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A bilateral cochlear implant user with exceptional musical hearing ability

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Abstract

Although the perception of music is generally poor in cochlear implant users, there are a few excellent performers. **Objective:** The aim of this study was the assessment of different aspects of music perception in one exceptional cochlear implant user. **Design**: The assessments included pitch direction discrimination, melody and timbre recognition, relative and absolute pitch judgment and consonance rating of musical notes presented through the sound processor(s). **Study sample:** An adult cochlear implant user with musical background who lost her hearing postlingually, and five normally hearing listeners with musical training participated in the study. **Results:** The CI user discriminated pitch direction for sounds differing by one semitone and recognized melody with nearly 100% accuracy. Her results in timbre recognition were better than average published data for cochlear implant users. Her consonance rating, and relative and absolute pitch perception were comparable to normal hearing listeners with musical training. **Conclusion:** The results in this study are an "existence proof" that excellent performance is possible on musical perception tasks including pitch perception using present day cochlear implant technologies. Factors that may explain this user's exceptional performance are short duration of deafness, pre and post deafness musical training and perfect pitch abilities before the onset of deafness.

ABBREVIATION: CAMP (Clinical Assessment of Music Perception)

KEY WORDS: pitch direction discrimination, melody recognition, timbre recognition, absolute pitch, relative pitch, consonance rating, cochlear implant, music perception

Introduction

The perception of speech in noisy conditions and music perception are difficult for most cochlear implant users (Stickney et al., 2004, McDermott, 2004). Music has a more complex sound spectrum, a wider dynamic range and less redundancy in the signal than speech signals and also is much more affected by limitations of electrical hearing. Although music perception abilities remain poor for many cochlear implant recipients (McDermott, 2004), several music perception studies have indicated that some cochlear implant recipients are able to perceive features such as tempo (Kong et al., 2004), rhythm and lyrics fairly well (McDermott, 2004, Gfeller et al., 2005, Drennan, 2008, Gfeller et al., 2010). However, the perception of pitchrelated features proves extremely challenging to most listeners (Drennan, 2008, McDermott, 2004).

Several studies have shown that music perception and appreciation in cochlear implant users are influenced by factors such as residual low-frequency acoustic hearing (Gfeller et al., 2006, El Fata et al., 2009, Brockmeier et al., 2010), bilateral implantation (Veekmans et al., 2009), preor postlingual hearing loss (Eisenberg, 1982 , Lassaletta et al., 2008 , Chen et al., 2010), age of implant users (Trehub et al., 2009), musical training before deafness (Gfeller et al., 2008, Chen et al., 2010), and the cognitive capacities of cochlear implant recipients (Gfeller et al., 2008). Results from different studies show a large amount of variability but some exceptional cases have been reported in the literature (Gfeller et al., 2005, Kang et al., 2009). The abilities of one such "Star Performer" (SP) on many aspects of music perception experiments will be reported in this paper.

The inability to appreciate music has been primarily attributed to pitch perception deficits (Trehub et al., 2009). The pitch of a pure tone is determined primarily by its frequency, with low frequencies eliciting low pitch sensations and high frequencies inducing high pitch sensations. Although there is apparently a straightforward relationship between the frequency of a harmonic sound and its pitch, it is not clear exactly what information the brain uses to represent pitch in more complex sounds (Oxenham, 2008). Several possible theories for pitch coding have been proposed and are mainly categorized as place-pitch, time-pitch or a mixture of both classifications (Oxenham, 2008). Time information in acoustic events includes the amplitude envelope, periodicity and temporal fine structure cues (Shannon, 1992). Current cochlear implant technologies have enabled temporal information to be transmitted to the auditory nerve to some extent using envelope modulation , but the CI apparently does not represent temporal fine structure (Shannon, 1992, Zeng, 2002) which has been shown to be highly important for difficult listening tasks, such as music perception and speech perception in fluctuating background noise (Nelson et al., 2003, Zeng, 2002, Qin and Oxenham, 2003). Many researchers have been working on improvement of pitch perception with cochlear implants by designing new sound processors and electrode arrays, but with limited success (Vandali et al., 2005, Laneau et al., 2006, Hochmair et al., 2006, Swanson, 2008)**.**

Pitch can be assessed in different levels of difficulty from simple detection and discrimination tasks to absolute pitch identification which is a very difficult task even for most normal hearing listeners with or without musical training. A small percentage of the population has absolute pitch, which is the ability to identify a given musical note without using an external reference (Ward, 1963, Drayna, 2007). Detection tasks test the ability to perceive a difference between two pitches and do not require any musical training. Relative pitch is the ability to specify the musical interval of two sequential notes in terms of a unit like the number of semitones. Forinstance, the distance of a musical note from a set point of reference is 12 semitones if the interval between the reference and comparison notes is one octave (Hove et al., 2010). Relative pitch perception ability has been shown to be critical to music perception (McDermott et al., 2008) and accordingly, absolute and relative pitch perception were assessed in this study.

The second most important feature of a musical note is its timbre, the physical attribute allowing discrimination of two different instruments when they are being played with the same fundamental frequency and intensity. The perception of timbre is highly dependent on changes in acoustic intensity over time, the spectral content, and temporal changes in the spectrum of a note.

Another important factor for music appreciation is the perception of consonance and dissonance between notes. This ability deteriorates as a consequence of cochlear hearing loss (Tufts et al., 2005, Plomp and Levelt, 1965, Kameoka and Kuriyagawa, 1969). A musical interval is described as consonant if it sounds harmonious and restful, while an interval is described as dissonant if it sounds discordant and tense. In western music, the common intervals are named as follows. The semitone difference between the two notes is shown in parentheses. “Unison” (0), “Second minor”(1), “Second major”(2), “Third minor”(3), “Third major”(4), “Perfect Fourth”(5),”Tritone”(6),”Perfect Fifth”(7), “Minor Sixth”(8), “Major Sixth”(9), “Minor Seventh”(10), “Major Seventh”(11) and “Octave”(12). The perfect intervals (Unison, Octave, Perfect Fourth and Perfect Fifth) are considered highly consonant. The Major and Minor Thirds and Sixths are considered as imperfect consonant intervals, whereas Major and Minor Seconds and Sevenths and Tritone are categorized as highly dissonant intervals (Huron, 2001, Hutchinson and Knopoff, 1978).

As music is often polyphonic it is important for the listeners to segregate the different melodic lines. Auditory streaming or auditory stream segregation is a process by which successive sounds from one source (such as a violin or a person talking) are perceptually grouped together and separated from other competing sounds at least partly on the basis of pitch (Gardner et al., 1989). In a streaming task, the brain may rely upon pitch perception to some extent (Oxenham, 2008, Assmann, 1996). Thus difficulty with pitch perception is a likely limiting factor in sound source separation for cochlear implant recipients.

One aim of this study was to describe the music perception abilities of an excellent cochlear implant user relative to those of average cochlear implant recipients and people with normal hearing using tasks from the literature. The second aim was to consider factors that might potentially account for her exceptional abilities.

Materials and Methods

Participant

The Star Performer, SP, was 30 years old at the time of this study. She lost her hearing three years previously as a result of an inner ear autoimmune disease. Her audiograms before the study revealed that she did not have any residual hearing in the left ear. Her residual hearing thresholds in the right ear for 250 Hz, 500 Hz, 1000 Hz, 2000 Hz and 4000 Hz were 70, 80, 70, 85, and 100 dB HL respectively. All hearing thresholds were measured with a Grayson Stadler audiometer in an acoustic booth.

SP had played piano for 17 years prior to losing her hearing and continued after her hearing loss. She reported that musical sounds after hearing loss were not enjoyable. She received simultaneous bilateral CP512 implants 7 months before participating in this study. During this study, she used two CP810 sound processors with the ACE sound processing strategy and the ADRO sound environment setting. SP performed well in speech perception three months after implantation (scoring 96% on an open-set monosyllabic CNC word test and 99% on CUNY sentences presented in background noise at 10 dB signal-to-noise ratio).

SP reported an unusually fast adaptation to the CI and claimed that she was able to perceive speech within seconds of the first activation. With the CIs on, her perception of pitch was also very good, and she claimed to be able to perceive pitch differences within a semitone. SP was selected for this study based on her exceptionally good performance on an auditory segregation task (Camilleri et al, 2010).

Five people (including one of the authors) were selected to form the normal hearing group, for those parts of the study where no directly comparable results were found in the literature. All of them had normal hearing and are amateur musicians.

Test Conditions

SP normally uses bilateral cochlear implants, and it was interesting to see whether purely electrical stimulation and every-day binaural listening had different effects on her music perception ability. Therefore, some tasks were performed in the unilateral left condition (which accessed purely electrical stimulation) and the bilateral condition (for the assessment of everyday listening). In the unilateral listening condition, an ear plug was worn in the contralateral ear to avoid the possibility of the acoustic stimulation of residual hearing in the right ear. The comparison between the data of the left ear (the ear without residual hearing) and that of the bilateral condition (the combination of electric and acoustic hearing in the right ear with electric hearing in the left ear) would show the potential contributions of the acoustic residual hearing and the bilateral electrical stimulation in the perception of music.

Experiment 1:

Clinical Assessment of Music Perception test (CAMP)

In studies of music perception in cochlear implant users, there are few widely accepted assessment measures, mainly due to the complex nature of music, the dependence of assessment materials on culture, and the difficulty of some tasks for most CI users. Some currently used materials are very specific and their use requires a large amount of music knowledge. The CAMP has been used to assess music perception in psychoacoustic studies of normal hearing, CI and hearing aid users (Kang et al., 2009, Nimmons et al., 2008, Zeng, 2002). It is easy to administer with an acceptable accuracy and can be repeated by researchers in clinical settings.

The CAMP test includes three subtests: pitch direction discrimination, melody recognition, and timbre recognition.

In the pitch direction discrimination subtests, three reference frequencies were assessed (262 Hz, 330 Hz and 392 Hz) that represented C4, E4 and G4 respectively in the piano scale. Although these three frequencies are not representative of a wide frequency range of music, they are commonly used in both the vocal and instrumental frequency ranges of western music. This range of frequency is limited to the middle of the piano scale. Two additional sets of reference frequencies were generated by shifting the fundamental frequencies of all pitch items 24 semitones below and above their standard values to test a wider range of frequencies. After this modification, the pitch items covered fundamental frequencies from 46 Hz to 3132 Hz. Pitch direction discrimination was tested in bilateral and unilateral left ear conditions by presenting the stimuli in free field at 65 dB SPL from the front using the standard CAMP test protocol. A two-alternative forced choice (2AFC), 1- up 1- down adaptive method was used for the pitch direction discrimination subtest. Pairs of reference and higher frequencies (separated by one or more semitones) were played in random order. Two buttons appeared on the computer screen and the participants were instructed to select the button corresponding to the sound with higher pitch (first or second note heard). Each correct response was followed by a smaller subsequent frequency interval, while each incorrect response was followed by a larger interval. A reversal was defined as an incorrect response after a correct response or vice versa. The largest interval used was 12 semitones (1 octave) which was played in the first item. The smallest interval used was 1 semitone. If participants consistently discriminated the pitch direction at the minimum interval, 0.5 semitones was recorded as the threshold on the psychometric function. The threshold for each reference frequency was the mean pitch interval in semitones for the last six of eight reversals. The mean discrimination threshold was calculated for the three reference frequency thresholds in each set of stimuli in each condition.

For both melody recognition and timbre recognition, digitally synthesized complex tones were used to provide both fundamental and overtone frequency cues present in real-world tones. The CAMP melody subtest comprises 12 well-known melodies: ”Frère Jacques,” “Happy birthday,” “Here Comes the Bride,” “Jingle Bells,” “London Bridge,” “Mary Had A Little Lamb,” “Old MacDonald,” “Rock-a-Bye Baby,” “Row Row Row Your Boat,” “Silent Night,” “Three Blind Mice,” and “Twinkle Twinkle Little Star.” SP was instructed to specify a title amongst twelve titles listed on the screen for the melody heard. All melodies were created in the octaves surrounding and above middle C. Melodies were played using only consistent repetitions of eight notes without any lyrics and without variation of note duration or timing. This approach was used in order to remove the rhythmic cues that have been reported as a confounding variable in a previous melody recognition study (Kong et al., 2004). The amplitude of each note was randomly changed over a range of ±4dB to eliminate the loudness cues which may be another contributory factor in the recognition tasks. The melody recognition test was presented in the bilateral and left conditions. Each block of stimuli included three instances of each melody differently randomized for each condition.

The timbre subtest comprised eight different types of musical instruments (string, brass, woodwind and percussion) playing the same five-note sequence of C4-A4-F4-G4-C5. Each item was presented three times randomly and SP’s task was to select a corresponding icon from eight icons on the screen for the timbre heard. Piano and guitar were the representatives for percussion, violin and cello for stringed instruments, trumpet for the brass family and flute, clarinet and saxophone for the woodwind class.

SP completed all the CAMP subtests in the bilateral and unilateral left ear conditions with each condition taking 25 minutes on average. According to standard CAMP administration, a short training period was mandatory before each test. In each condition the order of subtests was as follows: pitch direction discrimination, melody recognition and timbre recognition. All parts of the CAMP (including three subtests and short training periods) were administered using a computer-driven program. In order to advance to the subsequent subtest, it was imperative for the participant to complete each short training period and related subtest.

No feedback was given during the CAMP test after SP's responses. The entire test was performed in a sound-proof booth with a loudspeaker in front of the participant at ear level at a distance of 1 meter. Mean sound level was calibrated on the test day at 65 dBA.

Results

CAMP - Pitch Direction Discrimination

Figure 1 shows SP's composite scores (the average of the adaptive threshold values for three reference frequencies) of the standard and F0-shifted pitch direction discrimination subsets. While the average thresholds for normal hearing listeners and cochlear implant users from Kang et al.'s 2009 study were 1.0 (SD = 0.3) and 3.0 (SD = 2.3) semitones respectively, SP's pitch direction discrimination thresholds were close to 0.5 semitones, the minimum possible threshold in the CAMP pitch subtest (a floor effect) in both unilateral and bilateral conditions for all three sets of pitches (low, mid, high). Both unilateral and bilateral cochlear implant users participated in Kang's study.

CAMP - Melody Recognition

Figure 2a shows CAMP melody recognition results for SP. She scored 91.6% on this task in both bilateral and left conditions, compared with 87.5% (SD = 8.3%) for normally hearing listeners and 25.1% (SD = 22.2%) for cochlear implant users (Kang et al, 2009). The confusion matrix for the left condition showed that SP confused "Happy Birthday" with "Silent Night" for all three repetitions and did not select "Happy Birthday" at all. This confusion was not seen in the bilateral condition.

CAMP - Instrument Recognition

Figure 2b shows the results for instrument recognition. While normal hearing listeners could recognize different instruments (timbre) with 94.2% ±4.0% accuracy, and the CI group could do so with an average of 45.3% ±16.2% correct (Kang et al, 2009), SP selected the correct instrument on average 66.67% and 58.33% of the time. The confusion matrix showed that the most common confusion between instruments made by SP was between the cello and violin (an intra-family confusion). Her next most common confusion was between the clarinet and flute, followed by the violin and saxophone (an inter-family confusion). Other confusions occurred less frequently.

Experiment 2:

Absolute and Relative Pitch

For assessment of absolute pitch ability, SP and five normal hearing participants were asked to listen to a single piano note presented at 65 dBA and point to the note on the piano keyboard with 88 keys represented on a touch screen. Immediately after this first response, one octave of the piano was displayed, including the selected note, and the same note was played for the second time. The participant's task was to click the corresponding key among the displayed piano keys in that octave range. The piano notes were the sample of piano notes extracted from Abelton's database of real instrument recordings. Absolute pitch was tested in the unilateral left and bilateral conditions in freefield for SP and binaural condition in freefield for the normally hearing listeners. Before each condition, the participants were given training, and when they understood the task well, the absolute pitch test was administered.

To assess relative pitch perception, two consecutive notes were presented to the participants. The first note was a reference note which was highlighted on a piano keyboard represented on a touch screen. The second note (target note) was presented and the task was to point to the second note on the piano in relation to the reference note. The participants were asked to point to keys above or below the reference note or the same note as reference note. The paired notes were randomly presented with different intervals between the reference and target notes. In some trials, there was no interval between reference and target notes (i.e. both reference and target notes were the same). A short training period was provided before the initiation of the test.

Results:

Absolute and Relative Pitch

Figure 3 shows that in pitch magnitude estimation, for both SP and normally-hearing participants there were high correlations between their responses and the notes played when they were compared in terms of MIDI note numbers. The regression line equation of pitch magnitude estimation for SP was *Response=0.87 Target+ 12.60 + errors* and for normal participants was *Response=0.82 Target+13.66 + errors*. The general regression analyses showed that for both SP and the normally hearing participants, the slopes of the regression lines were significantly different from the perfect value of 1.0 (for SP, t= 3.026, df=81 and p<0.002 and for normally hearing participants, t=8.76, df=413 and p<0.001) but the slope of the regression line of SP was not significantly different from that of the normally hearing participants (t=0.86, df=81 and p>0.05).

In the absolute pitch test, when the responses and targets were compared in terms of their chromatic name within the octave, there was no significant correlation between targets and responses for either SP or the normal hearing participants. Neither SP nor the normal hearing participants were able to assign correct chromatic names to notes, indicating that no subject had perfect pitch judgment.

SP’s responses on the relative pitch task also did not approach the perfect response, as shown in Figure 4. The regression line equation for SP’s data was *Response=0.69 Target + 0.98+errors* and for normal hearing participants was *Response= 0.95 Target + 0.68+errors*. This Figure shows that neither SP (t=12.4, df=71, p<0.001) nor the normal hearing participants (t=2.008, df=363, p=.023) were perfectly accurate in their estimations of the intervals between notes. The slopes of regression lines for SP and the normal hearing group differed significantly from the slope of the perfect line (Response=Target) and there was a significant difference between the slope of regression line of the cochlear implant user and that of normal hearing listeners of this study (t=4.754, df=71, p < 0.001)

Experiment 3:

Consonance Rating

SP and the normally-hearing group participated in a consonance rating task. In this experiment, two simultaneous notes were presented at 65 dB SPL through loudspeakers to the participants and their task was to rate consonance on a touch screen from the far left (the minimum consonance) to the far right (the maximum consonance). The piano notes were the sample of piano notes extracted from Abelton’s database of real instrument recordings (Ableton Inc, Berlin). SP rated consonance in the unilateral left and bilateral conditions. Before training the concepts of consonance and dissonance were discussed to determine whether each subject had a thorough understanding of the task. After brief training, the main test was administered.

Results:

Consonance rating

Figure 5 shows the pattern of responses for normal hearing listeners and SP. The intervals were numbered in order from 0 (unison) to 12 (octave) along the abscissa of Figure 5 and the ordinate shows consonance and dissonance rating in which 100 points corresponds to maximum consonance (minimum dissonance) and 0 corresponds to minimum consonance (maximum dissonance). A two-way ANOVA was performed with subject groups (SP versus the normal hearing participants) and intervals (0 to 12 semitones) as factors and consonance rating as the dependent variable. The difference between SP and normal hearing participants was significant (F (1,412) = 6.68, p=0.010). Also, the difference between intervals was significant (F (12,412) = 16.62, p<0.001). There was no significant interaction between the participants and interval (F (12,412) = 1.39, p=0.170). The analysis showed that SP found the intervals less consonant than the normal hearing participants on average, but that the pattern of consonance rating across the intervals was similar for SP and the normal hearing participants.

Experiment 4

Melody Segregation

In this task, the listener was asked to detect any alteration of a 4 note repeating melody. A distracter, composed of random notes with the same temporal and spectral envelope, was interleaved with the melody. The melody and distracter were presented from the front loudspeaker at the participant's ear height at 65 dBA. In order to be able to detect any variation in the melody, the listener needed to be able to segregate the melody and distracter streams. This task was designed as a baseline at the most difficult level for other experiments on auditory stream segregation (Marozeau et al., 2010, Innes-Brown et al., 2011, Camilleri et al., 2010). The listener's performance in the task was recorded as the percentage of accuracy in the discrimination of the true and modified melodies.

Result:

Melody segregation

SP's results for melody segregation were compared with published data for normal hearing listeners with and without musical training (Camilleri et al. 2010). While the trained musicians and normal hearing listeners without musical training were able to segregate the deviant melody from the true melody 45% and 18% of the time respectively, SP was successful in the task 69% of the time on average in the bilateral aided condition.

The overall results showed that SP was an exceptional performer in pitch direction discrimination, melody segregation and timbre recognition. She out-performed the average cochlear implant user and her results are comparable to those of normal hearing listeners with musical training.

SP was able to discriminate the direction of pitch with the minimum possible threshold on the CAMP, which was much better than the average of the previously published data about CAMP pitch direction discrimination (Jung et al., 2010, Kang et al., 2009), although some individuals in these studies also performed well on this task. In another study (Fearn, 2001), adult cochlear implant users could discriminate the direction of pitch of piano notes with different fundamental frequencies from near 190 Hz to 3100 Hz with a change of 1.5 to 5.8 semitones. This is another indication of SP's exceptional performance among the population of cochlear implant users.

Some characteristics of the CAMP pitch direction discrimination test should be considered. Firstly, the threshold in the CAMP test is sought as the middle point on an S-shaped psychometric function with a tracking procedure. However, it has been suggested that the perception of pitch direction versus fundamental frequency difference for cochlear implant users does not follow an S-shaped psychometric function and therefore the tracking procedures may not be suitable for threshold determination in cochlear implant users (Looi, 2006). Secondly, for each pair, the reference note is always lower in pitch than the comparison notes (Kang et al., 2009). By repetition of the reference notes, the participant might be able to recognize the reference notes using some non-pitch characteristic and tend to *discriminate* the other note as being higher in pitch regardless of the perceived pitch direction. Even if the pitch subtest of the CAMP is accepted as a "discrimination test" rather than a "pitch direction discrimination", SP's performance in discrimination of musical notes that are one semitone apart is still far better than the published average for cochlear implant users (Fearn, 2001, Fujita and Ito, 1999, Gfeller et al., 2007, Sucher and McDermott, 2007).

SP's performance in the melody segregation experiment and the pitch subtest of the CAMP proved that she has exceptional pitch discrimination ability. This exceptional performance was not due to the effect of residual hearing, because there was no difference between the pitch perception results for her left ear (which has no residual hearing) and those for the bilateral condition with the combination of some residual hearing in the right ear and electric hearing in both ears. On the other hand, we cannot say whether there was a difference in her performance between unilateral and bilateral cochlear implants because she performed almost perfectly in both conditions (a ceiling effect for the CAMP pitch direction subtest).

The inability to appreciate music has been attributed to pitch perception deficits (Trehub et al., 2009). Exceptional performance in cochlear implant users is sometimes discussed in terms of place pitch and temporal pitch perception processes. In order to examine and isolate the effects of place pitch and temporal pitch, we shifted the fundamental frequencies of the pitch items towards two extremes (very low and very high). The CAMP pitch results at very high frequency suggest that temporal pitch cues cannot account for SP's good results because at those frequencies no temporal cues were available. Therefore, we concluded that SP must be using place pitch cues very well. In order to consider this hypothesis, an electrodogram of piano notes was generated using SP's cochlear implant map. The electrodogram (Figure 6) shows the output of an ACE strategy sound processor. The horizontal axis represents the fundamental frequencies of the piano notes from low to high and the vertical axis shows SP's electrode numbers. The line passing through the figure reveals the center of gravity of the activation pattern of the stimulated electrodes for different fundamental frequencies. The line shows that place pitch cues are available to SP, although the representation is not completely monotonic (shown as fluctuations in the line) in mid and high frequencies.

Among the three subtests of the CAMP test, timbre (instrument) recognition was the most difficult task for SP, with results close to average cochlear implant recipients, and much poorer than for normal hearing listeners. It is possible that good timbre recognition relies on changes in acoustic intensity over time, recognition of the spectral content, and temporal changes in the spectrum. A possible reason for SP's suboptimal performance in the instrument recognition task may be that although she had extensive experience in listening to piano notes through her piano playing, she was not as familiar with other instruments.

In terms of the absolute and relative pitch perception that is important for music appreciation, SP did not show perfect results, but she performed at a level similar to normal hearing listeners. In pitch magnitude estimation, the slopes of the regression lines of SP and the normal hearing participants did not differ significantly. This suggests that her ability in pitch magnitude estimation in particular did not deteriorate after her hearing loss, and that her experience in playing music helped her to preserve such abilities.

The results of the consonance rating test showed that SP's performance was not due to her residual hearing because her performance with the left ear was comparable with consonance ratings of the normal hearing participants with binaural listening. It appears that SP's exceptional performance is not related to the use of bilateral implants because SP's results in the bilateral condition did not yield a better result than in the unilateral condition. The factor most likely to account for SP's exceptional performance is her continued musical experience with the 1 piano, which extended throughout the period in which she experienced hearing loss, including the post-operation period. It is noticeable that the tests on which she performed exceptionally well all used recording of real piano notes as stimuli presented freefield via her usual sound processor map.

It should also be noted that music composers and musical instrument makers are well-aware of the pitch perception capabilities of people with normal hearing. Although SP's performance on pitch perception tasks was not perfect or ideal, her performance was reasonably close to that of people with normal hearing and therefore likely to produce near-normal appreciation of music, especially piano music, as evidenced by her good performance on the melody recognition task.

Conclusion

Most of the experiments in this study have shown that SP's performance in musical tasks is within the range of normally-hearing listeners' performance. Her results also prove that a sound processor designed to improve speech perception can also provide acceptable music perception, given sufficient experience of musical sound via the processor. This may stem from place pitch representation that is adequate for the perception of pitch and changes in pitch over time. The result shows that the current sound processor is able to code these changes at an acceptable level for subjects like SP who have had a long period of familiarization. Therefore, it is possible for cochlear implant users to attain enough elements of music using current speech processing schemes. A further weakness of current sound processors for music perception is revealed when factors besides pitch cues are needed, for instance fine temporal cues for timbre recognition. It is probable that improved place and temporal coding will reduce the training time required for cochlear implant recipients to achieve music perception capabilities similar to SP's.

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Declaration of Interest

The authors report no conflict of interest in this study.

References

Assmann, P. 1996. Modeling the perception of concurrent vowels: Role of formant transitions. *J Acoust Soc Am,* 100**,** 1141-1152.

Brockmeier, S. J., Peterreins, M., Lorens, A., Vermeire, K., Helbig, S., et al. 2010 Music perception in electric acoustic stimulation users as assessed by the Mu.S.I.C. test. *Adv. Otorhinolaryngol,* 67**,** 70-80.

Camilleri, M., Marozeau, J., Innes-Brown, H. and Blamey, P. J. 2010. Effect of sound localisation on melody segregation. *Australasian International Conference on Speech Science and Technology* 197-200.

Chen, J., Chuang, A., McMahon, C., Hsieh, J., Tung, T., et al. 2010. Music training improves pitch perception in prelingually deafened children with cochlear implants. *Amer Acad Pediatrics,* 125**,** 793-800.

Drayna, D. T. 2007. Absolute pitch: A special group of ears. *Proc Natl Acad Sci U S A,* 104**,** 14549-14550.

Drennan, W. R. 2008. Music perception in cochlear implant users and its relationship with psychophysical capabilities. *J Rehab Res Dev,* 45**,** 779-790.

Eisenberg, L. S. 1982 Use of the cochlear implant by the prelingually deaf. *Ann Otol Rhinol Laryngol Suppl,* 91**,** 62-66.

El Fata, F., James, C. J., Laborde, M.-L. and Fraysse, B. 2009. How much residual hearing is useful for music perception with cochlear implants? *Audiol. Neurootol.,* 14**,** 14-21.

Fearn, R. A. 2001. Pitch discrimination of pure and complex tones:Differences in the Limens. *PhD thesis***,** Chapter 7:135-156.

Fujita, S. and Ito, J. 1999. Ability of nucleus cochlear implantees to recognize music. *Ann Otol Rhinol Laryngol :* , 108**,** 634-640.

Gardner, R. B., Gaskill, S. A. and Darwin, C. J. 1989. Perceptual grouping offormants with static and dynamicdifferences in fundamental frequency. *J Acoust Soc Am,* 85**,** 1329-1337.

Gfeller, K., Jiang, D., Oleson, J. J., Driscoll, V. and Knutson, J. F. 2010. Temporal stability of music perception and appraisal scores of adult cochlear implant recipients. *J Am Acad Audiol,* 21**,** 28-34.

Gfeller, K., Oleson, J., Knutson, J. F., Breheny, P., Driscoll, V., et al. 2008. Multivariate Predictors of Music Perception and Appraisal by Adult Cochlear Implant Users. *Journal of the American Academy of Audiology,* 19**,** 120-134.

Gfeller, K., Olszewski, C., Rychener, M., Sena, K., Knutson, J. F., et al. 2005. Recognition of “real-world” musical excerpts by cochlear implant recipients and normal-hearing adults. *Ear Hear,* 26**,** 237–250.

Gfeller, K., Turner, C., Oleson, J., Zhang, X., Gantz, B., et al. 2007. Accuracy of cochlear implant recipients on pitch perception, melody recognition, and speech reception in noise. *Ear Hear,* 28**,** 412-423.

Gfeller, K. E., Olszewski, C., Turner, C., Gantz, B. and Oleson, J. 2006. Music perception with cochlear implants and residual hearing. *Audiol Neurootol,* 11**,** 12-15.

Hochmair, I., Nopp, P., Jolly, C., Schmidt, M., Schosser, H., et al. 2006. MED-EL cochlear implant: state of the art and a glimpse into the future. *Trends Amplif,* 10**,** 201-219.

Hove, M. J., Sutherland, M. E. and Krumhansl, C. L. 2010. Ethnicity effects in relative pitch. *Psychon Bull Rev,* 17**,** 310-316.

Huron, D. 2001. Tone and voice: A derivation of the rules of voice-leading from perceptual principles *Music Percept,* 16**,** 1-64.

Hutchinson, W. and Knopoff, L. 1978. Acoustic component of western consonance *Interface Journal of New Music Research,* 7**,** 1-29.

Innes-Brown, H., Marozeau, J. and Blamey, P. 2011. The effect of visual cues on difficulty ratings for segregation of musical streams in listeners with impaired hearing. *PLoS ONE,* 6**,** e29327.

Jung, K. H., Cho, Y.-S., Cho, J. K., Park, G. Y., Kim, E. Y., et al. 2010. Clinical assessment of music perception in Korean cochlear implant listeners. *Acta Oto-Laryngologica,* 130**,** 716-723.

Kameoka, k. and Kuriyagawa, M. 1969. Consonance theory part II: consonance of complex tones and its calculation method *J Acoust Soc Am,* 45**,** 1460-1469.

Kang, R., Nimmons, G. L., Drennan, W., Longnion, J., Ruffin, C., et al. 2009. Development and validation of the university of Washington clinical assessment of music perception test. *Ear Hear,* 30**,** 411-418.

Kong, Y.-Y., Cruz, R., Jones, J. A. and Zeng, F.-G. 2004. Music perception with temporal cues in acoustic and electric hearing. *Ear Hear,* 25**,** 173-185.

Laneau, J., Wouters, J. and Moonen, M. 2006. Improved music perception with explicit pitch coding in cochlear implants. *Audiology and Neurotology,* 11**,** 38-52.

Lassaletta, L., Castro, A., Bastarrica, M., Pérez-Mora, R., Herrán, B., et al. 2008 Musical perception and enjoyment in post-lingual patients with cochlear implants. *Acta Otorrinolaringol Esp,* 59**,** 228-234.

Looi, V. 2006. *Music perception of cochlear implant users.* PhD Thesis.

Marozeau, J., Innes-Brown, H., Grayden, D. B., Burkitt, A. N. and Blamey, P. J. 2010. The effect of visual cues on auditory stream segregation in musicians and non-musicians. *PLoS ONE,* 5**,** e11297.

McDermott, H. J. 2004. Music perception with cochlear implants: A review. *Trends Amplif,* 8**,** 49-82.

McDermott, J. h., Lehr, A. and Oxenham, A. J. 2008. Is relative pitch specific to pitch. *Psychol Sci,* 19**,** 1263-1271.

Nelson, P. B., Jin, S.-H., Carney, A. E. and Nelson, D. A. 2003. Understanding speech in modulated interference: Cochlear implant users and normal-hearing listeners. *J. Acoust. Soc. Am,* 113**,** 961-968.

Nimmons, G. L., Kang, R. S., Drennan, W. R., Longnion, J., Ruffin, C., et al. 2008. Clinical assessment of music perception in cochlear implant listeners. *Otol Neurotol,* 29**,** 149-155.

Oxenham, A. J. 2008. Pitch perception and auditory stream segregation: implications for hearing loss and cochlear implants. *Trends Amplif,* 12**,** 316-331.

Plomp, R. and Levelt, V. J. 1965. Tonal consonance and critical bandwidth. *J Acoust Soc Am,* 38**,** 548-560.

Qin, M. K. and Oxenham, A. J. 2003. Effects of simulated cochlear-implant processing on speech reception in fluctuating maskers. *J Acoust Soc Am,* 114**,** 446 -454.

Shannon, R. V. 1992. Temporal modulation transfer functions in patients with cochlear implant. *J Acoust Soc Am,* 91**,** 2156-2164.

Stickney, G. S., Zeng, F.-G., Litovsky, R. and Assmann, P. 2004. Cochlear implant speech recognition with speech maskers. *J Acoust Soc Am,* 116**,** 1081-1091.

Sucher, C. M. and McDermott, H. J. 2007. Pitch ranking of complex tones by normally hearing subjects and cochlear implant users. *Hear Res,* 230**,** 80-87.

Swanson, B. A. 2008. *Pitch perception with cochlear implants.* PhD thesis, Department of Otolayngology, University Of Melborne.

Trehub, S. E., Vongpaisal, T. and Nakata, T. 2009. Music in the lives of deaf children with cochlear implants. *Ann N Y Acad Sci,* 1169**,** 534–542.

Tufts, J. B., Molis, M. R. and Leek, M. R. 2005. Perception of dissonance by people with normal hearing and sensorineural hearing loss. *J Acoust Soc Am,* 118**,** 955-67.

Vandali, A. E., Sucher, C., Tsang, D. J., McKay, C. M., Chew, J. W. D., et al. 2005. Pitch ranking ability of cochlear implant recipients: A comparison of sound-processing strategies. *The Journal of the Acoustical Society of America,* 117**,** 3126.

Veekmans, K., Ressel, L., Mueller, J., Vischer, M. and Brockmeier, S. J. 2009. Comparison of music perception in bilateral and unilateral cochlear implant users and normal-hearing subjects. *Audiol Neurootol,* 14**,** 315-26.

Ward, W. D. 1963. Absolute pitch: II. *SOUND,* 2**,** 33-41.

Zeng, F.-G. 2002. Temporal pitch in electric hearing. *Hear Res,* 174**,** 101-106.

Figure 1-Mean semitones of pitch direction discrimination test of SP’s in three frequency ranges (low-, mid- and high-frequency) is highlighted by different colors in two conditions (Left and Bilateral). The results of the cochlear implant users (CI) and normally hearing listeners (NH) in mid-frequency was derived from Kang et al. (2009). The means expressed as thresholds with the unit of semitones.

Figure 2- SP’s results in two conditions of monaural Left (Left) and Bilateral (Bi) in a) CAMP melody recognition and b) CAMP timbre recognition were compared with the results of the normally hearing listeners (NH) and cochlear implant users of Kang et al.(2009). The correct selections are expressed in percentage.

Figure 3- SP’s results (in circle) and normally hearing listeners (in triangle) in pitch magnitude estimation test. The dashed line shows the regression between her responses while the solid line indicates the regression between normally hearing listeners’ responses. Every note which should be selected is assigned by a MIDI note number.

Figure 4- SP’s results (in circle) and normally hearing listeners (in triangle) in the relative pitch test. The dashed line shows the regression between her responses while the solid line indicates the regression between normally hearing listeners’ responses. The difference between every pairs is expressed in semitones. The minus symbol indicates the second note in a pair has lower frequency.

Figure 5- SP’s results (in circle) and normally hearing listeners (in triangle) in the consonance rating test. The dashed line shows pattern of her responses while the solid line indicates the regression between normally hearing listeners’ responses. The difference between every pairs is expressed in semitones. The minus symbol indicates the second note in a pair has lower frequency.

Figure 6 –Electrodogram of SP. The figure shows the activation pattern of her different electrodes (from number 22 to 1) for stimuli with different fundamental frequencies (X axis). The vertical ax in the right side shows the center frequency of each channel. In the left vertical side, the electrode numbers have been shown from very low frequency electrode (number 22) to very high frequency electrode (number 1). The line passing through the figure reveals the center of gravity of the activation pattern of the stimulated electrodes for different fundamental frequencies.

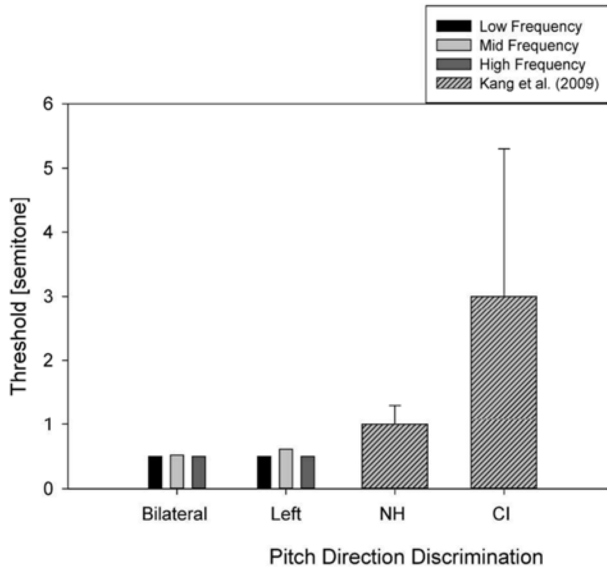

Low Frequency
Mid Frequency
High Frequency
Kang et al. (2009)
Threshold [semitone]
0
1
2
3
4
5
6
Bilateral
Left
NH
CI
Pitch Direction Discrimination

Fig 1

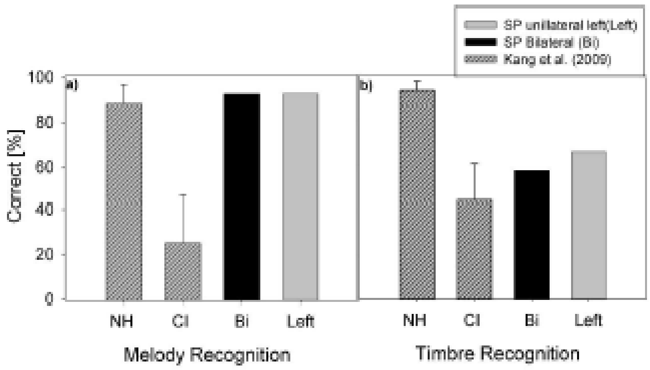

SP unilateral left(Left)
SP Bilateral (Bi)
Kang et al. (2009)
a)
b)
Correct [%]
0
20
40
60
80
100
NH
CI
Bi
Left
Melody Recognition
NH
CI
Bi
Left
Timbre Recognition

Fig 2

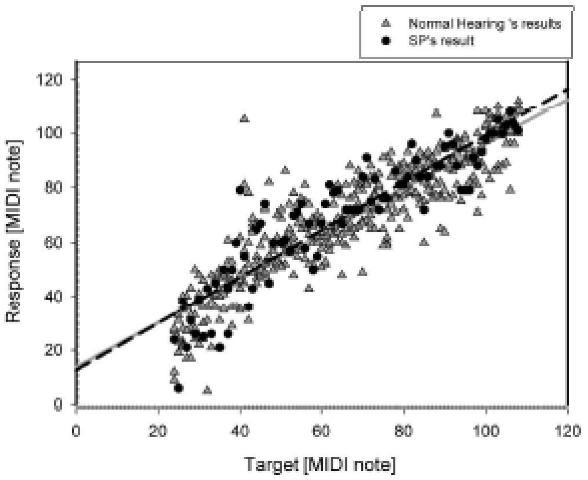


Fig 3

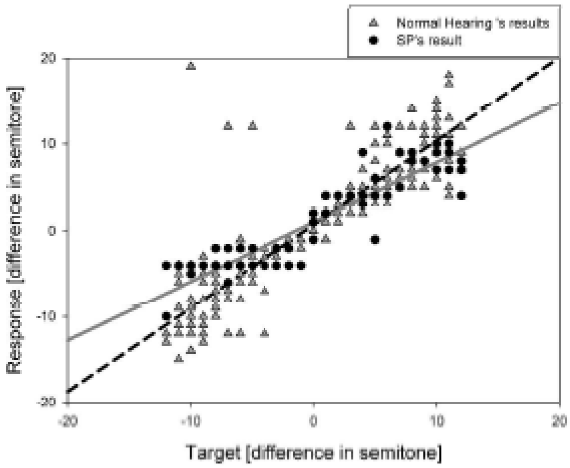


Fig 4

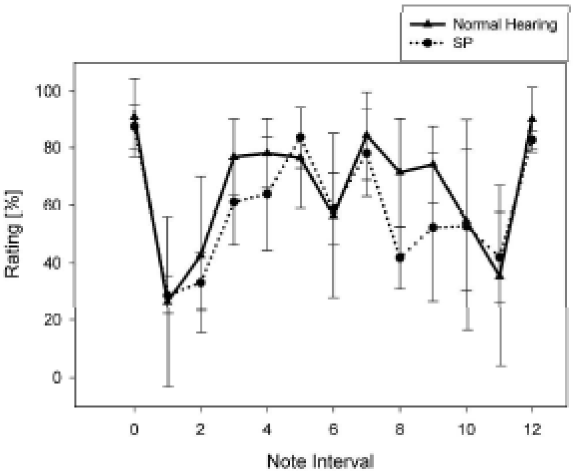
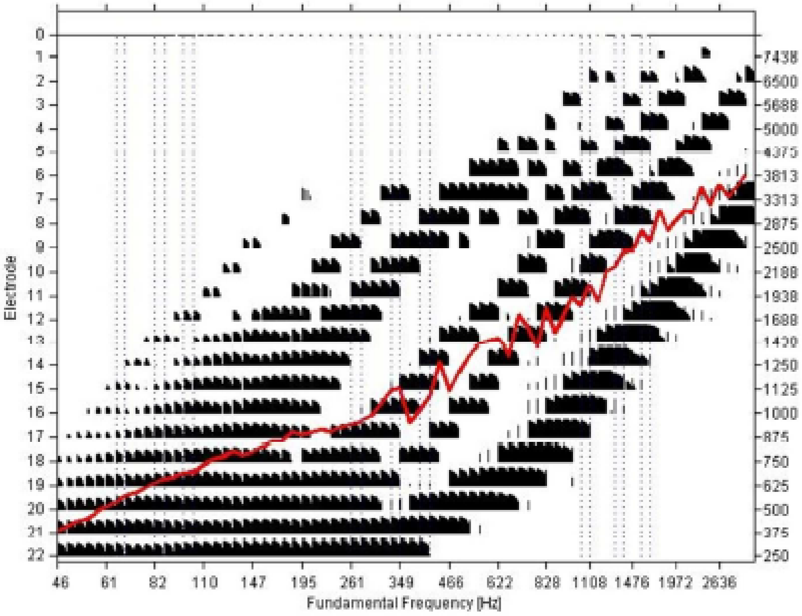


Fig 5


Electrode
0
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16
17
18
19
20
21
22
7438
6500
5688
5000
4375
3813
3313
2875
2500
2188
1938
1688
1420
1250
1125
1000
875
750
625
500
375
250
46
61
82
110
147
195
261
349
466
622
828
1108
1476
1972
2636
Fundamental Frequency [Hz]

Fig 6