhythm cues. Dark bars show baseline performance; light bars show posttraining performance.

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TABLE 1

Cochlear implant (CI) user demographics for the present experiment

Subject	Device	Strategy	Input frequency range (Hz)	Stimulation rate per channel (Hz)	Age	Sex	Cause of deafness	CI use (yr)	Vowel (%)	Consonant (%)
S1	CII	HiRes	250–8000	2578	52	M	Unknown	6	82	79
S2	N24	ACE	188–7938	900	62	F	Genetic	2	83	85
S3	N22	SPEAK	120–8658	250	64	M	Unknown	15	73	72
S4	N22	SPEAK	120–8658	250	75	M	Noise-induced	9	86	67
S5	N22	SPEAK	150–10853	250	46	M	Trauma	13	92	81
S6	CII	HiRes	250–8000	2578	72	M	Unknown	6	74	69
S7	N24	SPEAK	188–7938	1200	72	F	Unknown	5	63	63
S8	MedEI	CIS+	300–7000	1488	26	M	Prenatal rubella	3	70	86
S9	N22	SPEAK	150–10853	250	67	M	Hereditary	14	78	75
S10	CII	HiRes	250–8000	5156	42	F	Unknown	2	56	52
S11	MedEI	CIS+	300–5500	1488	41	F	Congenital	5	50	57

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TABLE 2

Mean performance, for each subject, for the MCI and FMI tasks, in percent correct

		Melodic contour identification										
		Base note			Semitones between notes						Familiar melody identification	
Subject	%	A3	A4	A5	1-semi	2-semi	3-semi	4-semi	5-semi	Number of MCI tests	With rhythm cues	Without rhythm cues
S1	90.7	90.0	88.9	93.3	63.0	96.3	98.1	98.1	98.1	2	87.5	50.0
S2	89.0	83.1	92.0	92.0	62.2	91.8	97.0	97.0	97.0	5	83.3	58.5
S3	72.3	64.8	74.6	77.3	47.4	71.1	71.8	83.7	87.4	9	45.0	4.1
S4	65.6	55.9	65.4	75.8	37.0	58.1	69.8	77.2	84.3	16	41.7	12.5
S5	64.5	64.6	58.3	70.7	27.2	52.8	73.7	81.5	87.5	12		
S6	62.3	59.6	65.0	62.2	30.6	57.1	72.5	76.7	74.6	7	95.8	45.8
S7	40.9	32.5	44.4	45.9	18.5	38.2	39.4	46.9	61.7	3	75.0	25.0
S8	31.1	31.1	35.1	27.1	21.4	29.6	35.5	34.0	34.7	5	16.6	4.1
S9	28.3	19.4	32.2	33.3	11.1	31.4	29.6	29.6	39.8	4	41.6	25.0
S10	27.5	34.6	28.4	19.5	17.7	29.6	29.6	31.8	27.8	5		
S11	14.0	11.1	15.5	15.5	13.5	14.8	17.2	11.1	13.5	3	54.1	29.1
Mean	53.3	49.7	54.5	55.7	31.8	51.9	57.6	60.7	64.2	6.4	60.1	28.2
SD	26.2	25.6	25.3	28.6	18.5	26.4	28.3	30.6	30.3	4.3	26.5	19.7

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TABLE 3

Mean percent correct (across subjects) for the nine melodic contours and mean percent (across subjects) of total responses for each type of contour.

Melodic contour	Percent correct	Percent of total responses
Rising	48.6	9.7
Rising-Flat	49.6	11.5
Rising-Falling	53.0	10.0
Flat-Rising	54.6	12.1
Flat	75.5	15.7
Flat-Falling	49.1	10.6
Falling-Rising	53.8	11.3
Falling-Flat	45.6	10.4
Falling	39.4	8.7

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TABLE 4

Results of linear regression between MCI, FMI (no-rhythm cues), and phoneme (vowel and consonant) recognition performance for 11 cochlear implant users

	Vowel		**Consonant**		**FMI (no rhythm cues)**	
Task	r^2	p	r^2	p	r^2	p
MCI	**0.54**	**0.01**	0.29	0.09	0.22	0.25
FMI (no rhythm cues)	0.03	0.64	0.02	0.74		

Significant correlations are shown in **bold** type.

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TABLE 5

Mean performance measures (across subjects) for the MCI and FMI tasks, before (baseline) and after (post-) training, in percent correct

		Melodic contour identification										
		Base note			Semitones between notes					Familiar melody identification	
Subject	**%**	**A3**	**A4**	**A5**	**1-semi**	**2-semi**	**3-semi**	**4-semi**	**5-semi**	**With rhythm cues**	**Without rhythm cues**
S3	87.8	83.3	87.8	92.2	66.7	85.1	92.6	98.2	96.3	62.5	29.2
S4	85.2	82.2	84.4	88.9	60.5	80.3	95.1	91.4	98.8	62.5	33.3
S5	86.3	88.9	86.7	86.7	51.9	100.0	96.3	92.6	96.3		
S7	69.6	47.0	64.8	65.6	28.7	45.4	63.0	75.9	82.7	58.3	33.0
S9	73.7	62.2	73.4	85.6	31.5	72.3	81.5	88.9	94.5	62.5	54.2
S10	66.7	74.8	75.6	49.6	39.5	67.9	69.2	80.3	76.6		
Baseline mean (from Table 2)	49.9	45.4	50.6	53.8	26.5	46.9	52.4	58.5	64.8	52.4	16.7
SD	20.1	19.0	18.6	24.4	13.6	16.5	21.7	25.3	26.1	15.3	10.2
Post-train mean	78.2	73.1	78.8	78.1	46.5	75.2	82.9	87.9	90.9	61.5	37.4
SD	9.3	15.7	9.1	16.8	15.7	18.4	14.2	8.3	9.0	2.1	11.3

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TABLE A1

Analysis of melodic and rhythm components for melodies used in the FMI task

Familiar melody	Total notes	Novel notes	Changes in note	Semi-tone range	F0 range (Hz)	Melodic index	Novel beats	Changes in beat	Beat range	Rhythm index
Twinkle, twinkle little star	14	6	7	9	523–880	0.52	2	3	2.00	0.17
Old MacDonald had a farm	12	5	6	9	440–740	0.56	3	3	2.00	0.22
Brahm’s lullaby	13	5	10	8	440–698	0.59	4	9	4.00	0.44
Star spangled banner	12	7	11	16	415–1047	0.94	4	3	4.00	0.31
Happy birthday	12	5	9	7	523–784	0.58	4	7	8.00	0.53
London bridge	13	5	12	7	587–880	0.62	2	5	2.00	0.23
Mary had a little lamb	13	3	7	4	523–659	0.36	2	5	2.00	0.23
This old man	13	5	11	7	494–740	0.59	2	4	2.00	0.21
Yankee doodle dandy	14	5	11	9	440–740	0.60	2	1	2.00	0.12
She’ll be comin’ round the mountain	11	4	7	8	440–698	0.58	2	1	2.00	0.15
Take me out to the ball game	13	6	12	12	440–880	0.77	4	5	5.00	0.36
Auld lang syne	15	6	13	13	415–880	0.71	4	10	6.00	0.44
Mean	12.92	5.17	9.67	9.08	279	0.62	2.92	4.67	3.42	0.28
SD	1.08	1.03	2.39	3.20	178	0.14	1.00	2.84	2.02	0.13

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TABLE A2

Melodic and rhythmic components for melodies used in the MCI task

Melodic contour	Total notes	Novel notes	Changes contour	Semi-tone range	F0 range A3 (Hz)	F0 range A4 (Hz)	F0 range A5 (Hz)	Melodic index	Novel beats	Changes in beats	Beat range	Rhythm index
Rising	5	5	4	20	220–698	440–1397	880–2794	2.00	1	0	0	0.07
Rising	5	5	4	16	220–554	440–1109	880–2217	1.73	1	0	0	0.07
Rising	5	5	4	12	220–440	440–880	880–1760	1.47	1	0	0	0.07
Rising	5	5	4	8	220–349	440–698	880–1397	1.20	1	0	0	0.07
Rising	5	5	4	4	220–277	440–554	880–1109	0.93	1	0	0	0.07
Flat-Rising	5	3	2	10	220–392	440–784	880–1568	1.07	1	0	0	0.07
Flat-Rising	5	3	2	8	220–349	440–698	880–1397	0.93	1	0	0	0.07
Flat-Rising	5	3	2	6	220–311	440–622	880–1245	0.80	1	0	0	0.07
Flat-Rising	5	3	2	4	220–277	440–554	880–1109	0.67	1	0	0	0.07
Flat-Rising	5	3	2	2	220–247	440–494	880–988	0.53	1	0	0	0.07
Falling-Rising	5	3	4	10	220–392	440–784	880–1568	1.20	1	0	0	0.07
Falling-Rising	5	3	4	8	220–349	440–698	880–1397	1.07	1	0	0	0.07
Falling-Rising	5	3	4	6	220–311	440–622	880–1245	0.93	1	0	0	0.07
Falling-Rising	5	3	4	4	220–277	440–554	880–1109	0.80	1	0	0	0.07
Falling-Rising	5	3	4	2	220–247	440–494	880–988	0.67	1	0	0	0.07
Rising-Flat	5	3	2	10	220–392	440–784	880–1568	1.07	1	0	0	0.07
Rising-Flat	5	3	2	8	220–349	440–698	880–1397	0.93	1	0	0	0.07
Rising-Flat	5	3	2	6	220–311	440–622	880–1245	0.80	1	0	0	0.07
Rising-Flat	5	3	2	4	220–277	440–554	880–1109	0.67	1	0	0	0.07
Rising-Flat	5	3	2	2	220–247	440–494	880–988	0.53	1	0	0	0.07
Flat	5	1	0	0	220–220	440–440	880–880	0.13	1	0	0	0.07
Falling-Flat	5	3	2	10	220–392	440–784	880–1568	1.07	1	0	0	0.07
Falling-Flat	5	3	2	8	220–349	440–698	880–1397	0.93	1	0	0	0.07
Falling-Flat	5	3	2	6	220–311	440–622	880–1245	0.80	1	0	0	0.07
Falling-Flat	5	3	2	4	220–277	440–554	880–1109	0.67	1	0	0	0.07
Falling-Flat	5	3	2	2	220–247	440–494	880–988	0.53	1	0	0	0.07
Rising-Falling	5	3	4	10	220–392	440–784	880–1568	1.20	1	0	0	0.07
Rising-Falling	5	3	4	8	220–349	440–698	880–1397	1.07	1	0	0	0.07

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Melodic contour	Total notes	Novel notes	Changes contour	Semi-tone range	F0 range A3 (Hz)	F0 range A4 (Hz)	F0 range A5 (Hz)	Melodic index	Novel beats	Changes in beats	Beat range	Rhythm index
Rising-Falling	5	3	4	6	220–311	440–622	880–1245	0.93	1	0	0	0.07
Rising-Falling	5	3	4	4	220–277	440–554	880–1109	0.80	1	0	0	0.07
Rising-Falling	5	3	4	2	220–247	440–494	880–988	0 67	1	0	0	0.07
Flat-Falling	5	3	2	10	220–392	440–784	880–1568	1.07	1	0	0	0.07
Flat-Falling	5	3	2	8	220–349	440–698	880–1397	0.93	1	0	0	0.07
Flat-Falling	5	3	2	6	220–311	440–622	880–1245	0.80	1	0	0	0.07
Flat-Falling	5	3	2	4	220–277	440–554	880–1109	0.67	1	0	0	0.07
Flat-Falling	5	3	2	2	220–247	440–494	880–988	0.53	1	0	0	0.07
Falling	5	5	4	20	220–698	440–1397	880–2794	2.00	1	0	0	0.07
Falling	5	5	4	16	220–554	440–1109	880–2217	1.73	1	0	0	0.07
Falling	5	5	4	12	220–440	440–880	880–1760	1.47	1	0	0	0.07
Falling	5	5	4	8	220–349	440–698	880–1397	1.20	1	0	0	0.07
Falling	5	5	4	4	220–277	440–554	880–1109	0.93	1	0	0	0.07
Mean	5.00	3.44	2.93	7.32	129	258	517	0.98	1.00	0.00	0.00	0.07
SD	0.00	0.95	1.10	4.70	110	220	441	0.40	0.00	0.00	0.00	0.00