THE EFFECT OF COCHLEAR IMPLANTATION ON MUSIC PERCEPTION BY ADULTS WITH USABLE PRE-OPERATIVE ACOUSTIC HEARING

Valerie Looi[a,b,c], Hugh McDermott[a], Colette McKay[a,d], & Louise Hickson[e]

[a]Department of Otolaryngology, The University of Melbourne, Melbourne, VIC, Australia

[b]Cooperative Research Centre for Cochlear Implant and Hearing Aid Innovation, Melbourne, VIC, Australia

[c]Department of Communication Disorders, The University of Canterbury, Christchurch, New Zealand

[d]School of Psychological Sciences, The University of Manchester, Manchester, United Kingdom

[e]Division of Audiology, School of Health and Rehabilitation Sciences, The University of Queensland, Brisbane, Australia

Corresponding author:

Valerie Looi

Department of Communication Disorders,

The University of Canterbury,

Private Bag 4800,

Christchurch 8020. New Zealand

Phone: 64-3-3642987 (ext: 3051). Fax: 64-3-3642760

Email: valerie.looi@canterbury.ac.nz

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Abbreviations:

ACE – Advanced Combination Encoder

ANOVA – Analysis of Variance

CI – cochlear implant

CUNY – City University of New York

DAI – Direct Audio Input

dB – decibels

HL – hearing level

SPL – sound pressure level

F0 – fundamental frequency

HA – hearing aid

Hz - Hertz

MTB – Music Test Battery

NH – normally hearing

SD – standard deviation

SDM – score-difference mean

SPEAK – Spectral Peak strategy

ABSTRACT

This study investigated the change in music perception of adults undergoing cochlear implantation. Nine adults scheduled for a cochlear implant (CI) were assessed on a music test battery both prior to implantation (whilst using hearing aids; HAs), and 3 months after activation of their CIs. The results were compared with data from a group of longer-term CI users and a group of HA-only users. The tests comprised assessments of rhythm, pitch, instrument, and melody perception. Pre-to-post surgery comparisons showed no significant difference in the rhythm, melody, and instrument identification scores. Subjects' scores were significantly lower post-implant for ranking pitch intervals of one octave and a quarter octave ($p = 0.007$, and $p < 0.001$, respectively), and were only at chance levels for the smaller interval. However, although pitch perception was generally poorer with a CI than with a HA, it is likely that the use of both devices simultaneously could have provided higher scores for these subjects. Analysis of the other tests' results provided insights into factors affecting music perception for adults with severe to profound hearing impairment.

INTRODUCTION

A full appreciation of music requires the perception of four basic perceptual attributes, as identified by Krumhansl & Iverson (1992): pitch, duration, loudness, and timbre. Timbre is "that attribute of auditory sensation in terms of which a listener can judge that two sounds similarly presented and having the same loudness and pitch are dissimilar" (Acoustical Society of America (1960), cited in Gfeller et al. (2002b), p. 349). It includes the features of a sound that do not directly relate to pitch or loudness, and is usually assessed by instrument identification tasks. Music perception primarily involves pattern perception, be it rhythmic, pitch, loudness, or timbral variations (Gfeller et al., 1997). Whereas the sequencing or patterning of pitches forms the musical correlates of melody and harmony, the sequencing of durations or temporal patterns forms the foundation of rhythm. However, although these attributes are separate entities, the combinations of, and interactions between the different attributes largely contribute to music as we commonly know it. This paper reports a study which investigated the change in perceptual accuracy for music for patients undergoing cochlear implantation by comparing their perception pre-surgery to that at 3 months after activation of the device. Specifically, scores on tasks of rhythm discrimination, pitch ranking, instrument identification, and familiar-melody recognition were compared.

Studies that investigated levels of music listening, participation, and enjoyment amongst the adult CI population have generally concluded that, when compared to a time prior to having a hearing loss, many CI users report music to sound less pleasant, and also that they spend less time listening to it (Gfeller et al., 2000). When compared to normally hearing (NH) listeners, CI users tend to appraise musical excerpts to sound less pleasant. For example, Gfeller et al. (2002c) compared 41 postlingually deafened CI users to 11 NH subjects in their appraisal ratings for eight musical instrument sounds (violin, cello, trumpet, trombone, flute, clarinet, saxophone, and piano). When compared to the NH subjects, the CI subjects provided lower overall appraisal scores, with the higher-frequency instruments being perceived to sound more scattered (i.e., noisier) and less brilliant (i.e., duller). In a recent study comparing CI users to HA users with equivalent levels of hearing loss, Looi et al. (2007) found that a group of newly implanted CI recipients provided significantly higher ratings of 'pleasantness' post-surgery with the CI than pre-surgery whilst using HAs for musical excerpts involving both solo instruments and musical groups. The authors also found a similar trend in the comparisons between a group of longer-term CI users and a group of HA-only users; mean ratings for the CI subjects were generally higher than for the HA subjects. All of the subjects in that study had a moderately-severe to profound bilateral hearing loss. The HA subjects were selected to meet the implantation criteria (i.e, hearing loss levels and speech perception scores) for a Nucleus CI24 implant with the standard-length electrode array.

Gfeller et al. (2003) investigated the appraisal of melodies, both in regard to 'liking' and perceived complexity, across the musical styles of pop, country and western, and classical. The CI subjects provided similar ratings across the three genres with a strong preference for stimuli perceived to be 'simple', whereas the NH group demonstrated definite stylistic preferences, and preferred stimuli perceived to be more complex. The authors hypothesised that it was possible that implantees could not reliably differentiate between the three styles, hence the consistency in their ratings. Looi et al. (2007) found that their hearing-impaired subjects (who all had moderately-severe to profound hearing losses bilaterally) rated musical extracts played by a single instrument to sound significantly more pleasant than more-complex extracts involving multiple instruments, regardless of whether they used a CI or HA.

In published studies where music perception was assessed via tasks involving discrimination or identification, the performance of CI users has usually been compared to that of NH subjects. The consensus across these studies is that, although adult CI users perceive rhythm approximately as well as the NH population (Gfeller & Lansing, 1992; Gfeller et al., 1997, 2000; Schulz & Kerber, 1994), CI users score significantly lower on pitch-based tests. Unlike CI users for whom electrical stimulation of hearing is used, listeners with NH and those using HAs perceive sound via acoustic stimulation. Fujita & Ito (1999), Galvin et al. (2007), Gfeller et al. (1997, 2007), and Schulz & Kerber (1994) have shown that CI users perform significantly worse than NH listeners on a range of pitch-perception tasks, including pitch ranking, melodic contour identification, and pitch discrimination. This difference in pitch perception between CI and NH listeners is also apparent in tasks involving timbre perception, which is usually assessed via instrument identification tasks. As variations in the spectral characteristics of an acoustic signal change the perceived timbre, the manner in which CIs code these spectra will affect the listener's ability to differentiate between timbres (Gfeller et al., 1998). It appears that the representation of spectral information by current CI systems is inadequate for accurate timbral perception. For example, Gfeller et al. (2002c) found a significant difference between 51 CI and 20 NH subjects in their ability to recognise eight different musical instruments. The NH subjects scored 91% correct whilst the CI patients scored only 47% correct.

Tests of melody recognition have also reflected the difficulty experienced by CI recipients in accurately perceiving pitch, regardless of whether both rhythm and pitch cues are left intact, or whether only the pitch cues are preserved (Galvin et al., 2007; Gfeller et al., 2002a, 2007; Schulz & Kerber, 1994). The inclusion of vocal cues has been shown to assist CI users in identifying familiar melodies, with both Leal et al. (2003) and Fujita & Ito (1999) finding that melody-recognition scores improved when verbal cues were added to the stimuli.

Most studies into music perception of CI users, including those cited above, have made comparisons mainly to subjects with an unimpaired auditory system. There are few studies comparing CI users to subjects with a hearing loss. One such study by Kong et al. (2005) involved five CI subjects with residual hearing in the non-implanted ear (i.e., they wore a HA in the contralateral ear). The authors compared melody-recognition skills for three listening modalities: CI-alone, HA-alone, and both devices simultaneously. Three sets of 12 familiar melodies devoid of rhythm cues (i.e., containing pitch cues only) were used. The HA-alone mean score of 45% correct was, on average, 17 percentage points better than the average CI-alone score, with little difference between the HA-alone and combined device conditions.

Looi et al. (*in press*) compared the music perception skills of 15 experienced CI users (tested with only their CI) to those of 15 HA-only users who met the audiological criteria for implantation. For that study, this was a moderately-severe to profound bilateral hearing loss, with open-set speech perception scores for sentence stimuli ≤70% in the best-aided condition, and ≤40% in the ear to be implanted. There was no difference between the groups' mean scores in the rhythm discrimination test. There was a significant difference between the two groups' scores for the pitch-ranking and melody-recognition tests, with the HA subjects obtaining better scores for both tasks. There was no significant difference in the two groups' ability to identify musical instruments or ensembles, despite the contrasting modes of auditory stimulation involved. The study also found that whilst the HA users obtained higher scores than the CI users on some tests, the HA group's results suggested that they did not achieve optimal music perception either. For example, although the HA group scored higher on the pitch-perception task than the CI group, the performance of the former group was still significantly poorer than that achieved by a group of NH subjects who verified the music tests used in the study.

Thus, it appears that many CI users score poorly on frequency-based perceptual tests such as musical instrument identification, melody recognition, and pitch discrimination. However, as mentioned earlier, most published studies have compared CI users to NH listeners, thereby discounting the effect that a significant hearing loss may have on music perception. Hence, the primary aim of the present study was to investigate the effectiveness of acoustic and electrical stimulation for music perception by recruiting hearing-impaired subjects whose hearing loss was severe enough to meet the criteria for a conventional long-electrode array CI. These subjects were initially tested prior to implantation whilst using their HA (acoustic stimulation), and subsequently 3 months post-implantation using only their CI (electrical stimulation). This within-subjects design allowed direct comparisons between HA-alone and CI-alone listening conditions for music perception, for each subject. This is advantageous given the considerable variability amongst both HA and CI recipients, which can make interpretation of comparisons between two separate group of HA and CI users difficult. Unlike the Looi et al. (*in press*) study which compared the results of two separate groups of subjects (i.e., a group of HA users and a group of CI users), this study recruited patients on the waiting list for an implant and tested them prior to surgery with HAs and again, 3 months after activation of their CIs. This allowed a direct comparison to be made between CI-alone and HA-alone conditions on tests investigating music perception. As the subjects in this study were retested post-implantation using the same tests undertaken pre-surgery with HAs, it was possible that a learning or training effect may have occurred over time. Therefore, the data reported by Looi et al. (*in press*) for test-retest score changes were utilised as control-group comparisons. In that study, the subjects in the CI and HA groups also undertook the music tests used in the present study on two occasions separated by the same time interval. The results from that study showed that there was a learning effect between the two test administrations for both groups.

METHODS

Subjects

Experimental Group

Nine postlingually deafened adults (7 male, 2 female) on the waiting list for an implant, and who subsequently received an implant, were involved in this study (Table 1). They ranged in age from 41 to 71 years (mean: 54.3 years; SD: 10.72), and were recruited from two CI clinics in Australia. The audiological criteria for implantation at these clinics included having a bilateral moderately severe to profound sensorineural hearing loss (i.e., hearing thresholds 55 dBHL or worse) between 1 kHz and 4 kHz, with auditory-alone speech-perception scores for sentence stimuli (CUNY (City University of New York) sentences) presented at conversational levels in quiet listening conditions of less than 70% in the best-aided condition, and less than 40% in the ear to be implanted. The average pre-surgery thresholds of these subjects for the ear selected for testing are shown in Figure 1.

Place Table 1 near here

Place Fig. 1 near here

Pre-surgery, each subject was tested with his or her own HA, as detailed in Table 1. As part of the CI candidacy assessment process, each subject's HA had been fitted by an audiologist to optimise their speech perception. All subjects were subsequently implanted with a Nucleus CI24R device, and utilised the ACE sound-processing strategy at various rates (as detailed in Table 1).

Control Group 1 - Experienced Cochlear Implant (CI) Users

Fifteen postlingually deafened adult users of the Nucleus CI system (7 male, 8 female) served as a control group. These were the same subjects as the CI subject group in the Looi et al. (*in press*) study. Relevant details about these subjects are presented in Table 2. The subjects were recruited from the same CI clinics as the experimental group. All subjects had at least one year's experience with the CI, and ranged in age from 36 to 75 years (mean: 60.4 years; SD=11.66). There were eight subjects using the ACE strategy, and seven using the SPEAK strategy. Although four of these subjects (subjects 5, 6, 8, and 10) used a HA in their contralateral ear, all subjects were tested in a CI-only listening condition.

<u>Place Table 2 near here</u>

Control Group 2 - Hearing Aid (HA) Only Users

A second control group comprising fifteen postlingually deafened adult HA-only users also participated in this study. These were the same subjects as the HA subject group in the Looi et al. (*in press*) study; details about these subjects are shown in Table 3. All of these HA subjects were required to meet the same audiological CI-qualification criteria as the subjects in the experimental group. In order to ensure that these criteria were met, the researcher initially assessed potential subjects' aided speech-perception abilities, unilaterally as well as binaurally, using the CUNY sentence test. Sentences were presented at 65 dBSPL from a loudspeaker in a sound-treated booth. Similar to the CI control group, the HA subjects in this group were required to have had at least one year's of experience with wearing HAs. They ranged in age from 49 to 80 years (mean: 64.7 years; SD=8.64). Subjects utilised their personal HA for testing; all were digitally-programmable or digital behind-the-ear models, as listed in Table 3.

Place Table 3 near here

Music Test Battery (MTB)

This test battery, developed by the researchers, is described in more detail in Looi et al. (*in press*). Briefly, the MTB comprised four perceptual tasks – rhythm discrimination, pitch discrimination, timbre recognition (in the form of an instrument identification task), and melody recognition in which both the pitch and rhythm cues were preserved. The rhythm test consisted of 38 pairs of rhythmic sequences of tones having the same pitch. Subjects were asked to decide whether the sequences in each pair had the same or a different rhythmic pattern. For the pitch test, one-octave (12 semitones), half-octave (6 semitones), and quarter-octave (3 semitones) intervals were used in a pitch-ranking task. The stimuli consisted of the vowels /i/ (as in 'heed') and /a/ (as in 'hard'), sung by a male and female singer, encompassing a wide pitch range (see Table 4). Descending and ascending pitch sequences were presented in equal numbers, and the loudness levels were varied randomly to reduce the likelihood that any correlated loudness differences would affect the results. The number of pitch pairs in the ranking test was 96 for the one-octave and half-octave subtests, and 128 for the quarter-octave subtest.

Place Table 4 near here

The instrument identification test also comprised three subtests. The first subtest consisted of single-instrument stimuli, the second had solo instruments with background accompaniment, and the final subtest incorporated music ensemble stimuli. For each subtest, four 5-second extracts of 12 different instruments or ensembles were included (i.e., 48 stimuli per test), with the levels of the four extracts being randomised to minimise any unwanted loudness cues. In the first subtest, 12 solo instruments were presented. These instruments were: male singer, female singer, piano, guitar, bass drum (i.e., timpani), drum kit, xylophone, cello, violin, trumpet, flute, and clarinet. In subtest 2 the same 12 instruments were presented to subjects, but in a 'soloist with accompaniment' format. For the third subtest, the stimuli consisted of 12 different music ensembles, each playing as a cohesive, unified group without a soloist. The selected ensembles were: choir (four-part, a capella), orchestra, jazz band (instrumental only), rock band (instrumental only), country and western band (instrumental only), string quartet, percussion ensemble, violin and piano duet, cello and piano duet, male singer and piano duet, female singer and piano duet, and a trio consisting of one male and one female singer with piano accompaniment.

Prior to testing, each subject confirmed that they were familiar with each of the instruments or ensembles. A closed-set procedure was adopted for all three subtests. Each instrument or ensemble was presented four times, giving a total of 48 trials. For the second subtest (i.e., solo instrument with background accompaniment), two closed-set runs were conducted resulting in a total of 96 trials. In the first run, subjects had to identify the solo instrument from the same list as used in subtest 1. For the second run, subjects were additionally informed that the background ensemble in each extract was an orchestra.

The final test of the MTB was a familiar-melody recognition test incorporating ten melodies, each presented two times. These melodies were (in alphabetical order): Advance Australia Fair, Baa Baa Black Sheep, For He's a Jolly Good Fellow, Happy Birthday, Jingle Bells, O Come All Ye Faithful, Old Macdonald Had a Farm, Silent Night, Twinkle Twinkle Little Star, and Waltzing Matilda. Each melody had a duration of 15 seconds, and was played in C major (centering around middle-C on the keyboard) at a speed of 100 crotchet beats per minute with normal rhythm. All of the notes for each melody were in the range from C3 to C5 (131 to 523 Hz). Each subject's familiarity with all of the melodies was verified prior to testing.

Overall Procedure

For the experimental group subjects, the MTB was administered on two occasions: once pre-implant whilst using HAs (test block 1), and subsequently at about 3 months after activation of the CI (test block 2). For subjects in the two control groups (i.e., the CI and HA groups), the MTB was also administered on two occasions approximately 4 months apart. The MTB took about 3 hours to complete, conducted over 2 or 3 sessions. For the experimental group pre-surgery and the HA control group, tests were presented to the ear with which the subject obtained better speech-perception scores, or in cases with similar or fluctuating losses, the ear which the subject preferred. For 8 of the 9 subjects in the experimental group (i.e., with the exception of subject 1), this ear was contralateral to the one which received the CI (Table 1). The order of presentation of the stimuli constituting each test or subtest was randomised. No stimuli were repeated, and no feedback was given to subjects about their responses during the course of testing. However, standardised written instructions were provided to each subject for each of the tests and subtests.

Pre-surgery, the test stimuli were presented either via direct audio input (DAI) or a neck loop system (see Tables 1 & 3). DAI was configured via an audio shoe attached to the HA. For situations where DAI was not available, a neck loop system was used. Post-surgery, DAI was used with each subject's speech processor being directly connected to the sound output of the computer. Both DAI and the neck loop system bypassed the device's microphone system. For the testing procedure, subjects utilised their preferred listening settings on their device, and presentation levels were individually selected to produce a 'comfortable' loudness. None of the subjects used a special music-listening program or device setting for the tests, either pre- or post-surgery. Further details about the procedures and presentation modes for the control groups are provided in Looi et al. (*in press*).

RESULTS

Music Test Battery

For the experimental group, the pre-implant and post-implant mean scores from each item of the MTB are presented in Figure 2. With the exception of the pitch test, post-surgery scores were higher than pre-surgery scores. As previously mentioned, the task-learning effect in the control group was used to estimate the task learning in the experimental group. As can be seen in Figure 3, both of the control groups scored higher on the second test block than on the first test block for all of the tests, except for the rhythm test. This suggests that there was a task-related learning effect for these tests. The asterisks in Figure 3 indicate the individual subtests that were significantly different using a paired t-test ($p<0.05$). For the two control subject groups, only the results applicable to this learning effect analysis will be reported. Direct comparisons between the experienced CI subject group and the HA-only subject groups' performance on these music tests were reported in Looi et al. (*in press*).

Place Figure 2 near here

Place Figure 3 near here

To assess whether any changes in the pre-to-post surgery test scores for the experimental group were solely attributable to a learning effect, or if obtaining an implant had an additional effect on the scores, the differences in the experimental group's pre-to-post surgery scores were compared with the corresponding differences in scores for the CI and HA groups. That is, statistical tests were conducted to determine whether the change between the pre-surgery and post-surgery test scores for the experimental subject group was significantly different from the change in scores between the two test blocks completed by the CI and HA groups. For each subject, the difference between their second test block score and their first test block score was calculated. The mean of this was calculated for each group, and is referred to below as the score-difference mean (SDM).

To assess whether there was any difference between the SDMs across the three groups, a 2-way repeated-measures Analysis of Variance (ANOVA) was conducted with a between-subject factor of group (i.e., experimental group, CI control group, and HA control group), and a within-subject factor of subtest. There was a significant difference for the factor of subtest ($p < 0.001$), with no significant main effect of group ($p = 0.529$), and a highly significant interaction between the two factors ($p < 0.001$). This indicates that the degree of change in the scores between the two test blocks for each group was not consistent across the different tests and subtests, which can be observed from the graphical representation of the SDM in Figure 3.

As shown in Figure 3, there appears to be little difference between the two control groups for the change in scores between the two test blocks. This was confirmed with independent-samples t-tests showing no significant difference in the SDM between the two control groups for any of the tests. That is, the extent of the learning effect for the music tests was similar for the control groups. Therefore, the SDMs for these two groups were combined for subsequent comparisons to the experimental subject group; the combined value is referred to below as the controls' SDM. Independent-samples t-tests between the controls' SDM and the experimental group's SDM were then performed in order to assess whether the changes in the pre-to-post surgery test scores for the subjects in the experimental group were attributable to more than a learning effect. As the degree of learning effect observed for the two control groups was similar, it would be reasonable to expect that the experimental subject group would also exhibit a similar learning effect. Hence, a significant p-value for the independent-samples t-test of the SDMs would suggest that there was more than just a learning effect contributing to the change in scores for subjects in the experimental group. The results of this test and other relevant analyses are reported below.

Rhythm Test

An independent-samples t-test showed no significant difference between the controls' SDM and the experimental group's SDM ($p = 0.551$). That is, the pre-to-post surgery change in scores for the experimental group from 95% correct (SD = 3.48%) to 96% correct (SD = 2.63%) was not significantly different from the change in scores over time for the combined CI and HA control groups.

Pitch Test

For the experimental group, pre-implant, the mean scores for the one-octave, half-octave, and quarter-octave pitch-ranking subtests were 84% (SD = 11.2%), 72% (SD = 12.0%), and 66% (SD = 10.1%) correct, respectively. Post-implant, the corresponding mean scores were 74% (SD = 14.2%), 72% (SD = 12.1%), and 55% (SD = 10.8%) correct. An independent-samples t-test comparing the controls' SDM to the experimental group's SDM showed significant differences for the one-octave and quarter-octave subtests ($p = 0.007$ and $p < 0.001$, respectively). For the difference between the pre- and post-implant scores for the half-octave subtest, $p = 0.061$. Importantly, the change in the pitch test scores for the subjects in the experimental group was in the opposite direction to the change observed for the two control groups (see Figure 1). Whereas the control groups' scores increased from the first to second test blocks, the experimental group's post-surgery scores for the one-octave and quarter-octave subtests were lower than their pre-surgery scores.

To determine whether there were any significant differences between the experimental group's scores across the three subtests, and between the scores for the male-sung and female-sung vowels, separate 2-way repeated-measures ANOVAs were conducted for the pre-implant and post-implant blocks. Pre-implant, there was a significant difference for the factor of subtest ($p < 0.001$), but no significant difference for the factor of singer's sex ($p = 0.973$). Post-hoc pairwise comparisons with Bonferroni corrections showed the significant effect for the factor of subtest to arise from differences between the scores for the one-octave and half-octave subtests ($p = 0.014$), and between the one-octave and quarter-octave subtests ($p < 0.001$). For the difference between the half-octave and quarter-octave subtests' scores, $p = 0.068$. Mean scores were highest for the one-octave subtest and lowest for the quarter-octave subtest. Post-implant, increased interval size also resulted in higher mean scores. The post-implant 2-way repeated-measures ANOVA showed that both the factors of subtest and singer's sex were significant ($p < 0.001$ and $p = 0.018$, respectively). The scores for the male-sung vowels were higher than those for the female-sung vowels within each of the subtests. Post-hoc pairwise comparisons with Bonferroni corrections showed the significant effect of subtest to arise from the difference between the half-octave and quarter-octave interval scores, and between the one-octave and quarter-octave interval scores ($p < 0.001$ for both comparisons).

A 1-sample t-test was conducted to assess if there was any difference between the experimental group's mean scores for each of the subtests and the chance score of 50%. All pre-implant scores were significantly better than the chance score. However, the post-implant quarter-octave mean of 55% correct was not significantly different from chance-level performance ($p = 0.219$), implying that, on average, these subjects were not able to rank pitches one quarter of an octave apart when listening with the implant.

Instrument Identification Test

For the single instrument, instrument with background accompaniment, and music ensembles subtests, the subjects scored 54% (SD = 14.7%), 43% (SD = 13.2%), and 35% (SD = 10.5%) correct respectively pre-implantation, and 65% (SD = 11.6%), 47% (SD = 8.6%), and 46% (SD = 8.5%) correct post-implantation. An independent-samples t-test showed no significant difference between the controls' SDM and the experimental group's SDM (subtest 1: $p = 0.275$; subtest 2: $p = 0.945$; subtest 3: $p = 0.072$). That is, the slight improvement pre-to-post surgery for the experimental group's scores for all three subtests was not significantly different from the change in scores recorded by the two control groups.

To investigate if there was any significant difference between the experimental group's performance across the three subtests, separate 1-way repeated-measures ANOVAs were conducted for the pre-implant and post-implant scores. Results of these analyses showed that there was a significant difference for the factor of subtest both pre- and post-implant ($p = 0.002$ and $p < 0.001$, respectively). Tests of the within-subjects contrasts showed that both pre- and post-implant, there were significant differences between scores on subtests 1 and 2 (pre: $p = 0.004$; post: $p = 0.001$), and subtests 1 and 3 (pre: $p = 0.009$; post: $p = 0.002$). There were no significant differences between the scores of subtests 2 and 3, either pre- or post-surgery.

Analysis of the responses provided by subjects in the experimental group revealed that pre-implant, the most accurately recognised single instruments were the drum kit, piano, and xylophone. Post-implant, the piano and the male singer were the most recognised instruments. For the second subtest, the timpani and male singer were the most recognised stimuli, both pre- and post-implantation. The guitar was the least accurately recognised instrument for both of these subtests pre-implantation. Post-implantation, the flute and clarinet were the least accurately recognised instruments in the first and second subtests, respectively. For the music ensemble stimuli, the choir was the most-recognised group pre-implantation, whereas the male singer and piano duet was the most-recognised group post-implantation. The least-recognised ensembles were the string quartet pre-implantation, and both the country and western band, and the violin and piano duet post-implantation.

Melody Test

The pre-implant mean score for the experimental group was 75% (SD = 25.7%) correct, and the post-implant mean score was 80% (SD = 24.0%). An independent-samples t-test showed no significant difference between the controls' SDM and the pre-to-post surgery improvement shown by the experimental group (p = 0.776). For the experimental group prior to surgery, Waltzing Matilda and Baa Baa Black Sheep were the best-recognised melodies, whilst post-surgery, For He's A Jolly Good Fellow, and Happy Birthday were the best-recognised melodies.

DISCUSSION

Overall, the only significant difference between the pre- and post-implant results from these newly implanted subjects was for the pitch test. For the one-octave and quarter-octave subtests, there were significant differences between the difference in the experimental group's pre-to-post surgery scores and the change between the control groups' subtest scores for the two test administrations. That is, the degree of difference between the experimental group's post-surgery and pre-surgery scores was significantly greater than the degree of change over time for the control groups for these subtests only. The differences between the other pre-to-post surgery scores for the experimental group were not significantly different from the improvement in scores associated with the learning effect observed for the CI and HA control groups.

The lack of difference between the pre-to-post surgery scores for rhythm perception is consistent with existing literature where it is well established that adults with hearing impairments generally perceive rhythm as well as adults with normal hearing (Gfeller & Lansing, 1992; Gfeller et al., 1997, 2000; Looi et al., *in press*; Schulz & Kerber, 1994). For the melody test, there was also no significant difference between performance pre-surgery with HAs (mean = 75% correct) and post-surgery with CIs (mean = 80% correct). The slight increase in the subjects' scores post-surgery was not significantly different from the degree of the learning effect observed for the CI and HA control groups. This lack of difference for the pre-to-post surgery melody test results is somewhat surprising, considering that two different hearing modalities were utilised. It is also inconsistent with findings previously reported (Looi et al., 2004, *in press*), in which experienced HA users scored significantly higher than experienced CI users in recognising familiar melodies. Kong et al. (2005) reported that melody-recognition scores in their HA-only condition were, on average, 17 percentage points higher than those obtained in the CI-only condition. It is possible that the lack of difference in the current study may be partially attributable to the 'ceiling effect', with two of the subjects scoring 95% or 100% both pre- and post-surgery, as well as the high level of inter-subject variability both pre- and post-surgery. It is also worth mentioning that one subject scored only 15% correct pre-implant and 20% correct post-implant. If the scores of this outlier are eliminated, the mean scores for the remaining eight subjects rise to 83% correct pre-surgery and 88% correct post-surgery. This result suggests that the other subjects in this study were able to recognise most of the melodies, irrespective of whether they were wearing a HA or a CI.

The higher melody recognition scores in this study than many previous studies may be in-part attributable to differing methodologies. The current study involved closed-set recognition of melodies with intact rhythm cues; these rhythm cues would have aided melody recognition. Fujita & Ito (1999) found that their CI users scored at chance level in distinguishing between four nursery rhymes with identical rhythms. Gfeller et al. (2002a) reported that their CI subjects scored between 0% to 44% correct (mean = 13% correct) for recognising familiar melodies, with two-thirds of these correctly identified melodies having been classified as 'rhythmic' in nature. The authors speculated that CI recipients are potentially far more reliant on rhythm cues for melody recognition tasks than normally hearing listeners (Gfeller et al., 2002a). Factors such as open- versus closed- set recognition, as well as the number of melodies incorporated, would also contribute to differences between the melody recognition scores of current studies.

For the pitch test, the experimental group's mean scores post-surgery with the CI were lower than those obtained with the HA. Statistical analyses showed that this difference was significant for the one-octave and quarter-octave subtests. It is noteworthy that the score changes for both control groups were in the opposite direction; that is, their pitch-ranking scores increased from the first test block to the second test block (Figure 2). Therefore, it can be postulated that if the experimental group had similarly been tested on two occasions with their HAs, their scores would also have been likely to improve. However, their scores were lower when they were tested on the second test block while using CIs. Further, the mean post-surgery score for the quarter-octave subtest was not significantly different from the chance score of 50%. This finding is consistent with previous results obtained with more-experienced CI users (Looi et al., 2004, *in press*).

It is also worthwhile pointing out that the experimental group's speech perception scores were significantly better than the CI control group's scores ($p = 0.01$; independent-samples t-test). This could indicate that the experimental group had better residual auditory system function and/or obtained greater benefit from their implant than the CI control group. It is unclear the extent that this would effect the degree of task learning between sessions for the music tasks. However, if this issue did impact on learning capability, then it is probable that the experimental group would show a greater amount of learning effect than the control group. Therefore, the estimate from the control group would be an underestimate of that for the experimental group. For example, this would mean that results for the pitch test would be more in favour of the HA, as subjects scored lower post-surgery with the CI.

The difficulty of providing reliable information about pitch to CI users has been frequently reported (Fujita & Ito, 1999; Galvin et al., 2007; Gfeller et al., 1997, 2002a, 2007; Looi et al., 2004, *in press*). Pitch perception for electrically stimulated hearing via a CI relies on place and/or temporal cues to provide fundamental frequency (F0) information. The preservation, coding, and effective use of these cues all play important roles in the perception of pitch with a CI. Factors such as poor frequency resolution, a frequency mismatch between the CI's spectral analysis filters and the corresponding stimulated places in the cochlea, and the distance separating the stimulating electrodes from the target neural populations may affect CI users' ability to use place-pitch cues. This is discussed in more detail in Looi et al. (*in press*), and McDermott (2004).

Pitch information can also be provided by temporal cues in the stimuli. Such information can be present in either the amplitude modulations or the rate of the stimulating pulse train (Geurts & Wouters, 2001; McDermott, 2004; McKay & McDermott, 1996; McKay et al., 1994, 1995; Pijl, 1995). For the ACE strategy used by the subjects in this study, stimulation occurs at a constant rate. Therefore, post-surgery, subjects would have had to rely on periodic variations in the pulses' amplitude to obtain temporal-pitch information. However, research indicates that CI users are able to extract reliable pitch cues from amplitude modulations only for frequencies up to about 300 Hz (McKay, 2004; McKay et al., 1994, 1995; Zeng, 2002). The availability of information from amplitude modulations would also be affected by other factors including details of the sound-processor design such as the sampling and stimulation rates, the modulation depth, and the temporal alignment of modulations across electrodes (McDermott, 2004; McKay, 2004, 2005; McKay & McDermott, 1996; McKay et al., 1994, 1995).

Interestingly, subjects scored significantly higher post-surgery with vowels produced by the male rather than the female singer, a discrepancy not observed when they were tested pre-surgery. This is consistent with the results presented in Looi et al. (*in press*) in which the CI subject group was significantly more accurate at ranking the male-sung vowels than the female-sung vowels. The reasons for this may relate to the preceding discussion on perceiving temporal-pitch information: the lower F0s of the male vowels may have enabled more effective use of temporal-based pitch cues (Geurts & Wouters, 2001; McDermott, 2004; McKay & McDermott, 1996; McKay et al., 1994, 1995; Pijl, 1995). If CI users can perceive amplitude modulations only below about 300 Hz, they would not be able to perceive reliable temporal pitch cues for notes above approximately middle-C.

In addition, it is possible that the subjects' responses on the pitch-ranking tests were affected by which cues they attended to in making their judgments. For example, the subjects in the present study frequently commented that the two notes within a particular pair were the "same" or "very close". Even for intervals of the same size, it sometimes happened that one pair of notes was judged to have similar pitches, whereas the notes in another pair were judged to be very different. It is probable that when the pitch was ambiguous or indistinct for the subject, other cues, such as timbral differences, may have influenced their responses. Previous research suggests that variations in the place of stimulation affect timbre more than pitch (McDermott, 2004; McDermott & McKay, 1997; Moore & Carlyon, 2005; Pijl &

Schwarz, 1995), with studies by Beal (1985), Crowder (1989), Pitt (1994), and Pitt & Crowder (1992) finding that there were interactions between the perceptual dimensions of pitch and timbre, even for normally hearing listeners. These factors may account for some of the variability both within and between the subjects' pitch-ranking scores. Such variability has been reported in previous publications (Galvin et al., 2007; Gfeller et al., 1997, 2002a; Looi et al., *in press;* McDermott, 2004).

Although the changes in the pre-to-post surgery scores for the other tests in the MTB were not statistically significant, further consideration of the data provides insight into music perception by hearing-impaired adults. In particular, there was a significant difference between the subtests' scores; subjects were more accurate in identifying the single-instrument stimuli of subtest 1 than those involving multiple instrumentation (i.e., subtests 2 and 3). This is in accordance with previous reports (Leal et al., 2003; Schulz & Kerber, 1994). The additional instruments present in the second and third subtests added to the complexity of the sound, which may have reduced the subjects' ability to recognise the stimuli.

Generally it was noted that instruments from the percussion family, such as the piano, drum kit, and timpani, were more likely to be correctly identified by the subjects, both pre- and post-surgery. The distinctive temporal envelopes of these instruments may have provided salient durational or rhythmic cues. Listeners relying on either a CI or a HA may use such temporal-envelope cues in preference to other, less-salient cues, when identifying auditory stimuli.

Analyses of the subjects' error patterns for each subtest provide further information about the cues used for identifying musical instruments. Pre-implantation, for both subtests 1 and 2, several of the instruments, such as the clarinet, cello, trumpet, flute, and the female singer, were often mistaken to be a violin. With the exception of the cello which represented a confusion within the same instrumental family, these instruments had a similar pitch range to that of the violin. Other common errors for these two subtests were a confusion between the timpani and drum kit, and between the guitar and the piano. These confusions may be related to the similarity in the instruments' temporal envelopes. For the third subtest, common errors included confusions between the orchestra and string quartet, between the rock band and the percussion group, and between the string quartet and the violin with piano duet or an orchestra. Post-surgery, the subjects' error patterns were more diffuse. Also, it was interesting that the greater accuracy for male-sung than female-sung vowels in the pitch test was somewhat reflected in the error patterns for the instrument identification tests. For example, the excerpts with a male singer were more accurately identified than those with a female singer in all three subtests. Furthermore, in the third subtest, the most common error for the trio of a male singer, female singer, and piano was its identification as a duet between a male singer and piano, indicating that the female voice in the extract was not perceived by some subjects.

Numerous factors may have affected these subjects' ability to identify the instruments in the tests. Some of these factors may be associated with the reasons mentioned earlier for pitch perception with current CI systems. The perception of timbre is dependent upon information present in both the spectral envelope and the fine temporal structure of sound signals (Handel, 1989; Kohlrausch & Houtsma, 1989). CI sound processors employ a relatively coarse spectral analysis of the input signal and present little or no information about the fine structure. Fine spectral details are important for perceiving complex stimuli such as most music (Oxenham et al., 2004; Rubinstein & Hong, 2003). For the pre-surgery tests, the perception of timbral cues may have been reduced by the poorer frequency selectivity and other auditory filter anomalies associated with sensorineural hearing loss (Arehart, 1994; Moore, 1995; Summers & Leek, 1994).

Nevertheless, the use of a HA in the contralateral ear by CI users with hearing sensitivity similar to that of the subjects in the present study could provide benefit for music perception. The bimodal listening condition was not assessed in these experiments but warrants further consideration. For example, it has been shown that HAs provide more reliable F0 information than CIs, at least at low frequencies, and that bimodal listening may be beneficial for pitch perception (Gantz & Turner, 2003, 2004; Gantz et al., 2005; Gfeller et al., 2007; Kiefer et al., 2005; Kong et al., 2005). The use of a HA may also enable some of the lower-frequency fine-structure cues in acoustic signals to be perceived. Taken together, the findings of the present study and previous studies suggest that music perception may be improved for those with a moderately severe to profound hearing loss when CIs and HAs are used simultaneously, compared with the use of either type of device alone.

CONCLUSIONS

This within-subjects study assessed the effect of cochlear implantation on the music perception of adults who had usable acoustic hearing pre-operatively. Nine patients scheduled to receive a CI were tested prior to implantation with HAs, and subsequently 3 months after activation of their implant with a music test battery that examined rhythm discrimination, pitch ranking, instrument identification, and familiar-melody recognition. Their pre- and post-surgery scores on tests of rhythm discrimination, pitch ranking, instrument identification, and melody recognition were compared. Results on the same tests from a separate group of experienced CI users and a group of HA-only users who met the audiological criteria for an implant were used as control-group comparisons. The results for the experimental group showed no significant difference pre-to-post surgery for the rhythm or melody perception tests. For the pitch test, the group's mean scores for the one-octave and quarter-octave intervals were significantly worse with the CI than with the HA. Post-surgery, subjects were unable to reliably rank pitches a quarter of an octave apart when using only their CIs. Further, subjects were more accurate at pitch-ranking vowels sung by a male singer than vowels sung by a female singer post-surgery. This difference was not apparent in the pre-surgery test results. Cochlear implantation had no significant effect on these subjects' instrument identification scores. However, scores were significantly higher for the single-instrument than for the multi-instrument stimuli both pre- and post-implantation. Overall, the findings of this study indicate that pitch perception is generally poorer with a CI than with a HA. It is likely that the use of both types of device simultaneously would optimise music perception for people having sufficient acoustic hearing sensitivity post-operatively.

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TABLE 1 – Details of subjects in the experimental group.
Aetiology: C/P=Congenital/Progressive.
Speech perception test: CUNY sentences, presented auditory alone. The best pre-implant and post-implant (up to 3 months) scores are shown.

Subject (sex)	Age (yrs)	Aetiology	HA type	HA experience (mths)	Speech score; pre-CI (%)	Ear tested pre-CI	Ear implan-ted	Speech score; post CI (%)	CI sound processor	CI sound-processing strategy
1 (M)	45	Ménière's disease	Siemens Prisma 2	60	23	L	L	100	Esprit3G	ACE 900Hz
2 (M)	70	Otosclerosis	Oticon Ergo	96	64	R	L	99	Esprit3G	ACE 900Hz
3 (M)	51	Ménière's disease	Phonak Claro	18	61	R	L	96	Esprit3G	ACE 900Hz
4 (M)	71	C/P	Bernafon LS16D	300	20	R	L	94	Sprint	ACE 1200Hz
5 (F)	60	Familial	Siemens Prisma 2	600	3	R	L	100	Esprit3G	ACE 900Hz
6 (F)	50	German measles	Phonak Piconet	336	67	L	R	99	Esprit3G	ACE 250Hz
7 (M)	46	Familial	Simens MusicD SP	456	57	R	L	99	Esprit3G	ACE 900Hz
8 (M)	41	Familial	Widex Senso	420	40	R	L	98	Esprit3G	ACE 900Hz
9 (M)	55	C/P	BE-15 (from UK – analog aid)	636	21	L	R	88	Esprit3G	ACE 900Hz
Mean	54.3			324.7	39.6			97		

Table 2. Details of subjects in the CI control group.
Aetiology: C/P=Congenital/Progressive.
Device experience: For subjects marked *, who had been reimplanted, the total number of months with both devices is shown.
Speech perception test: CUNY sentences, presented CI-alone.

Subject (sex)	Age (yrs)	Aetiology	Duration of profound hearing loss (yrs)	Device experience (mths)	Speech perception score (%)	Ear implan-ted	Type of Nucleus CI	CI sound processor	CI sound-processing strategy
1 (M)	47	C/P	1.58	16	95	R	24R	Sprint	ACE 1200Hz
2 (M)	67	Otosclerosis	10	60	75	L	24M	Sprint	ACE 1200Hz
3 (F)	45	C/P	5	22	99	R	24M	Sprint	ACE 1800Hz
4 (F)	36	Rubella	10	108	61	R	22M	Esprit22	SPEAK
5 (F)	72	C/P	14	24	96	L	24M	Esprit3G	ACE 720Hz
6 (F)	56	C/P	11.25	17	100	L	24R	Esprit3G	ACE 900Hz
7 (M)	71	Trauma	27	300*	97	L	24M	Sprint	ACE 275Hz
8 (F)	75	C/P	11	38	95	R	24R	Esprit3G	ACE 900Hz
9 (F)	70	C/P	9	180*	84	L	22M	Esprit22	SPEAK
10 (F)	61	C/P	7	18	78	L	24R	Esprit3G	ACE 500Hz
11 (M)	48	C/P	14	135	72	R	22M	Esprit22	SPEAK
12 (F)	66	Meningitis	18	211	90	R	22M	Esprit3G	SPEAK
13 (M)	69	C/P	12	138	37	L	22M	Esprit22	SPEAK
14 (M)	64	C/P	30	184	79	L	22M	Spectra	SPEAK
15 (M)	59	Trauma	32	185	94	L	22M	Spectra	SPEAK
Mean	60.4		14.1	109.1	83.9				

Table 3. Details of subjects in the HA control group.
Aetiology: C/P=Congenital/Progressive.
Speech perception test: CUNY sentences, presented in the best aided condition, auditory alone.

Subject (sex)	Age (yrs)	Aetiology	Duration of profound hearing loss (yrs)	Device experience (mths)	Speech perception score (%)	Type of HA	Ear tested
1 (F)	62	Viral	7	96	48	Phonak Supero	R
2 (F)	56	Otosclerosis	10	240	65	Phonak Perseo 311dAZ	L
3 (F)	56	C/P	19	276	51	GN Resound Canta7	L
4 (F)	61	C/P	10	384	38	Bernafon PB675	L
5 (F)	74	Unknown	5	180	0	Phonak Supero	L
6 (M)	67	C/P	41	492	23	Bernafon PB675	L
7 (M)	76	Infection	20	240	7	Phonak Supero	R
8 (M)	70	Otosclerosis	22	264	48	Phonak Supero	R
9 (F)	60	Otosclerosis	26	408	67	Phonak Supero	R
10 (F)	80	Ménière’s disease	10	360	17	Phonak Supero	R
11 (M)	70	Noise Exp	10	120	50	Phonak Supero	R
12 (M)	70	Unknown	5	120	27	Oticon Digifocus II	R
13 (F)	49	C/P	3	156	56	Phonak Supero	R
14 (F)	62	Ménière’s disease	15	180	63	Siemens Music Pro	R
15 (M)	57	Unknown Progressive	2	96	63	Phonak Sonoforte2	R
Mean	64.7		13.7	240.8	41.5		

Table 4. Fundamental frequencies of stimuli tested in the pitch test.
For each pitch-pair, half of the presentations used an ascending sequence, with the other half using a descending sequence.

Interval size		Fundamental frequency of stimuli utilized for each interval
Subtest 1 One octave	Female	*C4-C5* (262-523 Hz); *D#4-D#5* (311-622 Hz); *F#4-F#5* (370-740 Hz)
	Male	*G2-G3* (98-196 Hz); *A#2-A#3* (117-233 Hz); *C#3-C#4* (139-277 Hz)
Subtest 2 Half octave	Female	*C4-F#4* (262-370 Hz); *F#4-C5* (370-523 Hz); *C5-F#5* (523-740 Hz)
	Male	*G2-C#3* (98-139 Hz); *C#3-G3* (139-196 Hz); *G3-C#4* (196-277 Hz)
Subtest 3 Quarter octave	Female	*C4-D#4* (262-311 Hz); *D#4-F#4* (311-370 Hz); *F#4-A4* (370-440 Hz); *A4-C5* (440-523 Hz)
	Male	*C#3-E3* (139-165 Hz); *E3-G3* (165-196 Hz); *G3-A#3* (196-233 Hz); *A#3-C#4* (233-277 Hz)

FIGURE LEGENDS:

FIGURE 1 – Average unaided hearing thresholds pre-surgery for the experimental subject group.
The circle represents the mean hearing threshold level across the 9 subjects for each frequency tested in the ear used by each subject for the pre-CI surgery test block. The error bars indicate ±1 standard deviation. In cases where a measured threshold was equal to or greater than 110 dB, or was beyond the maximum output of the audiometer, a level of 110 dBHL was assumed.

FIGURE 2 – Mean scores pre-implant and post-implant on the music test battery for the 9 subjects in the experimental group.
Error bars indicate one standard deviation. The dotted lines indicate the score corresponding to chance performance on each test.

FIGURE 3 – Difference between the mean scores of the two test blocks for the three subject groups.
Tests and subtests are presented along the horizontal axis. The score difference in percentage points between the two test blocks is shown on the vertical axis. The error bars indicate ±1 standard deviation. Negative values indicate that the mean score from the first test block was higher than that from the second test block.
* = significant difference between the scores for the two test blocks ($p<0.05$; paired t-test).

FIGURE 1 – Average unaided hearing thresholds pre-surgery for the experimental subject group. The circle represents the mean hearing threshold level across the 9 subjects for each frequency tested in the ear used by each subject for the pre-CI surgery test block. The error bars indicate ±1 standard deviation. In cases where a measured threshold was equal to or greater than 110 dB, or was beyond the maximum output of the audiometer, a level of 110 dBHL was assumed.

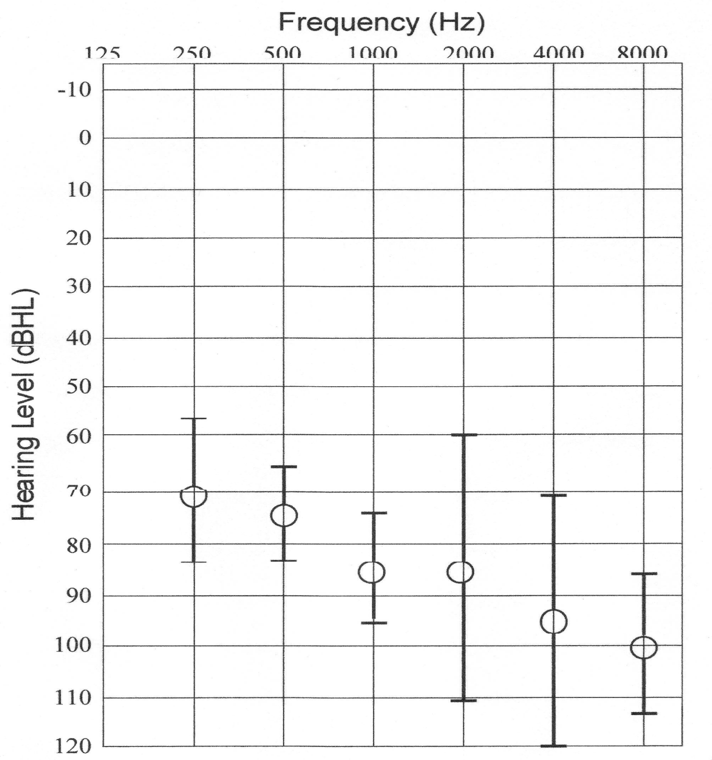
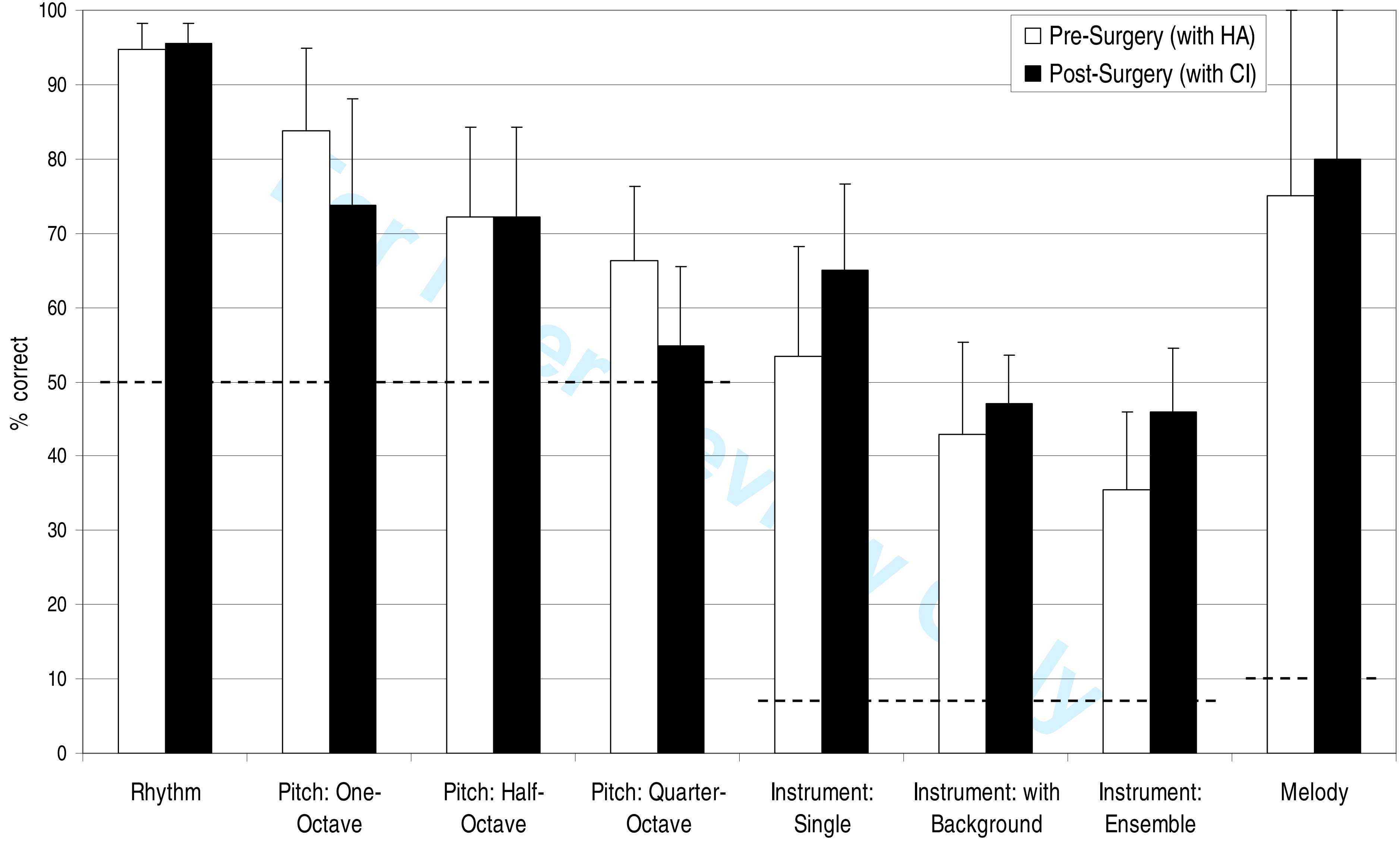
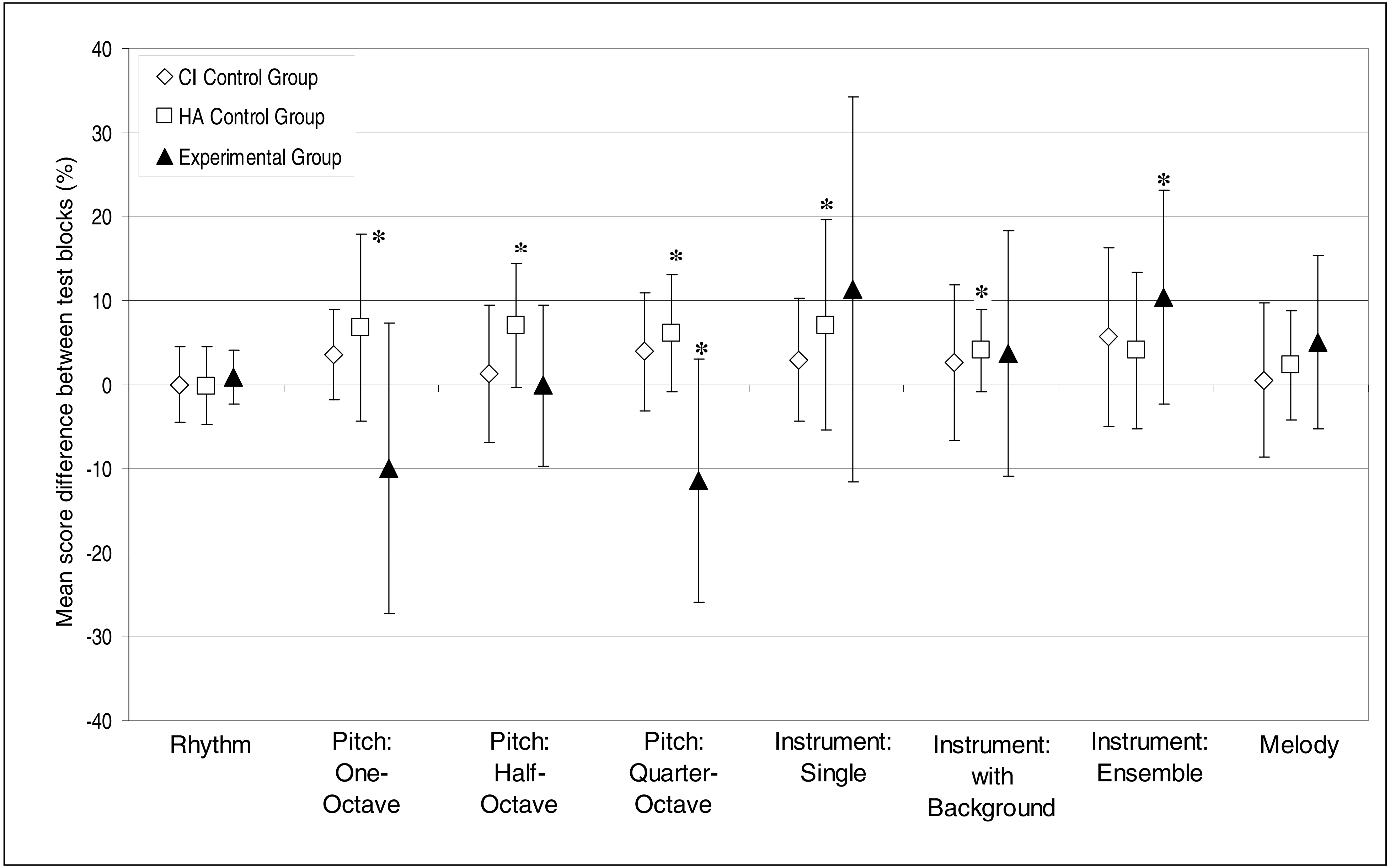

Frequency (Hz)
125 250 500 1000 2000 4000 8000
-10
0
10
20
30
40
50
60
70
80
90
100
110
120
Hearing Level (dBHL)

FIGURE 2 – Mean scores pre-implant and post-implant on the music test battery for the 9 subjects in the experimental group. Error bars indicate one standard deviation. The dotted lines indicate the score corresponding to chance performance on each test.



Pre-Surgery (with HA)
Post-Surgery (with CI)
% correct
100
90
80
70
60
50
40
30
20
10
0
Rhythm
Pitch: One-Octave
Pitch: Half-Octave
Pitch: Quarter-Octave
Instrument: Single
Instrument: with Background
Instrument: Ensemble
Melody

FIGURE 3 – Difference between the mean scores of the two test blocks for the three subject groups.
Tests and subtests are presented along the horizontal axis. The score difference in percentage points between the two test blocks is shown on the vertical axis. The error bars indicate ±1 standard deviation. Negative values indicate that the mean score from the first test block was higher than that from the second test block.
* = significant difference between the scores for the two test blocks ($p<0.05$; paired t-test).


CI Control Group
HA Control Group
Experimental Group
Mean score difference between test blocks (%)
40
30
20
10
0
-10
-20
-30
-40
Rhythm
Pitch: One-Octave
Pitch: Half-Octave
Pitch: Quarter-Octave
Instrument: Single
Instrument: with Background
Instrument: Ensemble
Melody