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MUSIC AND COCHLEAR IMPLANTS

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Abstract

Currently, most people with modern multichannel cochlear implant systems can understand speech in quiet environment very well. However, studies in recent decades reported a lack of satisfaction in music perception with cochlear implants. This article reviews the literature on music ability of cochlear implant users by presenting a systematic outline of the capabilities and limitations of cochlear implant recipients with regard to their music perception as well as production. The review also evaluates the similarities and differences between electric hearing and acoustic hearing regarding music perception. We summarize the research results in terms of the individual components of music (e.g., rhythm, pitch, and timbre). Finally, we briefly introduce the vocal singing of prelingually-deafened children with cochlear implants as evaluated by acoustic measures.

Key words: Music perception; vocal singing; cochlear implants

Since the advent of multichannel cochlear implant (CI) technology, thousands of severely to profoundly deaf people have acquired satisfactory speech communication[1]. However, the ability to perceive or express music in these hearing-impaired listeners using CIs is not so encouraging[2]. Music exerts an important role in human history. It is a unique way to express emotion and affection. Perception of music has become an indicator of post-operational effectiveness and an essential part of evaluation of quality of life for CI users. With the advance of the CI technology and the increasing understanding of disciplines such as psychophysics and neuroscience, people have heightened their expectations on this innovative device. Nevertheless, in recent years, researchers have noted that there is a significant deficit for CI users to perceive music as well as the lexical tones in tonal languages[3,4].

Signal Processing of Cochlear Implants

Before discussing the musical ability for CI users, a brief introduction of the signal processing of CIs is necessary. Almost all contemporary speech-processing strategies are so-called vocoder-centric strategy or some variations of it[5]. Briefly, in a CI system, the acoustical signal is picked up by the microphone and then passed through a bank of band-pass filters. Each of these filters has a distinct central frequency and bandwidth that change systematically across filters according to the principle of tonotopic organization of the cochlear basilar membrane. For the band-passed signals that come out of each frequency channel, a half-wave rectification and low-pass filtering are followed to extract the temporal envelope of the signal. Next, a pulse train with a fixed rate is modulated by this envelope and then sent to individual electrodes located in different areas of the cochlea. The electrodes assigned to lower frequency band-pass filters are located in more apical area to stimulate the auditory nerve fibers sensitive to lower frequencies, while the electrodes assigned to higher frequency band-pass filters are located in more basal area to stimulate the auditory nerve fibers sensitive to higher frequencies. Thus, hearing is elicited electrically. In CI acoustic simulation, the band-passed noise instead of the electrical pulse train is used as a carrier and the synthetic acoustical signal is sent to a loudspeaker so that normal-hearing (NH) listeners can hear the simulated sound of a CI[6].

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Acoustic Features of Music

There are three primary acoustic features in music: rhythm, pitch, and timbre. Rhythm reflects the temporal characteristics of music, represents the inter-relations of duration of notes in a musical excerpt. Pitch is probably the most important feature in music. It is the fundamental element of melody, related to the fundamental frequency (F0) of the sound. It requires an excellent frequency resolution to capture pitch information, especially in chords that a series of harmonics are presented simultaneously. Timbre can be regarded as the "sound color" that is defined as a specific attribute through which a listener can tell the differences between two sounds with the same loudness and pitch[7]. Timbre is related to the distribution of acoustic energy across frequencies and represents the inherent characteristic of the sound source such as a specific instrument or speaker. The unique frequency-amplitude function of the source gives a specific shape to the sound spectrum, which is sometimes referred to as spectral shape or spectral envelope. Despite some common features between music and speech, music is considered to be more complicated than speech in several aspects. The spectrum of music is usually much wider and more varied than that of speech. For example, the typical F0 of speech by an adult male is 100-125 Hz, and is higher for a female or child voice. The F0 of music can be as low as 40-50 Hz for some low-frequency instruments like drum or bassoon[8], and can be occasionally as high as several thousand Hz for some other instruments[9]. Music also usually shows a wider dynamic range of loudness than speech[10]. Additionally, music is more abstractive than speech, including various essential cues which, however, are redundant for speech. Removal of those cues does not do any harm for the recognition of speech, but, is devastating for appreciation of music. For example, the rhythm and timbre of speech is only used for enhancement of rhythmical image and discrimination of different speakers, while for music, these two cues contribute massively to the appreciation of music[10].

Music Perception With CIs

A variety of music test materials have been developed in the last decade[9]. For example, Appreciation of Music in Cochlear Implantees (AMICI)[11], Montreal Battery for Evaluation of Amusia (MBEA)[12], Melodic Contour Identification test (MCI) [13], and University of Washington Clinical Assessment of Music Perception(UW-CAMP)[14] are all recently developed music test batteries. Despite the diversity, most tests put the emphasis on the pitch, which is the most essential perceptual indicator. These tests can be roughly classified as six levels according to their difficulties. Namely, detection—to tell if there is a sound; discrimination—to tell whether the two sounds are the same or not; ranking—to tell which sound in the pair has a higher or lower pitch; interval estimation—to tell the musical interval between two sounds; resolution—to tell the components of a complex tone or the note structure of a chord; and, absolute identification—to identify exactly the note name. There is a specific experimental design for a specific purpose. The three main attributes of music can be tested together or separately. The commonly used melody recognition test can be seen as a combined test of both pitch and rhythm because the listeners can use either the pitch contour or the rhythmic cues to make their judgments. For timbre assessment, the most often used method is to ask the listeners to identify the sounds from various kinds of instruments.

Performance of adult CI users

It is probably more straightforward to evaluate the music ability of postlingually-deafened adult CI users than the prelingually-deafened children because the adult listeners should have prior perceptual knowledge about what music sounds like. Studies have shown that rhythm is probably the easiest attribute that can be captured accurately by CI listeners. In a study by Looi et al.[15], pairs of short note sequences were used to directly evaluate the subjects' rhythm discrimination ability. These pairs were either identical or differed exclusively in the rhythmic pattern. The CI group obtained an amazing average score of as high as 93% correct. Galvin et al.[16] provided indirect evidence that the rhythmic cues could be utilized by CI users. In that study, recognition of 12 familiar melodies was tested in CI listeners with and without rhythmic cues. The average performance was 58% correct when rhythmic cues were preserved and only 29% correct when rhythmic cues were removed. In a similar study by Kong et al.[17], the melody recognition score with and without rhythmic cues were 63% and 12% correct, respectively, with the latter score being not significantly different from the chance level. These results implied that the CI users relied mainly on the rhythm rather than the pitch contour to recognize the melodies. Other studies on CI users' music ability have revealed similar results that the ability of listeners with CIs to perceive rhythm is comparable to that of NH listeners[18-20]. These results are not surprising because CI tends to deliver accurate timing information to the users.

Rhythm is far from enough for music appreciation. Perceptual deficiency of pitch could be expected from the very limited number of analysis frequency channels that are used in current devices. Studies in CI users or NH listeners listening to simulated CI processed sound have all demonstrated such deficits[21-23]. In a recent study by Wright and Uchanski[9], the CI users and the NH listeners either listening to natural sound (NH) or CI-simulated sound (CIsim) were evaluated for their musical ability. The pitch contour scores for NH, CI, and CIsim conditions were 84%, 61%, and 70% correct, respectively. The score of the NH condition is significantly higher than either the CI or the CIsim conditions with no significant difference between the latter two conditions. Although not statistically significant, the relatively lower score of the CI compared to the CIsim conditions may imply that CI users could encounter more difficulties through electrically-mediated hearing.

The method used in Wright and Uchanski study[9] was regarded as a "discrimination" procedure. On the other hand, pitch interval discrimination test provides a discrimination threshold and reveals the pitch-resolving ability more directly. Kang et al.[24] found their adult CI users' interval discrimination threshold was 3 semitones on average, while their NH group's threshold averaged at 1 semitone, the smallest interval tested in their study. In Wang et al. study[25], the data were 5.66 and 0.44 semitones for the CI and NH groups, respectively. More interestingly, this study also reported that the interval discrimination threshold was negatively correlated with the subjects' tone perception ability. Sucher and McDermott [26] showed that when the F0 gap was as large as half an octave (i.e., 6 semitones) in the stimulus pairs, CI users' discrimination score was only 60.2% correct (chance level = 50% correct) and was significantly lower than the NH group's mean score of 89.0% correct. All these studies showed that pitch interval discrimination ability was varied tremendously across individual CI users. Despite that a very small portion of the CI users performed comparably to the NH listeners, the ability to discriminate pitch was dramatically degraded in listeners with CI.

Besides the limited frequency resolution that affects pitch perception in CI users, many other factors may play a role in the poor pitch perception in CI users. For example, there is an inevitable mismatch between the frequencies that the electrodes are assigned and those that the spiral ganglion neurons are tonotopically tuned to. In a study by DiNardo et al.[27], the authors found with the mismatch degree reducing, the pitch ranking, melody discrimination, as well as the overall perceived sound quality all improved in CI users. However, the measures to improve the specificity of current delivering, such as using bipolar electrode configuration rather than monopolar configuration, served little for the improvement of pitch perception in the CI users[3].

Another essential attribute of music is timbre. This attribute is used for the differentiation of different speakers in speech and does not contribute to the understanding of speech. However, music appreciation cannot be independent from this attribute. Timbre recognition ability of CI users has been shown much poorer than that of NH listeners. In Wright and Uchanski study[9], the average of timbre recognition scores for NH and CI listeners were 82.0% and 36.7% correct, respectively. Although the score of the latter group was significantly higher than the chance level (12.5%), it was much lower than that of the NH group. Gfeller and colleagues recruited 51 adult CI recipients and 20 NH listeners and tested eight different instruments from four instrumental families[28]. The average score of the NH and CI listeners were 90.9% and 46.6% correct, respectively. Furthermore, the confusions present in the CI users' responses were more diffused across instrument families, whereas the errors made by the NH subjects were often confusions between instruments within the same family. Despite the variety of testing methods or materials used, the conclusion that CI users cannot perceive musical timbre very well was supported by several other studies[3,29-31]. A recent study by Zhang et al.[32] further strengthened this notion through a different, but interesting perspective. They recorded auditory evoked potential called mismatch negativity (MMN) as the indicator to reflect the cortical response to timbre change. Either the MMN occurrence or the MMN peak amplitude and duration in the CI listeners were significantly smaller or shorter compared to those in the NH listeners, suggesting that the timbre information is poorly registered in the auditory cortex of the CI users. This electrophysiological result was somewhat consistent with the behavioral results mentioned above. It should be noted that even with the same loudness and pitch, the spectral envelopes (i.e., spectral shapes) of different sound sources such as different instruments or speakers could produce very different stimulation pattern in the electrode array. Such difference in stimulation patterns may be perceived by CI users as pitch difference rather than timbre difference. For example, for a standard A4 note (440 Hz) played by either a piano or flute, the CI users probably perceive one note higher than the other in pitch, even though they are identical in pitch according to the conventional acoustic musical definition. This deficiency can be ultimately attributed to the limited frequency resolution arisen from both the implant device and the cochlear hearing loss.

Performance of pediatric CI users

It is relatively more difficult to evaluate the music ability of children with CIs. The primary reason is the general lack of musical knowledge or experience of music in those prelingually-deafened children. It may also involve certain issues in cognition. Nonetheless, there are a series of preliminary studies that have explored the musical ability in children with CIs. In a recent study by

Stabej et al.[33], the children with CIs performed significantly poorer than the age-matched, NH children with respect to rhythm discrimination (55% vs. 82% correct), indicating that children CI users could not capture the duration cues well. Another study by Hsiao[34] examined the relative contributions of pitch, rhythm, and lyrics to melody recognition in pediatric CI recipients. The author found that although rhythm could help with identification of the target melodies, the CI recipients' performance was still less accurate than that of the NH listeners when the rhythmic cues were present. Interestingly, a study using adult implant users[35] also found that the CI listeners performed 5-25 percentage points poorer than the NH listeners in rhythmic pattern identification. These recent reports as well as what will be discussed below on singing ability of pediatric CI users challenge the previous viewpoints that CI users' rhythm perception/production ability was comparable to that of NH listeners. The rhythmic ability of CI users is likely to be related to their modulation sensitivity or intensity sensitivity which has been demonstrated to be similar to that of NH listeners[36,37]. It is not clear whether this inconsistency among studies is resulted from the large variation of rhythmic ability in the CI population.

A pitch perception test may be theoretically less reliable for prelingually-deafened children than for postlingually-deafened adults because the children may have no concept of what pitch is since they have never had the natural or acoustical experience of what different pitches sound like. The effectiveness of music training to improve pitch perception in children with CIs should be evaluated cautiously since the instructors and the participants may have completely different hearing experiences or percepts. However, studies trying to evaluate the pitch perception ability of children CI users have found generally similar results to those of the adult CI users[38-42], that is, their pitch perception ability is degraded compared to their age-matched NH counterparts. For example, in Vongpaisal et al. study[41], the melody recognition scores for children with CIs and children with NH were 37% and 76% correct, respectively. When the melodies were played by an instrumental assembly, this gap became even larger. See et al.[42] recently reported that the pitch-ranking limen in pediatric CI users was almost as twice as that of the NH control group, even though their NH group had a relatively younger age at test. A study by Jung et al.[38] compared the complex pitch direction discrimination in children CI users with the previously published data from adult CI users. The average scores of children and adult CI users were 2.98 and 2.93 semitones, respectively. For NH children, the difference limen to identify the direction of pitch changes demonstrated as small as 0.3 semitones[43]. Note that these results seems to be better than those reported in Wang et al.[25] as discussed in the section above. Nonetheless, the melody identification test showed that the performance of the pediatric CI users was not significantly different from the chance level, apparently worse than that of adult CI users[38]. Therefore, the poor melody perception ability in children with CIs was probably due to a number of factors besides the pitch extraction ability, such as an immature temporal perceptual ability[44].

It is difficult to interpret the testing results on children CI users' timbre perception ability, especially for the congenitally-deafened children. Since they have rarely or never heard what a piano or a flute sounds like naturally, how can they be expected to identify the instrument? Well, if they could discriminate the two sounds from two individual instruments through their electric hearing, this issue can be addressed with training theoretically. There appear to be few published studies reporting CI children's ability to perceive timbre. In Jung et al. study[38], the children CI users were asked to identify the instrument among eight different instruments. The average score was only 34.1% correct (chance level was 12.5%), which is significantly poorer than the score of 45.3% correct from the adult CI users. However, the better-than-chance scores suggested that the children CI users did hear the sounds from different instruments as "different". Although it is difficult to identify the music experience of these subjects and, as far as we know, no longitudinal studies on pediatric CI users' timbre perception ability have been reported, there is clear evidence indicating that musical training focused on timbre perception improves the postlingually-deafened adult CI recipients' recognition of timbre[45]. Thanks to the more favorable plasticity of the central auditory system in pediatric CI users, music training could be promising to improve the recognition of timbre in pediatric CI users.

Comparison between CIs and hearing aids (HAs)

Both CIs and HAs are originally designed to optimize the signal processing of speech[3,46], and both are found performed unsatisfactory on music perception. The deficit of CIs on music perception has been discussed above. The performance of CI simulation (CIsim) using the technique of vocoder was considered as the representation of the best performance level which the CI users could achieve. This was shown in the Wright and Uchanski study[9] where the investigators compared music perception performance (included rhythm, pitch, melody, and timbre) of the CI group to the CIsim group using a total of 14 music subtests. All except two of the subtests showed that the CIsim listeners either performed similarly or better than the CI users. Nevertheless, the performance of the CIsim group was still significantly poorer than that of the NH subjects listening to unprocessed sounds in most of the subtests.

Actually, music fidelity is almost always less than optimal for HA users too. Listeners wearing HAs complain of reduced sound quality while listening to music[46]. It can be readily seen that the acoustic signal would be somewhat distorted through HAs, yet, HAs still need to make use of all the essential peripheral auditory organs including the ossicular chain, basilar membrane, and hair cells which are bypassed by CIs. Since the CIs and HAs use ultimately different principles to compensate for the hearing loss, it would be interesting to make a comparison between these two kinds of hearing devices. In a study with both CI and HA adult users, Looi and colleagues[47] selected the HA participants who met the current audiological criteria for CI candidacy and used a music test battery to evaluate all the essential aspects of music perception, including rhythm, pitch, timbre, and melody. The results of the rhythm test for the CI group and the HA group were almost identical, 93% and 94% correct, respectively. Results of the timbre test also did not show statistically significant difference between the two groups. However, for the test of pitch ranking, the HA users obtained higher mean scores than the CI users for all three interval sizes used, i.e. one-octave (12 semitones), half-octave (6 semitones), and quarter-octave (3 semitones) intervals. In the melody test, the mean scores of the CI users and HA users were 52% and 91% correct, respectively. The difference was statistically significant.

Dorman and colleagues[48] studied melody recognition in a group of 15 conventional implant adult users who wore hearing aids on the contralateral ear. They found that the score on melody recognition when using acoustic stimulation alone was 70.6% correct, significantly higher than the 52.0% correct rate when using electric stimulation alone. These results suggest that HAs may be superior to CIs in pitch perception, probably because HAs may have provided more reliable F0 information than CIs. However, this speculation is not supported by another study[49], in which Lee and colleagues failed to find a pitch-related perceptual difference between their pediatric CI and HA subjects. It looks like the age of the subjects at test contributed to the inconsistency among the studies. Although there is no definite conclusion about whether HAs can provide better pitch information than CIs, there is a consensus with regard to the additional benefits obtained with bimodal hearing (i.e., the concurrent use of electric hearing and acoustic hearing) in music perception when compared to electric hearing alone. The Dorman et al. study mentioned above showed that the concurrent use of CIs and HAs produced an average melody recognition score of 71.2% correct, an increment of nearly 20 percentage points as compared to electric stimulation alone[48]. Another study by Gfeller et al.[50] selected a special group of CI users who were implanted with a short electrode array placed in the basal end of the cochlea while their relatively unimpaired low-frequency region were kept undisturbed. The melody recognition score of this special group was 46.5% correct, significantly higher than 15.2% correct of the CI users with the full-inserted, long electrodes. Although the subjects in Gfeller et al. study[50] did not use HAs, this result indicates the potential advantage of electrically-acoustically combined hearing mode in music perception.

Vocal Singing in CIs

Since the music perception ability in CI users is impaired, what about their music production ability? If the music perception is regarded as an input, then the output (i.e., vocal singing) should be more complicated than the input because it involves coordination of motor output with the auditory feedbacks. It is expected that the prelingually-deafened CI users would also have difficulties to vocally express music. Few studies focused on vocal singing of CI users so far. Yuba et al.[51] tested eight children CI users' pitch accuracy of singing. Using the F0 of the sung note as the index value, the authors found the mean deviation of the sung pitch from the standard pitch was 49.2 Hz with a SD of 38.2 Hz. Nakata and colleagues[52] measured the singing ability of twelve congenitally deaf children with CIs in terms of pitch and timing. Each subject in their study was asked to sing at least one familiar song. The results showed that the rhythmic pattern accuracy of their sung renditions was comparable to that of the NH children, while the pitch pattern accuracy is less accurate than the control group. This result was somewhat consistent with the above-mentioned studies that the CI users' rhythm perception ability was similar to that of the NH listeners[18-20].

Xu et al. also did a study on vocal singing ability of prelingually-deafened children with CIs[53]. In that study, five metrics were used to systematically evaluate the singing ability from both pitch- and rhythm-related aspects, i.e. (1) percent correct of F0 contour direction of the adjacent notes, (2) F0 compression ratio of the entire song, (3) mean deviation of the normalized F0 across the notes, (4) mean deviation of the pitch intervals, and (5) standard deviation of the note duration difference. The first four metrics were pitch-related and the fifth was rhythm-based. For metrics 1, 3 and 4, the CI users performed significantly poorer than the age-matched NH children, while for metrics 2 and 5, the performance did not differ significantly between the two groups. Recently, we have completed another study with a larger sample size and replaced the fifth metric of standard deviation of the note duration difference in Xu et al.[53] by the mean deviation of duration ratio because the previous metric was related to the absolute singing speed of the subjects[54]. Our data revealed that the pediatric CI users did perform significantly poorer than their hearing counterparts in both pitch- and rhythm-based aspects of vocal singing. Given the previously reported correlation between pitch-related perception and production[55,56], the results mentioned above imply that the vocal singing proficiency of CI users is severely affected, at least in part, by their markedly poor music perception ability. It is noteworthy to pay attention to other underling factors that might influence the vocal music expression since it involves the complicated processes of the central nervous system and complex executive functions[57] as well as the operation of the articulators.

Summary

Contemporary multichannel CIs do not provide adequate pitch information due to the insufficient frequency resolution. This deficiency affects the music perceptual ability including pitch-ranking, melody recognition as well as timbre identification. Apparently, the deficits in music perception are related to the issue with lexical tone perception in tonal-language speakers who use CIs. Poor pitch perception also results in poor performance on vocal singing in prelingually-deafened children with CIs. Either the rhythm-based perception or production accuracy in CI users is not always comparable to that of their NH counterparts. It seems that the general deficit in music perception of CI users is resulted not only from the technical limitations of the device but also from the physiological limitations arisen from the cochlear hearing loss and electric hearing. It is a great challenge to the CI research community to improve music appreciation as well as lexical tone perception in CI users, particularly in noise conditions. Meanwhile, although not a topic discussed in this article, music training program has been shown helpful for music perception, appraisal as well as music expression of CI users[16, 58-62] and is becoming more and more valued for the music habilitation of the CI recipients.

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