Title

Long Title: A comparison of the speech recognition and pitch ranking abilities of children using a unilateral cochlear implant, bimodal stimulation or bilateral hearing aids.

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Abstract

Objective

The present study compared the speech recognition and pitch ranking abilities of normally-hearing children (n = 15) to children using a cochlear implant (CI) alone (n = 8), bilateral hearing aids (HAs) (n = 6), or bimodal stimulation (BMS) (n = 9). It was hypothesised that users of BMS would score higher on tasks of speech and pitch perception than children using a CI alone, but not children using HAs.

Methods

Participants were assessed on tasks of monosyllabic word recognition in quiet, sentence recognition in quiet and noise (10dB signal-to-noise ratio), and a pitch ranking task using pairs of sung vowels one, half, and a quarter of an octave apart.

Results

There were no significant differences between the mean percentage-correct scores of the four participant groups for either words in quiet or sentences in quiet and noise. However, the proportion of bimodal users who scored > 80% correct (80%) was significantly greater than the proportion of high-scoring unilateral CI (25%) or bilateral HA users (17%). Contrary to expectations, there was also no significant difference between the pitch ranking scores of users of BMS and users of a CI alone for all three interval sizes ($p < 0.05$, RM-ANOVA). However participants using only acoustic hearing (i.e. the NH and HA groups) scored significantly higher than participants using electrical stimulation (i.e. the CI and BMS groups) on the pitch ranking task ($p < 0.05$; RM-ANOVA).

Conclusions

Contrary to findings in postlingually deafened adults, we found no significant bimodal advantage for pitch perception in prelingually deafened children. However, the performance of children using electrical stimulation was significantly poorer than children using only acoustic stimulation. Further research is required to investigate the contribution of the non-implanted ears of users of BMS to pitch perception, and the effect of hearing loss on the development of pitch perception in children.

Key Words:

Cochlear Implants; Hearing Aids; Bimodal Stimulation; Pitch Perception; Speech Perception

Abbreviations

ACE	Advanced Combination Encoder Speech Processing Strategy
ANOVA	Analysis of Variance
BMS	Bimodal Stimulation
CI	Cochlear Implant
CNC	Consonant-Nucleus-Consonant word lists
F0	Fundamental Frequency
HA	Hearing Aid
HINT	Hearing in Noise Test
M	Mean
m	Metre
MEL	Musical Experience Level
NH	Normal Hearing
PMMA	Primary Measures of Music Audiation
PRT	Pitch Ranking Task
RM-ANOVA	Repeated Measures Analysis of Variance
SD	Standard Deviation
SGN	Spiral Ganglion Neuron
SNR	Signal to Noise ratio
SPEAK	Spectral PEAK Speak Processing Strategy

Introduction

Data from normally-hearing (NH) listeners indicates that access to low-frequency, low-order harmonics within complex sounds is important for the perceptual segregation of competing sounds [1]. These low-order harmonics, along with the fundamental frequency (F0), are also important for determining the pitch of a complex sound. However speech processing strategies used in the current generation of cochlear implants (CIs) provide little representation of individual harmonics [2, 3] and do not adequately convey F0 information, adversely affecting pitch perception.

Improvements in CI technology and concurrent improvements in speech perception outcomes have lead to an expansion of the implantation criteria to include individuals with low-frequency residual hearing in one or both ears. This residual hearing can be utilised through the use of a hearing aid (HA) in the non-implanted ear of a CI user; this is known as bimodal stimulation (BMS). The additional pitch cues provided via this low-frequency hearing have been associated with improved pitch perception [4, 5, 6], and improved speech recognition in quiet [7] and noise [6, 8].

Pitch Perception

Research has consistently shown that the pitch perception abilities of adult CI users are considerably poorer than those of NH listeners, and HA users with severe to profound hearing loss (see [9, 10] for reviews). Research into the pitch perception abilities of child CI users has predominantly involved song recognition tasks and has consistently shown that CI users score significantly lower than their NH counterparts, particularly for songs devoid of lyrics [11, 12, 13]. This implies that recipients are more dependent upon rhythm and speech information, and are less able to utilise pitch information.

Investigations into the pitch ranking abilities of CI users have predominantly involved adults [14, 15, 16]. Sucher and McDermott [16] compared the pitch ranking ability of 10 NH adults and 8 CI users for sung-vowel stimuli. As expected, CI users scored significantly lower than their NH counterparts, performing at chance levels when ranking 1-semitone stimuli. Looi and colleagues [17] found similar disparities between the performance of 15 CI users and 15 HA users with severe-profound hearing loss. The stimuli were similar to that used by Sucher and McDermott [16]. The HA group scored significantly higher than the CI group for all three interval sizes and the CI group scored at chance levels for the ¼ octave (3 semitone) interval size. Looi and colleagues [15] used the same pitch ranking task to assess the performance of nine participants on the waiting list for a CI prior to (with HAs), and three months, after implantation. Post-implantation score were significantly lower than pre-implantation scores for the 1 and ½ octave interval sizes and were at chance levels for the ¼ octave subtest. Overall, the results of the above studies indicate that the salience of pitch cues available to users of a unilateral CI is poor relative to acoustic hearing.

Studies investigating the effect of BMS on the pitch perception abilities of CI users have also predominantly examined postlingually deafened adults. For example, Kong et al. [6] investigated the melody recognition abilities of five adult users of BMS, who were assessed in CI-alone, HA-alone and BMS conditions. Despite providing little to no useful speech recognition, participants scored an average of 45% correct using their HA-alone, 17% points higher than in the CI-alone condition. Scores for the HA-alone and BMS conditions were not significantly different. This pattern of results has been replicated in similar studies [5, 6].

The only study known to the author investigating the pitch perception abilities of children using BMS is an unpublished thesis by Sucher [18] who assessed the performance of 7 children (*M* = 11.8 years old) on the tonal subtest of the Primary Measures of Music Audiation (PMMA) [19]. Participants were assessed in CI-alone and BMS conditions. Contrary to the results in adults there were no significant differences in score between the two conditions. However, Sucher noted that the children’s residual hearing may have been too poor to support accurate pitch discrimination with average thresholds of >90 dBHL above 250 Hz. An alternative explanation for the lack of bimodal benefit was that limited exposure to auditory stimuli may have impaired their central auditory development thereby restricting their ability to use the information provided via their residual hearing. In summary the additional pitch cues provided by a contralateral HA have been shown assist pitch perception in adult users of BMS. Whether children can obtain similar benefits is uncertain. The primary purpose of the present study was to compare the pitch ranking abilities of children using a unilateral CI, BMS or HAs.

Speech Recognition

Research has shown that the monosyllabic word recognition scores in quiet for both adult and child recipients improve significantly following the addition of a contralateral HA [7]. This may be due to a better perception of lower frequency phonemes with more information provided regarding the place and manner of articulation compared with a CI-alone [8].

This low frequency information can also help to improve speech recognition in noise by aiding in the segregation of competing sounds [6, 20, 21]. Unlike NH listeners, users of a unilateral CI and NH listeners listening to CI simulations are unable to utilise differences in the F0 frequency of individual voices to segregate target speech from that of a competing talker [22]. For example, Kong and colleagues [6] assessed the sentence in noise recognition abilities of four adult users of BMS in three listening conditions: HA-alone, CI-alone and BMS. Participants scored significantly higher in the BMS than in the CI-only condition for signal-to-noise ratios (SNR) of 10 and 15dB. Simulation studies have reported similar results [20, 21]; the performance of NH adults listening through CI simulations improved significantly following the addition of otherwise unintelligible low-pass-filtered acoustic speech. Overall these results indicate that the additional pitch information provided in BMS does allow for improved segregation of competing talkers in adults, however similar research has not been conducted in children.

BMS also provides binaural input to the central auditory nervous system enabling the utilisation of processing mechanisms that assist in segregating spatially separated speech and noise sources. One such mechanism is ‘binaural redundancy’ where information from each ear is combined and used in conjunction with a listener’s linguistic knowledge to fill in the ‘gaps’ in the speech stream. A study by Ching and colleagues [7] incorporating 25 children and 11 adults reported that the sentence recognition in noise scores of each group improved by an average of 12 and 17 percentage points, respectively, when using BMS over a CI-alone. ‘Binaural squelch’ refers to a range of central auditory processing mechanisms which improve the effective SNR by analysing differences in the phase and level of the signal arriving at each ear. Neither adult, nor child users of BMS are able to fully utilise binaural squelch mechanisms as current speech processing strategies are unable to reliably code phase information required for the perception of interaural timing and phase differences [7, 23]. The 'head shadow effect' is caused by interactions between the acoustic signal and the head which result in between-ear differences in the SNR at each ear. Selective attention to information from the ear with the better SNR allows for improved speech recognition. While adult users of BMS benefit from the head shadow effect regardless of which ear has the better SNR [24], child users of BMS exhibit no significant head shadow advantage when the better SNR is on the side of their HA [24, 25]. It appears that children using BMS may be more dependent upon information from their CI for speech recognition; children from two recent studies scoring higher when both their CI and HA had the same

SNR, than when their HA had a better SNR [25, 26]. In summary, although BMS can restore some binaural processing mechanisms that assist speech recognition in noise, outcomes differ between adults and children, the latter only appearing to benefit from 'binaural redundancy.' The secondary purpose of the present study was to compare the speech recognition abilities of children using BMS with those of children using only a CI or HAs on tasks of speech recognition in quiet and noise.

Existing Between-Group Comparisons

The majority of investigations into BMS have utilised within-participant designs, where groups of CI recipients have been assessed in CI-alone and BMS conditions. Recently, two studies compared the speech recognition performance of separate groups of participants using a unilateral CI or BMS [5, 27]. Gifford and colleagues [27] found no significant difference in the speech recognition in noise performance of 112 unilateral CI recipients and 11 BMS users. Similar results were found by Dorman et al. [5] who assessed 65 adults using a unilateral CI and 15 using BMS on a sentence recognition in noise task (10 dB SNR) and an arrhythmic melody recognition task. There were no significant differences between the groups on either task. However, the proportion of BMS users who obtained scores of ≥ 85% correct on the sentence in noise task (33%) was significantly greater than the proportion of CI-only users who obtained scores of ≥ 85% correct (6%). Similarly, the proportion of BMS users who scored ≥ 85% correct on the melody recognition task (53%) was significantly greater than the proportion of CI-only users who scored ≥ 85% correct on the same task (11%). Overall, it would seem that although the addition of a contralateral HA can improve the speech in noise and melody recognition performance of individual CI users, the strongest-performing CI users may still attain levels of performance that are similar to those using BMS [5]. However, the proportion of BMS users who obtain high scores on a given measure appears to be greater than the proportion of CI-only users who do the same [4]. The third purpose of the present study was to determine whether similar outcomes were also evident for pediatric CI recipients.

In summary, this study aimed to compare the pitch and speech perception skills of children using a unilateral CI, HAs or BMS. It was hypothesised that:

1. For tasks of word recognition in quiet, children who use BMS will score higher than children using a CI-only. HA-only and CI-only users will score at similar levels;

2. For tasks of sentence recognition in quiet, children who use BMS, a CI-only, or HA-only will score at similar levels;
3. For tasks of sentence recognition in noise, child users of BMS and HA-only users will score higher than their CI-only counterparts;
4. Children who use BMS will score higher on the PRT than those using a CI-only, but not children who use bilateral HAs.

Material and Methods

Participants

Participants were 8 prelingually deafened children using a unilateral CI (CI-only group); 9 prelingually deafened children using BMS (BMS group); 6 prelingually deafened children using bilateral HAs (HA-only group), and 15 normally hearing children (NH group).

Members of the CI-only group were between 11 and 14 years of age (*M* = 12.92) and used a Nucleus 24 device implant system with either the ACE or SPEAK strategy. Participant details are provided in Table 1. Members of the BMS group were between 6 and 13 years of age (*M* = 9.25) and used a Nucleus 24 device with the ACE processing strategy (see Table 2). Children in the HA-only group were between 6 and 13 years of age (*M* = 9.25 years) and used bilateral HAs (Table 3). All had unaided hearing thresholds that met the referral criteria for a CI assessment at the New Zealand CI program involved in this study. All of the HAs used in this study (i.e. both the HA and BMS groups) were multichannel digital BTEs with wide dynamic range compression, fitted using the NAL-NL1 prescriptive formula, except for those of participants' D2 and D3 which were fitted using the DSL pediatric formula. Fifteen children with NH (aged 8-16 years; *M* = 12.06) were used to verify the pitch ranking task. All had hearing thresholds of ≤ 20 dBHL at octave intervals between 250 and 8000 Hz.

<<Insert Tables 1, 2 & 3 around here>>

CI, HA and BMS participants were questioned regarding their musical preferences and participation. Their responses were subsequently used to categorise them into three Musical Experience Levels (MELs) (as reported in Tables 1-3) where: '3' represented ≥ 2 years of participation in formal music training and/or classroom music activities; '2' represented < 2 years of participation in formal music training and/or classroom music activities; and ‘1’ represented no participation in formal musical training and/or classroom music activities.

Materials

The Consonant-Nucleus-Consonant (CNC) word lists [40] (50 words per list) and Hearing In Noise Test (HINT) sentence lists [28] were used to assess participants’ speech recognition abilities. These were New Zealand English recordings spoken by a female talker.

The stimuli used in the pitch ranking task (PRT) were a reduced version of those used in Looi et al. [14]. Stimuli were recordings of the vowel */a/* sung by a trained male or female singer. Each stimulus consisted of two different notes of the same vowel, sung by the same singer, either one octave (12 semitones), half an octave (6 semitones), or a quarter of an octave (3 semitones) apart. Each interval size constituted a separate subtest. There were a total of eight recordings for each pitch pair – four where the first note was higher than the second note (i.e. descending), and four in the reverse order (i.e. ascending). The 1 and ½ octave subtests were scored out of a total 24, and the ¼ octave subtest was out of a total of 32; these were converted into a percent-correct score.

Procedure

Ethical approval was obtained from the University of Canterbury Human Ethics Committee and the New Zealand Multi-region Health and Disability Ethics Committee. The parents/caregivers of participants signed informed consent forms prior to the study.

In all sessions, participants were first assessed using standard clinical tympanometry, followed by the CNC word test, the HINT sentence test (in quiet and noise), and the PRT. The order of these latter three tests was pseudo-randomised as were the lists used for each speech test listening condition. The PRT was conducted in order of decreasing interval size, with singer-gender being randomised. The stimuli within each PRT subtest were randomised by the software used to present the PRT - MACArena [29]. All tests were conducted in a sound-treated room. Stimuli were presented via a computer connected to a Soundblaster Extigy external soundcard which in turn connected via a 4-way mixer box to a 2-channel amplifier which output to two loudspeakers. One of the loudspeakers was positioned 1.0 metre from, and 0° azimuth relative to the participant, with the second loudspeaker only used for the speech in noise assessments and positioned at 90° azimuth. Test stimuli were presented at 65 dBSPL measured at the listeners' ear.

For the CNC words test, one list was administered per appointment and was scored according to the percentage of words and phonemes correct. For the HINT tests, sentences were presented in four listening conditions: one in quiet (S0), and three with concurrent presentation of competing four-talker babble at a SNR of 10 dB (S0N0, S0NCI, S0NHA). In the first noise condition babble was presented from the same loudspeaker as the sentence material (S0N0 condition). In the second noise condition, babble was presented from the second loudspeaker positioned at 90° azimuth, on the side of the participant’s CI (CI-only and BMS groups) or better hearing ear (the ear with the lowest PTA; HA-only and NH groups; S0NCI condition). In the third noise condition babble was presented from this loudspeaker positioned at 90° azimuth, on the side of the participant’s non-implanted ear (CI-only and BMS groups) or poorer hearing ear (HA-only and NH groups; S0NHA condition). Two HINT sentence lists were presented for each of the four listening conditions at each appointment. For both the HINT sentences and CNC word lists, participants were instructed to repeat exactly what was heard and guess if unsure. Scoring was according to the total percentage of words correctly repeated for each listening condition.

For the PRT, participants were instructed to listen to each pair of vowels and decide whether the second note increased or decreased in pitch relative to the first. The concepts of higher and lower were explained using illustrated practice stimuli; a ladder represented increased pitch, and; a slide/chute represented decreased pitch. Participants were trained using stimuli from the 1 octave subtest, and responded by raising or lowering their arm, followed by a verbal confirmation (e.g. raising their arm then stating "up" for ascending pitch). Pilot testing found that the addition of the motor response reduced participant fatigue and improved attentiveness. Assessment commenced once each participant obtained either eight consecutive correct responses, or 10/12 correct responses, whichever came first. During training, repetition of stimuli was used where necessary and feedback was provided regarding the accuracy of responses. During testing, no feedback was provided regarding accuracy and responses were recorded by the MACArena software for further analysis. Participants were not assessed using a smaller interval size when their responses were inconsistent or unreliable despite training or instruction, and/or they admitted that they were unable to tell the difference between the two notes and were purely guessing.

The CI-only, HA-only and BMS groups attended two testing sessions, 3 months apart, where they were assessed with both speech tests and the PRT using their usual listening devices. For the CI-only group, puretone audiometry was also conducted in the first session to confirm the absence of aidable levels of residual hearing in the non-implanted ear. All participants used their everyday listening settings during testing, with the same settings used for each test session. Due to time constraints, participants in the NH group were only assessed once incorporating a hearing screen followed by the HINT sentence test and the PRT.

Results

Participant Variables

A one-way analysis of variance (ANOVA) revealed significant between-group differences in chronological age (*p* = 0.039). Post-hoc analysis using Bonferroni corrections revealed that the BMS group (*M* = 9.24 years) was significantly younger than the CI-only group (*M* = 12.92 years; *p* = 0.036). There were no significant differences between the ages of the other groups. There were also significant between-group differences for the age which the hearing loss was diagnosed (*p* = 0.002; 1-way ANOVA) with post-hoc analysis using Bonferroni corrections showing that the HA-only group (*M* = 41.17 months) were diagnosed significantly later than both the BMS (*M* = 11.75; *p* = 0.001) and CI-only groups (*M* = 20.25; *p* = 0.022). There were no significant differences between the CI-only and BMS groups (*p* = 0.884).

Independent samples t-tests revealed no significant difference between the mean age at implantation for the CI-only (*M* = 5.78) and BMS groups (*M* = 5.40; *p* = 0.997), but that the CI-only group had considerably more experience using their CI (*M* = 7.26 years) than the BMS group (*M* = 3.95 years; *p* = 0.047). There was no significant difference between the better-hearing ear PTA of the HA-only group (*M* = 60.0) and the non-implanted ear of the BMS group (*M* = 72.3; *p* = 0.151; t-test). A Kruskal-Wallis test found no significant between-group differences in the level of musical experience of all four participant groups (*p* = 0.198).

Speech Recognition

Technical difficulties that were beyond the researchers' control severely disrupted session one's speech recognition testing for the BMS group, therefore scores from this session were excluded from all analyses. Individual paired samples t-tests were conducted to investigate whether there were any significant between-session differences in score (i.e. a learning effect) for the CI-only and HA-only groups for the CNC word lists (words and phonemes correct scores) and each of the four HINT test listening conditions. There were no significant learning effects for either group, on any of the aforementioned measures, therefore data from each session was pooled in further analyses and reported in Table 4.

<<Insert Table 4 around here>>

A one-way ANOVA comparing the CNC percent phoneme and word correct scores of the CI-only, HA-only and BMS groups found no significant between-group differences. However, the results of separate Barnard’s exact tests revealed that the proportion of BMS users who scored ≥ 80% correct (80%) was significantly greater than the proportion of CI-only users (25%; $p = 0.038$) and HA-only users (17%; $p = 0.022$) who scored ≥ 80% correct (see figure 1). There was no significant difference in the proportion of CI-only and HA-only users who scored ≥ 80% correct.

<<Insert Figure 1 around here>>

A two-way repeated-measures (RM) ANOVA was conducted to assess for between-group differences in scores across the four HINT listening conditions. Significant effects were found between the groups ($p = 0.005$) and for the within-group factor of listening condition ($p < 0.001$), with a significant interaction between these factors ($p = 0.036$). Separate one-way ANOVAs found significant between-group differences in scores for the S0N0 ($p = 0.005$), S0NCI ($p = 0.002$) and S0NHA ($p = 0.001$) conditions, but not the S0 condition, although this approached significance ($p = 0.079$). Subsequent post-hoc analysis using Dunnett T3 corrections found no significant differences between the mean scores of the CI-only, HA-only and BMS groups. However, the NH group scored significantly higher than: the BMS group in the S0N0 condition ($p = 0.028$); the HA-only group in the S0N0 ($p = 0.025$) and S0NCI ($p = 0.010$) conditions, and; the CI-only group in the S0N0 ($p = 0.029$), S0NCI ($p = 0.016$) and S0NHA ($p = 0.036$) conditions. A comparison of the proportion of ‘high-performing’ participants in each participant group was not possible as the majority of participants scored above 85% correct across all four listening conditions (see figure 2). Separate one-way ANOVAs to investigate for differences between conditions found no significant differences between the scores for any listening condition for the four participant groups.

<<Insert Figure 2 around here>>

Pitch Ranking Task

Each group's mean PRT scores, averaged across both sessions, is reported in Table 5. Individual paired-samples t-tests for each group and each subtest were conducted to determine whether there was any effect of singer gender. There was no significant effect of singer gender for any group or subtest, and therefore scores were pooled in further analyses. Wilcoxin signed-ranks tests were used to determine whether there were any significant learning effects for each group. The CI-only group showed a significant improvement in scores for the 1 octave subtest ($p = 0.028$) but not the ½ ($p = 0.833$) or ¼ octave ($p = 0.406$) subtests. Scores for the HA-only group improved significantly for the 1 ($p = 0.042$), ½ ($p = 0.027$), and ¼ ($p = 0.043$) octave subtests. The BMS group showed a significant learning effect on the 1 octave subtest ($p = 0.025$), but not the ½ ($p = 0.483$) or ¼ octave subtests ($p = 0.600$). In summary, the HA-only group showed a significant improvement in performance on all three PRT subtests, but the performance of the CI-only and BMS groups improved for the 1 octave subtest only. Separate one sample t-tests also showed that all four participant groups' scores were significantly better than chance levels ($p < 0.05$) for all subtests.

<<Insert Table 5 around here>>

A two-way RM ANOVA was used to determine whether there was any difference for the factors of group and/or subtest. Significant effects were found for the factors of subtest ($p < 0.001$) and group ($p < 0.001$), and there was a significant interaction between these factors ($p = 0.014$). In view of the significant interaction, separate one-way ANOVAs were conducted for each subtest to determine the effect of group on PRT score. Significant between-group differences were found for all three PRT subtests ($p < 0.001$). Post-hoc analysis using Dunnett T3 corrections revealed that the HA-only group scored significantly higher than both the CI-only and BMS groups on the 1 and ½ octave subtests ($p < 0.05$), and the NH group scored significantly higher than both the CI-only and BMS groups on all three subtests ($p < 0.01$; see figure 2). There were no significant between-group differences in PRT scores for the CI-only and BMS groups, or the HA-only and NH groups.

<<Insert Figure 3 around here>>

Separate one-way ANOVAs were also conducted for each group to determine the effect of subtest on the PRT scores. This was significant for all groups (CI-only: $p = 0.006$; HA-only: $p = 0.005$; BMS: $p = 0.045$; NH: $p = 0.001$). Post-hoc analysis using Bonferroni (CI-only and BMS groups) or Tamhane T2 (HA-only and NH groups) corrections revealed that all groups scored significantly lower on the ¼ octave subtest than the 1 octave subtest ($p < 0.05$). There were no significant differences between scores on the 1 and ½ octave subtests, or the ½ and ¼ octave subtests for any group.

Correlations

Spearman's rho (ρ) nonparametric correlations were used to investigate potential relationships between test scores and variables known to impact on the performance of such tasks including chronological age [43, 44, 45], duration of listening device usage [46, 47], better ear PTA [48, 49], and musical experience level (MEL) [29]. For these correlations summary scores were calculated for each hearing-impaired participant including: mean CNC words correct; mean HINT sentences in quiet correct; mean HINT sentences in noise correct (average score for the S0N0, S0NCI and S0NHA conditions); and mean PRT accuracy (average PRT score across all sessions and subtests).

As expected, significant correlations were found between mean scores on the various speech recognition tasks (CNC vs. HINT quiet, $\rho = 0.769$, $p < 0.001$; CNC vs. HINT noise $\rho = 0.776$, $p < 0.001$; HINT quiet vs HINT noise $\rho = 0.738$, $p < 0.001$). There were no significant correlations between mean PRT accuracy and any of the speech recognition test scores.

No significant correlations were found between the participant variables of chronological age or duration of listening device usage and performance on any of the perceptual tests. Although there were no significant correlations between better ear PTAs and speech recognition scores, a moderately strong negative correlation was found between better ear PTA and mean PRT accuracy ($\rho = -0.678$, $p = 0.011$). A moderately strong positive correlation was also found between MEL and mean PRT scores ($\rho = 0.628$, $p = 0.002$).

Discussion

The results of the present study partially supported hypothesis 1, but not hypotheses 2, 3 or 4.

Speech Recognition

Consistent with our first hypothesis, we found no significant difference between the word recognition scores of the CI-only (*M* = 71.87%; *SD* = 14.79) and HA-only groups (*M* = 65.39%; *SD* = 11.54). This is consistent with the results of previous studies indicating that children using a unilateral CI performed at levels similar to HA users with severe hearing loss [30, 31, 32, 33]. Unexpectedly, we also found no significant difference between the mean CNC scores of the CI-only (*M* = 71.87%) and BMS groups (*M* = 76.45%; *SD* = 14.79). This result is contrary to the findings of Gifford and colleagues [27], who reported that the CNC word recognition scores of a group of 36 adults using BMS (*M* = 71.8% correct) were significantly higher than those of a group of 162 adult using a unilateral CI (*M* = 55.7%). They are also not in agreement with the general consensus of within-group comparison studies, which indicate that CI recipients with residual hearing in their non-implanted ear obtain higher word recognition scores using BMS than when only using their CI [8, 24, 34]. However, upon further examination we found that the proportion of users in the BMS group (80%) who obtained scores of ≥ 80% correct was significantly larger than the proportion of CI-only (25%; *p* = 0.038) and HA-only users (16.7%; *p* = 0.022) who did the same. This is consistent with the results of Dorman et al. [5].

It is worthwhile noting that the BMS group had significantly less experience using their listening devices (*M* = 3.95 years; *SD* = 3.51) than the CI-only group (*M* = 7.26 years; *SD* = 3.51 years). Research indicates that the speech recognition abilities of pediatric recipients continues to improve until at least 3 years post-implantation, regardless of the duration of profound deafness [33]. Thus it is possible that half of the BMS group participants were yet to attain their maximal post-implant speech recognition performance compared to only a quarter of the CI-only group participants. Consistent with our second hypothesis, there were no significant differences between the sentence recognition in quiet scores of the CI-only, HA-only, and BMS groups. This is consistent with the results of several studies which reported no significant differences in the sentence recognition in quiet scores of adults using a unilateral CI and BMS [5, 27], nor between users of a unilateral CI recipients and HA users with a severe hearing loss [35].

Contrary to our third hypothesis, there were also no significant differences between the scores of the CI-only, HA-only and BMS groups for the S0N0, S0NCI and S0NHA listening conditions, nor were there any significant between-condition differences in sentence recognition scores for the CI-only, HA-only and BMS groups. This was probably due to a ceiling effect observed for the HINT sentence materials (see Figure 2). At present the HINT sentences are the only sentence recognition test materials available with a New Zealand accent. Gifford and colleagues [27] recently examined the validity of the HINT sentences as a measure of open-set speech recognition in quiet. CI-only and BMS users were assessed using HINT and AzBio sentences, and CNC words in quiet. Overall, CNC and AzBio percentage correct scores were normally distributed with no ceiling effects, with the BMS group scoring significant higher than CI-only users on both tests. In contrast, results for the HINT sentences in quiet were positively skewed; 30.7% of the sample (including two thirds of the BMS users) scored 100% correct, and 71% of participants scored ≥ 85% correct. No significant between-group differences in performance were found for the HINT sentence task. Further analyses revealed that CNC word scores were reasonable predictors of AzBio sentence scores but not HINT sentence scores. For example, an AzBio score of ≥ 85% correct was associated with a score on the CNC word lists of between 66% and 94% correct. In contrast, a HINT sentence score of 100% correct was associated with CNC word scores of between 20% and 94% correct. The authors concluded that the HINT sentence task was not a suitable tool for the assessment of speech recognition in quiet, and should only be administered in its intended adaptive format as per the recommendations of Luxford and colleagues [36]. Our results are consistent with those of Gifford et al. [27], with the majority of participants obtaining scores of ≥ 85% correct, even with a 10dB SNR.

Pitch Perception

The NH group scored 96.9%, 94.6% and 88.8% correct on the 1, ½ and ¼ octave subtests respectively. These scores are slightly lower than their adult counterparts [14, 16], but consistent with those obtained by Stalinski et al. [37] who assessed 60 NH children on a PRT. Differences in the degree of central auditory maturation, and exposure to music may have contributed to the slightly poorer performance of NH children relative to their adult counterparts.

On average, the HA-only group scored slightly higher than adult HA-users from previous studies [14, 15], however the children in the present study had considerably better residual hearing function and speech recognition scores. There were no significant differences between the performance of the HA-only and NH groups on any of the three subtests. This may be attributable to the fact that the smallest interval size assessed in this study was a quarter of an octave. With research suggesting that auditory filter bandwidths double for PTAs of ≥ 40-50dBHL [38], impairing the resolution of individual harmonics [39, 40], it is likely that significant differences would be found for smaller interval sizes.

As expected the NH group ranked pitch significantly more accurately than the CI-only group for all three subtests ($p < 0.01$; see figure 3). In addition, the HA-only group also scored significantly higher than the CI-only group on the 1 octave ($p = 0.035$) and ½ octave subtests ($p = 0.026$). Consistent with most existing studies, there was a large degree of participant variability with some individuals performing in the range of the NH group, and others at chance levels. The variability was greater for the children using a CI (i.e. the CI-only and the BMS groups), and for the smaller interval size (i.e. the ¼ octave subtest).

Accurate pitch perception requires that the listener extract F0 information from the acoustic signal. In both acoustic and electric hearing this information may be extracted by resolving the individual harmonics in a signal (place coding), and/or extracting information regarding the F0 from the temporal waveform output of auditory filters/ CI bandpass filters (temporal coding) (see [3] for a review). In acoustic hearing, place coding for complex sounds involves the resolution of individual low-order harmonics by narrow-bandwidth auditory filters. These harmonics appear as individual peaks in the basilar membrane excitation pattern which can be compared with pre-formed “harmonic templates” to determine the F0 [39]. The filterbanks involved in CI processing strategies are markedly different to the auditory filters of a normal cochlea, which are non-linear, level-dependent and have continuous centre frequencies (see [3] for a review). In contrast, CI filterbanks are comprised of a smaller number of wide bandpass filters (22 for ACE, 20 for SPEAK) with fixed centre frequencies that cover a more restricted frequency range [9]. Low-order harmonics may not be fully resolved by these wide bandpass filters, making it difficult for listeners to derive the pitch of harmonics and/or extract the F0 of complex sounds [9]. Even if individual harmonics are resolved, the user may only be able to determine which filter (or pair of filters) the harmonic falls into as this would result in the activation of the corresponding electrode(s) [19] [9]. While there is some evidence that CI users are able to use place cues to determine the position of puretones within a filterband or pair of filterbands [41], this may not be true for the harmonics of complex sounds. Laneau and colleagues [42] reported that following the removal of temporal pitch cues, adult CI users utilising the ACE strategy were unable to rank the F0 of pairs of synthetic vowels, even for F0 differences as large as 1.7 octaves. This suggests that the ACE filterbank does not allow for the adequate transmission of place-based pitch information, at least for F0 of the synthetic vowels used in their study.

The delivery of place-pitch cues is also limited by the nature of electrical stimulation. The number of independent sites of stimulation is physically limited by the number of, size of and spacing between intracochlear electrodes. Pitch perception is further limited by overlaps in the electrical currents generated at adjacent, and more distant, electrodes [43]. Overlapping electrical currents occur because intracochlear electrode arrays are surrounded by highly conductive fluid that fills scala tympani [2]. Current evidence suggests only 4 to 8 independent sites of stimulation are available, even for arrays with 22 electrodes [44, 45]. A host of biological variables can also limit the ability of CI users to use place cues including the density, and distribution of spiral ganglion neurons relative to electrode array and/or the pathophysiology of the hearing los [46, 47].

Pitch cues can also be provided to recipients via temporal codes. The ACE and SPEAK strategies use the temporal envelope of the input signal to modulate the amplitude of a biphasic pulse train which can also provide pitch cues [48, 49]. Multiple studies indicate that recipients are only able to utilise these cues to discriminate pitch for rates up to around 300 Hz [48, 49], implying that many CI users would have difficulty using these temporal pitch cues for stimuli with a fundamental frequency (F0) above middle-C (261.63 Hz) [9]. The salience of temporal pitch cues is also affected by a range of factors including: sufficient modulation depth [48, 49, 50] ; alignment of the phase of the pulse train across the electrode array [51]; and a high sampling rate [48, 49].

In summary, the pitch information provided to CI users contains only crude representations of the pitch cues present in the original acoustic signal. Even if place and temporal pitch cues are available to a recipient, the interaction between the cues may impede accurate pitch perception [9]. These factors may account for the relatively poor pitch ranking accuracy of the CI-only group relative to the NH and HA-only groups.

Although their performance was poor relative to acoustic hearing, the CI-only group ranked pitch considerably more accurately than adult recipients in previous studies [14, 15]. For example, unlike their adult counterparts [14, 15], the CI-only group scored above chance levels on the ¼ octave subtest ($p < 0.001$). One reason for these findings may be the higher cortical plasticity of child CI recipients. Another reason may be related to differences in the distribution of spiral ganglion neurons (SGNs) in congenitally deafened children and postlingually deafened adults. Studies using adult temporal bones have demonstrated a persistent, progressive deterioration in the size of the SGN population in the basal region of the cochlea with age [46]. In contrast, Miura and colleagues [47] reported a more uniform pattern of SGN degeneration across 50 pathological and 13 normal child cochleae. In addition, the SGN population reportedly remains stable over the first decade of life [47]. A larger, more evenly distributed SGN population may have allowed the child CI users in the present study to more accurately discriminate directional changes in the pattern of electrode activation across the array, improving the accuracy of pitch ranking judgements relative to their adult counterparts.

The finding of no significant differences between the pitch ranking scores of the CI-only and BMS groups was unexpected, as previous studies have consistently reported improvements in the pitch perception abilities of adult users of BMS over a CI-alone [4, 5, 6]. However, our findings are consistent with those of Sucher [18], who found no significant difference between the CI-alone and BMS conditions of 7 prelingually deafened children. Sucher noted that the poor residual hearing levels of the children in her study may have limited their ability to utilise acoustic pitch cues. Consistent with this, El Fata and colleagues] reported that a group of adults users of BMS with unaided thresholds similar to the children in Sucher's study exhibited no bimodal benefit on a melody recognition task.

Poor residual hearing is unlikely to be solely responsible for the similar PRT performance of the BMS and CI-only groups in the present study. The mean low-frequency PTA of the BMS group was an average of 21.9 dBHL better than participants in Sucher's [33] study and group II of El Fata et al. [48]. The BMS group's mean unaided thresholds are more comparable with those of adults from studies who demonstrated significant bimodal benefit on tasks of melody recognition [4, 5] (see figure 8). In addition, unlike Sucher, a moderate negative correlation was found between better ear PTA and mean PRT performance ($\rho = -0.678$, $p = 0.011$), indicating that lower (better) hearing thresholds were associated with higher PRT scores. As we did not test BMS participants using their HA in isolation, we cannot definitely determine the role that acoustic residual hearing played in their PRT performance.

We recommend that future research examine the PRT performance of the implanted and non-implanted ear simultaneously and in isolation.

The finding that MEL was correlated with PRT scores is consistent with existing music perception research conducted with postlingually deafened adults [52, 53, 54, 55]. For example, a retrospective analysis found that pre-implant musical training at a high-school level or beyond was a significant predictor of music perception performance for adult CI users [54]. These finding imply that formal training and/or focused listening practise may help recipients improve their music perception skills.

A potential confound in the results of our study is that participants in the BMS group were significantly younger (*M* = 9.24 years) than those in the CI-only group (*M* = 12.92 years). Research suggests that NH children are capable of ranking pitch at an adult level by 8 years of age [37] however, longitudinal studies of pitch perception in hearing-impaired children have yet to be conducted. It is possible that the pitch discrimination skills of the BMS group were not as fully developed as those of the older CI-only group. Such differences may have obscured any significant benefits that may have been obtained through the use of a contralateral HA when compared to the CI-only group in this study. In support of this, a strong correlation was found between the chronological age of participants in the BMS group and their mean PRT scores ($\rho = 0.714$, $p = 0.036$). The possibility of delayed development of the pitch ranking abilities of child BMS users should be investigated in future research involving a greater number of musically untrained CI-only, HA-only, BMS and NH listeners aged between 6 and 12 years of age.

Irrespective of age, it is also possible that the majority of the BMS group were simply unable to benefit from the pitch information provided by their non-implanted ear due to impaired central auditory development. Studies investigating the pitch perception abilities of postlingually deafened adult BMS users have consistently reported significant advantages for bimodal over electric-only stimulation, but no significant difference between BMS and HA-only scores [4, 6], perhaps indicating that participants in these studies were relying on pitch information from their non-implanted ear. In contrast, children in the BMS group performed at levels similar to their CI-only peers, suggesting that they may have been focusing upon the limited pitch information provided via their implants. Similarly, research has shown that postlingually deafened adult users of BMS are able to utilise the head shadow effect to improve speech recognition in noise regardless of whether their CI or HA has the better SNR [24], while children are only able to utilise the head shadow effect when their CI has the better SNR [25, 26]. It appears that unlike their postlingually deafened counterparts, prelingually deafened children using BMS may be less adept at using the acoustic signal from their HA. It is possible that the quality of the signal provided via the non-implanted ear is insufficient for the normal maturation of central auditory pattern recognition systems and tonotopic maps in prelingually deafened children. Thus, although children with a significant hearing loss may receive additional information via a HA in their non-implanted ear, they may be less able to utilise this information relative to their postlingually deafened adult counterparts, making them more reliant upon information from their CI.

An alternative explanation for the poorer than expected performance of the BMS group is that their HA and CI may have provided conflicting information regarding the direction of the pitch change. Such conflicts may have resulted in increased confusion and reduced accuracy when making pitch ranking decisions, resulting in poorer overall scores. The assessment of children in a CI-alone, HA-alone and BMS conditions is an area of future research to determine whether binaural interference is present for pitch ranking. Finally, aetiology of the hearing loss may have also limited the pitch ranking accuracy of the BMS group. Unlike the CI-only group, the majority of children in the BMS group were born premature and/or experienced hypoxia or anoxia at birth (see Tables 3 and 4). Miura et al. [47] reported that children whose hearing loss was associated with congenital infectious diseases had significantly larger SGN populations than those whose loss was related to inherited genetic anomalies or asphyxia. It is possible that children in the BMS group had smaller SGN populations than their CI-only counterparts, potentially limiting their sensitivity to directional changes in stimulation across the electrode array, and/or limiting the independence of electrode stimulation, however this would be difficult to assess.

It should be noted that although pre-task instruction and training was provided to participants regarding the concept of pitch, it is impossible to verify conclusively if pitch ranking judgements were made solely on that one dimension. Participants may have used other cues such as timbral differences in their decision making process, particularly if pitch cues were not salient [9]. Numerous researchers have suggested that variations in the place of stimulation may affect timbre more than pitch for CI users [10, 56], and studies involving NH listeners have also found interactions between the perceptual dimensions of pitch and timbre, particularly for those with little musical experience [57, 58]. However this issue is inherent to pitch-based perceptual research, particularly where the participants have limited musical experience.

Conclusions

This study aimed to compare the speech recognition and pitch ranking abilities of children using a CI-only, HAs-only, and BMS. Contrary to expectations, there were no significant differences between the mean percentage correct scores of the participant groups for either words in quiet or sentences in quiet or noise. However, the proportion of BMS users who scored above 80% correct was significantly greater than the proportion of high-scoring unilateral CI or bilateral HA users. Also contrary to expectations, there was also no significant difference between the pitch ranking scores of users of BMS and users of a CI alone, nor any significant difference between the HA and NH groups. However participants using only acoustic hearing (i.e. the NH and HA groups) scored significantly higher than participants using electrical stimulation (i.e. the CI and BMS groups) on the PRT.

Unlike the findings for postlingually deafened adults, we found no significant bimodal advantage for pitch or speech perception in noise for prelingually deafened children. However, the use of a CI was associated with significantly lower pitch perception scores. Further research is required to investigate the contribution of the non-implanted ears of users of BMS to pitch perception, and the effect of hearing loss on the development of pitch perception in children.

Conflict of Interest Statement

The authors have no conflict of interest to declare. Although limited financial assistance was provided by Cochlear Ltd for this study, this in no way influenced any part of this study, its outcomes, the preparation of, and/or the decision to submit this manuscript for publication.

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Ethical Clearance

Ethical approval for this study was granted by the New Zealand Ministry of Health Multi-region Ethics Committee, and by the University of Canterbury Human Ethics Committee.

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Figure Legends

Figure 1: **Distribution of mean percentage words correct scores for participants in the CI-only, HA-only and BMS groups.**

Figure 2: **Distribution of HINT sentence scores for all four listening conditions.**

Each point represents a participants’ score for a particular testing session.

Figure 3: **Summary of between-group differences for the PRT.**

§Indicates the level of chance performance. Error bars represent ±1 *SD* from the mean.

Table(s)

Table 1: CI-only group participant details.
C = Congenital, P = Progressive, U = Unknown, CMV = Cytomegalovirus, MEL = Music Experience Level (see text for further details)

ID (sex)	Age (Yrs)	Type of HL	Age at Diagnosis (Months)	Aeitology	Degree of Loss at Diagnosis	Age at Implantation (Years)	Ear	CI Type	Processor	Strategy	CI Usage (Years, Months)	MEL
B1 (M)	14.2	C	13	Perinatal Anoxia	Profound (L, R)	3.2	R	24M	ESPrit 3G	ACE 900Hz	11, 2	2
B2 (F)	12.7	C, P	8	Mondini (L, R), CMV	Profound (L, R)	4.8	R	24M	ESPrit 3G	ACE 900Hz	7, 11	2
B3 (M)	14.4	U	25	Unknown	Profound (L, R)	3.5	R	24M	ESPrit 3G	ACE 900Hz	11, 0	2
B4 (F)	12.1	C	17	Unknown	Profound (L, R)	2.4	R	24M	ESPrit 3G	SPEAK	9, 9	1
B5 (M)	14.0	C, P	3	Mondini (L, R)	Mild (L) Severe (R)	5.1	R	24M	ESPrit 3G	SPEAK	8, 11	1
B6 (M)	11.6	C, P	8	Cochlear Dysplasia (L, R)	Moderate-Severe (L, R)	6.5	L	24M	ESPrit 3G	ACE 900Hz	5, 1	2
B7 (M)	13.4	C	1	Autosomal Recessive	Profound (L, R)	8.2	R	24R	ESPrit 3G	ACE 900Hz	6, 6	2
B8 (M)	11.1	C, P	19	Pendred's Syndrome	Mod-Sev. (L) Prof. (R)	8.7	L	24RE	Freedom	ACE 1200Hz	2, 4	2

Table 2 on next page

Table 3: HA-only group participant details.
C = Congenital, P = Progressive, U = Unknown, MEL = Music Experience Level (see text for further details)

ID (sex)	Age (Yrs)	Type of HL	Age at Diagnosis (Months)	Aeitology	Degree of Loss at Diagnosis	Duration of HA use (Years, Months)		Type of HAs	Mean PTA (0.5, 1, 2kHz) (dBHL)	MEL
						Overall	Current			
C1 (M)	13.1	U, P	18	Unknown	Mod-Sev. to Sev. (L, R)	12, 3	1, 7	Phonak Novoforte E4 (L, R)	76.7	
C3 (F)	9.7	U, P	60	Unknown	Moderate to Severe (L,R)	10, 7	3, 7	Widex SD-19 (L, R)	85.0	2
C4 (M)	15.0	C	61	Genetic Recessive, Cx26	Mod. to Sev. (L) Prof. (R)	6, 7	0, 3	Widex AK-19 (L) AK-9 (R)	81.7	3
C5 (M)	11.8	C	38	Genetic Recessive, Cx26	Severe-Profound (L, R)	7, 6	2, 6	Phonak PowerMAXX 411 (L, R)	84.2	2
C6 (F)	9.8	C, P	37	Enlarged Vestibular Aqueduct	Moderate to Severe (L,R)	12, 4	3, 2	Widex SD-9 (L, R)	55.0	2
C7 (F)	11.5	C	33	Unknown	Moderate (L, R)	8, 6	2, 8	Widex SD-19 (L, R)	70.0	2

Table 2: BMS group participant details.
C = Congenital, P = Progressive, U = Unknown, MEL = Music Experience Level (see text for further details)

ID (sex)	Age (Yrs)	Type of HL	Age at Diagnosis (Months)	Aeitology	Degree of Loss at Diagnosis	Age at Implantation (Years)	CI Details				Device Usage (Years, Months)		Type of HA	Non-implanted ear PTA (0.5, 1, 2kHz) (dBHL)	MEL
							Ear	Type	Processor	Strategy	CI	Current HAs			
A1 (F)	11.5	C	12	Unknown, Hypoxia	Prof. (L), Sev-Prof. (R)	9.8	L	24RE	Freedom	ACE 900Hz	1, 8	0, 1	Phonak Naida III UP	95.0	2
D1 (F)	9.4	C	6	Genetic Recessive	Severe-Profound (L,R)	4.9	R	24R*	Freedom	ACE 900Hz	4, 10	2, 9	Siemens Prisma 2 D SP	71.7	2
D2 (M)	6.9	C	36	Genetic Recessive	Sev-Prof. (L), Prof. (R)	4.3	L	24RE*	Freedom	ACE 900Hz	2, 8	0, 2	Siemens Cielo 2 P	76.7	1
D3 (M)	6.4	C, P	28	Genetic Recessive, Cx26	Prof. (L), Mod-Prof. (R)	5.5	L	24RE*	Freedom	ACE 900Hz	1, 0	0, 3	Siemens Cielo 2 D SP	101.7	1
D4 (F)	8.5	C	20	Possible Auditory Dysynchrony	Prof. (L), Mod-Sev. (R)	2.6	L	24R*	Freedom	ACE 900Hz	5, 10	0, 9	Siemens Prisma 2 D SP	96.7	1
D6 (F)	7.4	A, S	9	Pneumococal Meningitis	Mod-Sev. to Prof. (L,R)	4.1	R	24M*	Freedom	ACE 900Hz	7, 2	0, 4	Siemens Prisma 2 D SP	100.0	1
D7 (F)	11.1	C	21	Mondini (L, R), Ototoxocity	Mod-Prof. (L), Prof. (R)	4.3	R	24RE*	Freedom	ACE 900Hz	7, 2	0, 4	Siemens Prisma 2 VC+	91.7	2
D8 (M)	11.4	C	3	Genetic Recessive, Ototoxocity	Mod-Prof. (L), Prof. (R)	5.0	R	24RE*	Freedom	ACE 900Hz	2, 5	5, 2	Phonak PowerMAXX 411	90.0	1
D9 (M)	12.9	C	39	Genetic Recessive, Cx26	Mod-Sev. to Prof. (L,R)	11.7	L	24RE*	Freedom	ACE 900Hz	1, 2	2, 11	Widex SD-9M	70.0	3

Table 4: Summary of each group’s scores on the CNC word lists and HINT sentence lists.

	CI-only		HA-only		BMS	
Test	*M*	*SD*	*M*	*SD*	*M*	*SD*
CNC Words (% correct)						
Words	71.87	14.79	65.39	11.54	76.45	14.79
Phonemes	87.33	7.95	82.34	7.13	89.45	6.24
HINT Sentences (% correct)						
S0	92.97	11.56	96.64	4.64	95.74	4.21
S0N0	88.12	13.50	93.39	5.68	91.96	5.69
S0NCI	84.87	15.77	91.22	6.70	92.00	5.50
S0NHA	90.12	11.05	92.25	8.52	91.76	7.57

Table 5: Summary of across-session mean PRT percentage correct scores for each group.

	CI-only		HA-only		BMS		NH	
PRT Subtest	M	SD	M	SD	M	SD	M	SD
1 Octave	83.30	18.59	95.42	8.96	79.61	15.10	96.94	5.35
½ Octave	77.60	12.21	88.54	11.06	75.00	15.36	94.58	8.06
¼ Octave	67.45	14.54	79.11	19.74	63.99	19.99	88.79	11.033

Figure(s)

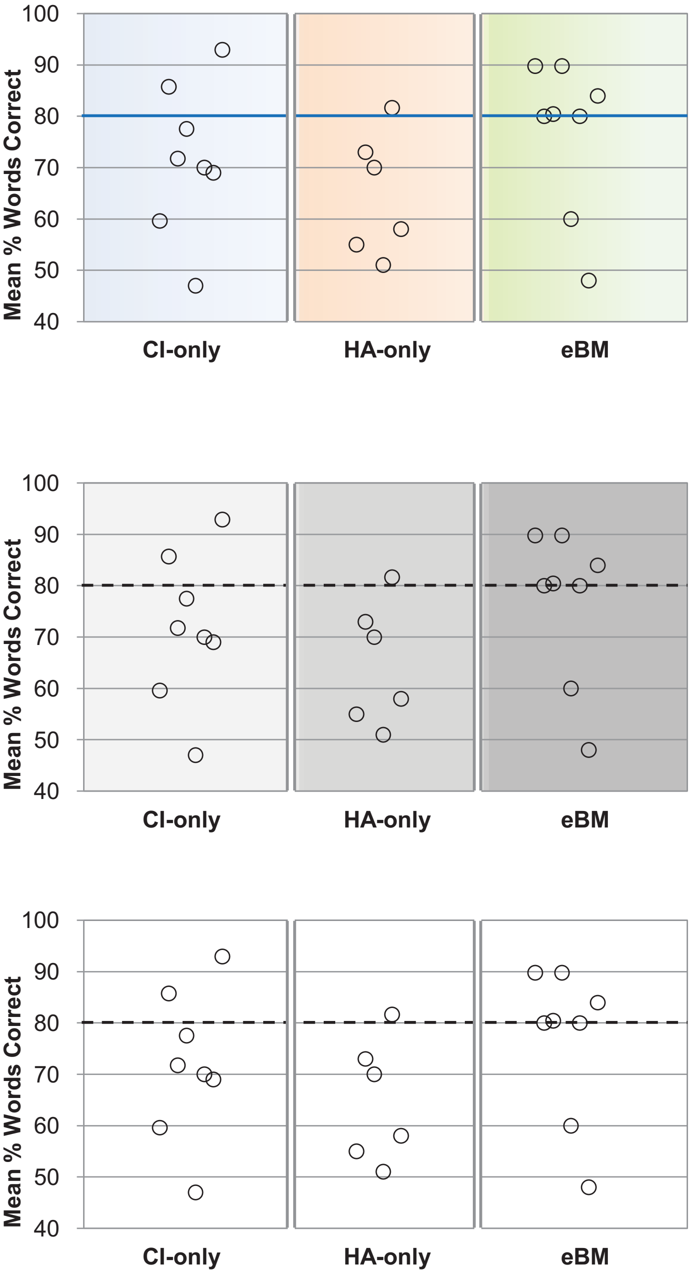


Figure 1

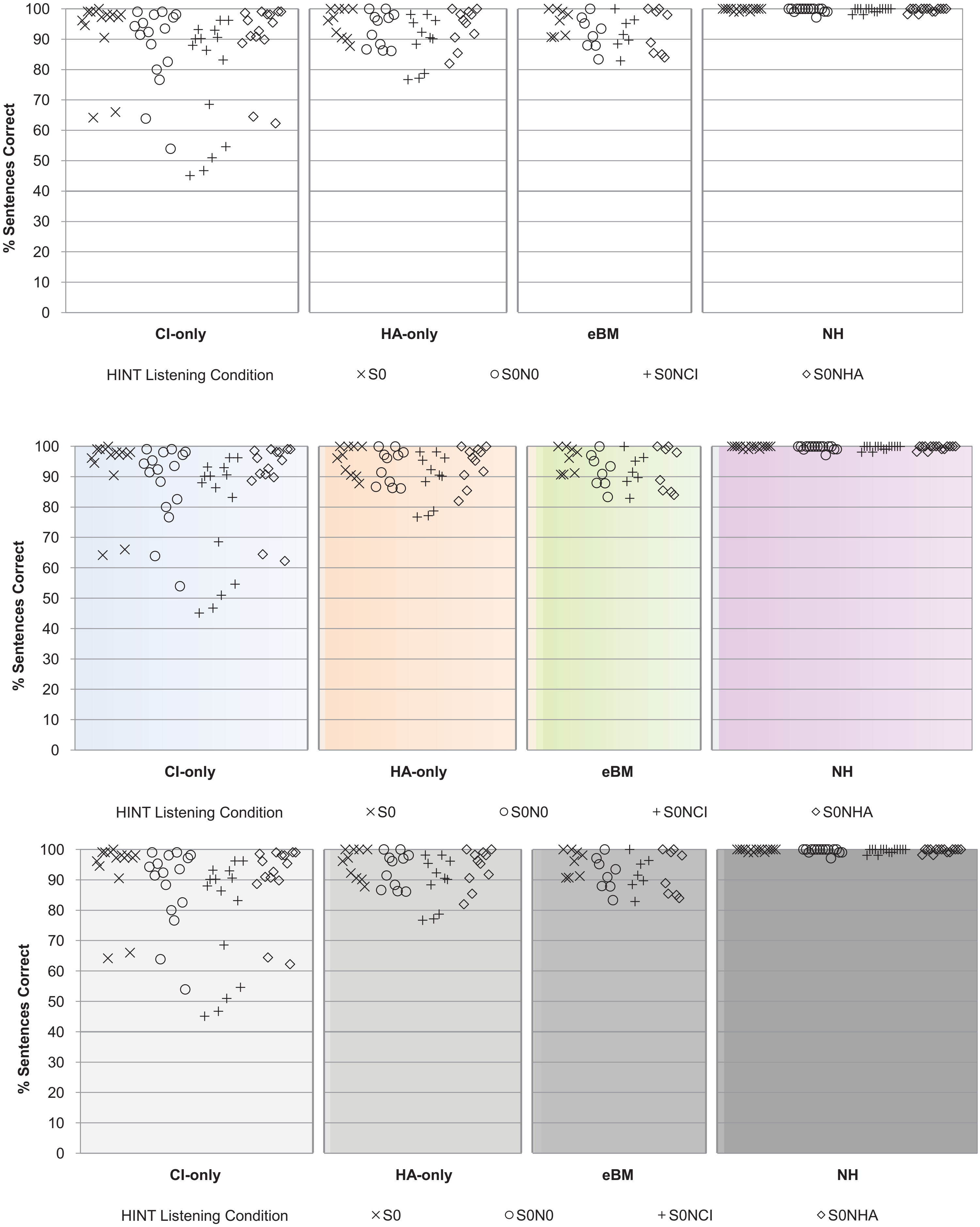
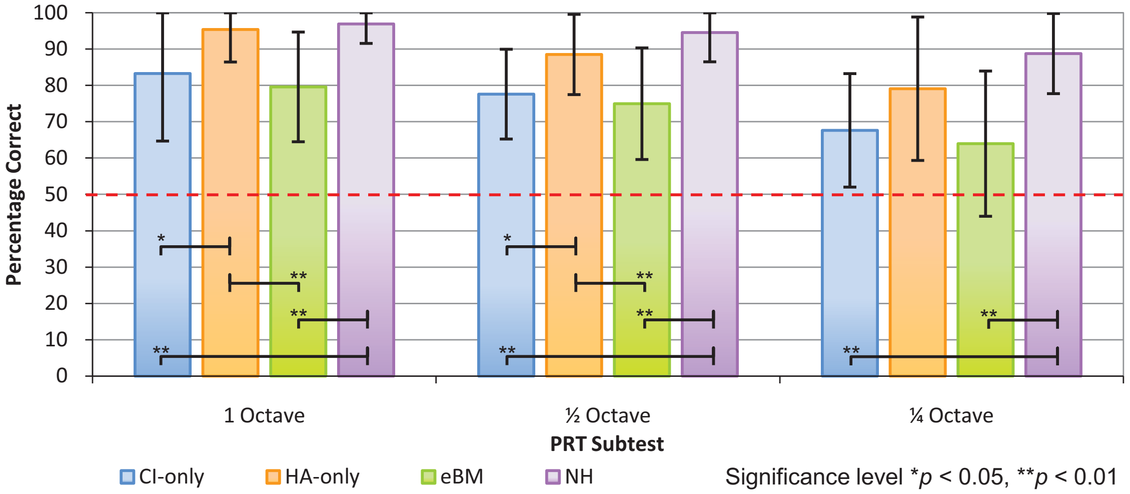

% Sentences Correct
0
10
20
30
40
50
60
70
80
90
100
CI-only
HA-only
eBM
NH
HINT Listening Condition
×S0
○S0N0
+S0NCI
◇S0NHA

Figure 2



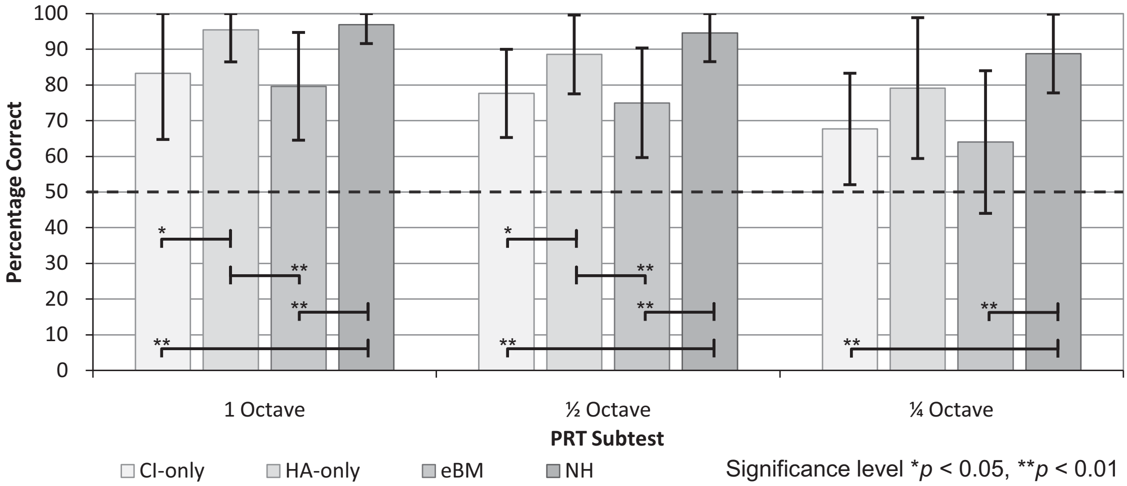


Figure 3

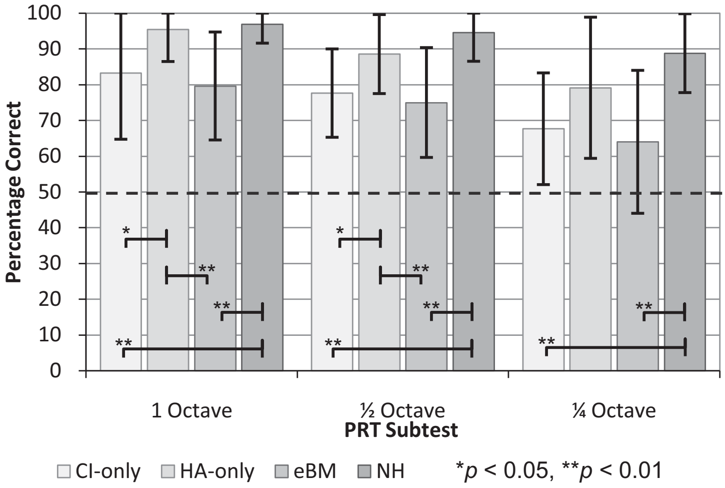


Figure 3 (single column width)