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The effects of pre-processing strategies for pediatric cochlear implant recipients

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THE EFFECTS OF PRE-PROCESSING STRATEGIES FOR PEDIATRIC COCHLEAR IMPLANT RECIPIENTS

by

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Abstract: The purpose of the present study was to compare pediatric speech perception performance across various pre-processing strategies with the Cochlear Corporation CP810 external speech processor when a specific mapping protocol was used.

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INTRODUCTION AND REVIEW OF THE LITERATURE

Cochlear implants (CIs) deliver sound to the auditory nerve through electrical stimulation. Sounds occurring in the CI user's environment are processed in the external speech processor, which is programmed for each individual user (Wilson & Dorman, 2009). Once the sound is processed through the programmed settings, the stimulus is sent to the internal receiver/stimulator that resides under the temporalis muscle via a transcutaneous coil. The receiver/stimulator obtains the stimulus from the coil, decodes it, and then produces the current that is sent down the internal electrical array, which resides in the cochlea. At this point, the stimulus is delivered as electrical current to the auditory nerve through the electrodes of the internal array (Wilson & Dorman, 2009).

CIs have been shown to improve users' speech recognition over traditional amplification for adults and children with severe to profound sensorineural hearing loss (Skinner, Holden, Holden, Demorest, Fourakis, 1997; Fetterman & Domico, 2002; Firszt et al., 2004; Spahr & Dorman, 2004). Despite these improvements, understanding speech, particularly at lower intensities and/or in the presence of background noise, is still difficult for CI users (Fetterman & Domico, 2002; Nelson, Jin, Carney, & Nelson, 2003; Firszt et al., 2004; Spahr & Dorman, 2004). The audiologist can apply a variety of programming options in an effort to enhance a CI user's speech recognition in challenging situations.

When programming a CI, goals include providing audibility of speech sounds, providing comfort for louder sounds, optimizing clarity and quality of sound, and optimizing performance in challenging listening environments. The programming, or mapping, of a Cochlear Corporation device allows the audiologist to determine the level of current that will be delivered to each electrode for soft and loud inputs (threshold levels, comfort levels, and gains) to optimize audibility and comfort. Other programming parameters can be manipulated to optimize overall clarity and quality such as ensuring a useable electrical dynamic range at each electrode and setting the number of maxima and rate of stimulation. The Cochlear Corporation device also offers pre-processing strategies that allow the audiologist to customize a program in an effort to improve performance in challenging listening environments. These pre-processing strategies include Automatic Dynamic Range Optimization (ADRO), Autosensitivity Control (ASC), Whisper, Beam, and Zoom, which apply various types and combinations of microphone gain, sensitivity control, and noise reduction. ADRO maintains speech input for soft and moderate intensities within the upper 50% of the CI user's electrical dynamic range utilizing statistical rules, in an attempt to highlight the speech signal by keeping it audible for the user (James et al., 2002). ASC attempts to improve comfort and speech recognition in the presence of background noise by automatically adjusting the microphone sensitivity in an effort to capture less of the environmental noise and more of the speech, assuming the person the CI user wants to hear is nearby (Cochlear Limited, 2010). Whisper attempts to capture softer inputs by increasing the input dynamic range (IDR) from 40 to 50 decibels (dB) bringing in more soft sounds (Cochlear Limited, 2002). Beam and Zoom attempt to increase speech intelligibility in background noise by applying microphone polar plots and noise cancellation algorithms. Beam utilizes adaptive polar plots in response to the location of the highest intensity noise detected (Cochlear Limited, 2010). Zoom utilizes a fixed hypercardiod polar plot with maximum detection at 0 degrees (°) azimuth (Cochlear Limited, 2010). Although several pre-processing strategies exist and can be used in combination, the current recommended default setting for pediatrics' everyday listening include ASC+ADRO in unison (Wolfe, Schafer, John, & Hudson, 2011b; Gifford, Olund, & DeJong, 2011).

Automatic Dynamic Range Optimization (ADRO)

ADRO was developed to place the sound stimulus optimally into the user's electrical dynamic range, the electrical current range existing between the user's measured threshold levels (Ts) and comfort levels (Cs) (Dawson, Decker, & Psarros, 2004). This is accomplished by utilizing four statistical rules: the comfort, audibility, hearing protection, and background noise rules. These rules assess incoming stimuli based on overall input level, competing noise level, and the most intense input level (Wolfe, Hudson, John, & Schafer, 2011a). The comfort rule applies if the channel output exceeds the C level greater than 10% of the time (Blamey, 2005). When this occurs, the gain is reduced in that channel to place the stimulus at a comfortable intensity within the dynamic range. The audibility rule is applied if the channel output is below the T level greater than 30% of the time. When this occurs, the gain is increased in that channel to place the stimulus within the dynamic range. The hearing protection rule limits output and is active to ensure that the maximum output of a channel is never surpassed. The background noise rule reduces the level of background noise by capping the maximum allowable gain in a processing channel. By utilizing these four rules, ADRO keeps the stimulus output within optimal limits on a channel-by-channel basis (Blamey, 2005). When the incoming signal stimulus does not fall into the CI user's dynamic range naturally, it is processed with ADRO to allow for comfort and audibility of soft and medium inputs while providing comfort and clear speech intelligibility of louder sound stimuli (James et al., 2002; Dawson et al., 2004; Blamey, Martin, & Fiket, 2004; Blamey, 2005). ADRO has been documented to improve sound quality in quiet conditions, without degrading speech perception in noise (Dawson et al., 2004; James et al., 2002).

Autosensitivity Control (ASC)

ASC adjusts microphone sensitivity prior to the stimulus being processed. The input noise level and the signal-to-noise ratio (SNR) are assessed and used to automatically manipulate the speech processor's microphone sensitivity (Cochlear Limited, 2010; Gifford et al., 2011). The sensitivity determines the amount of sound in the environment that the microphone will amplify and deliver to the CI user. If the sensitivity is increased, the microphones will detect softer sound levels in the environment, allowing the user to hear things that are farther away. If the sensitivity is decreased, the microphones will detect only louder sound levels in the environment, therefore capturing sounds that are closer to the user. For example, when the sensitivity is increased, a CI user can hear a speaker who is far away in a quiet conference room. Inversely, when the sensitivity is decreased, a CI user hears only the desired speech of a close conversational partner in a noisy environment.

Increasing or decreasing sensitivity will increase or decrease the automatic gain control (AGC) kneepoint, the input level above which compression occurs. Without pre-processing, the microphones pick up acoustic sound and amplify the sound in a linear manner until it reaches 65 dB Sound Pressure Level (SPL) (Dillon, 2001; Gifford et al., 2011). At this intensity, the sound is compressed (i.e. amplification becomes non-linear) to allow louder sounds to be mapped in the CI user's dynamic range without being amplified to an uncomfortable listening level. The sensitivity and AGC kneepoint are inversely related (Patrick, Bugsby, & Gibson, 2006). If the microphone sensitivity is decreased, the AGC kneepoint is increased. This results in allowing a greater amount of the sound stimulus to be amplified linearly. If the microphone sensitivity is increased, the AGC kneepoint is decreased. This results in greater gain of soft sounds, therefore more access to sound (Patrick et al., 2006).

Unlike ADRO, which adjusts the output on a channel-by-channel basis, ASC affects the entire frequency range captured by the microphones. Therefore, ASC is expected to augment the incoming stimulus more so than other pre-processing strategies (Gifford et al., 2011). As stated previously, without ASC turned on, Cochlear Corporation's default programming infinitely compresses any incoming stimuli that exceeds 65 dB SPL. When considering a speech signal: if peaks of the signal surpass 65 dB SPL, they will be compressed an unlimited amount which can cause distortion and lead to poor speech recognition (Gifford et al., 2011). When ASC is enabled, sensitivity of the external speech processor microphones are automatically decreased when the background noise surpasses 57 dB SPL (the manufacturer default). This allows the spectral peaks of speech to "exceed the long-term average speech spectrum by 15 dB SPL" before they are affected by infinite compression (Custom Sound 3.0 manual; Cochlear Limited, 2009). The purpose of ASC is to allow the desirable speech signal to be captured while avoiding infinite compression in the presence of moderate to loud background noise (Wolfe et al., 2009). In quiet conditions ASC is inactive (Wolfe et al., 2011a).

Utilizing Pre-Processing Strategies

Cochlear Corporation's software allows the CI to be programmed to employ pre-processing strategies individually or in combination with one another. The default setting for pediatrics' everyday programs activate both ASC+ADRO pre-processing strategies. ASC works to improve speech intelligibility and comfort in background noise and ADRO works to position soft and moderate speech levels into a CI user's audible range. Previous research has stated that using this specific combination of pre-processing strategies when programming children's CI processors has yielded the best speech perception abilities in various listening situations (Wolfe et al., 2011b; Gifford et al., 2011).

Wolfe et al. (2011b) examined the use of ADRO only and ASC+ADRO as pre-processing strategies in 11 preschool to school-aged children. Participants ranged in age from 4.4 to 12.0 years. All of the participants were using the Freedom or CP810 external speech processor either bilaterally or unilaterally. Participants were administered the Phonetically-Balanced for Kindergarten (PBK-50) monosyllabic word tests at 60 dB A-weighting (A) in quiet and the Bamford-Kowal-Bench Speech in Noise Test (BKB-SIN) list pairs at 75 dB SPL using two different pre-processing conditions: ADRO and ASC+ADRO. Wolfe et al. (2011b) found that participants performed significantly better in noise in the ASC+ADRO condition than the ADRO alone condition. Also, in the quiet condition, ASC+ADRO yielded scores above 90% for all of the participants indicating excellent speech recognition with this pre-processing combination.

Similarly, Gifford et al. (2011) performed a study to examine speech perception in noise using ADRO and ASC+ADRO. This study had twenty-two participants ranging in age from 5.6 to 16.8 years who used Freedom or CP810 external speech processors. Participants completed the Hearing in Noise Test (HINT) sentences in the R-SPACE with noise at 72 dBA, HINT sentences in quiet, and the Consonant-Nucleus-Consonant (CNC) or the Lexical Neighborhood Test (LNT) at 60 dBA. The results of this study showed that participants achieved significantly better speech recognition thresholds when using ASC+ADRO versus ADRO alone (Gifford et al., 2011).

Based on these results, ASC+ADRO is the recommended setting and default for the everyday program in children's speech processors (Wolfe et al., 2011b). However, these recommendations were based on studies that did not include information about how the participants' processors were mapped for T and C levels, in addition to audibility in the soundfield. It is possible that different mapping protocols (such as setting Ts at higher levels) could affect the benefit of pre-processing strategies for individual CI users.

Results of a recent study in adults conducted at Washington University in St. Louis, where mapping techniques were cited in the article, provided a differing recommendation for the application of pre-processing strategies. Brockmeyer & Potts's (2011) study tested 30 adults ranging in age from 25 to 82 years. All participants were tested with the Adaptive HINT sentences in the R-SPACE using the Freedom speech processor in four pre-processing conditions: no pre-processing active, ADRO, ASC, and Beam. Testing was conducted with an adaptive presentation level and a constant noise level of 60 and 70 dB SPL. The study found that the ASC condition resulted in the best speech recognition in the presence of loud, 70 dB SPL, background noise. Participants performed best with Beam in the moderate noise condition, at 60 dB SPL. However, no statistical difference was observed between Beam and ASC in the moderate noise condition. The authors suggest that ASC should be used when the CI user is in loud or moderate background noise to allow for the greatest speech understanding and that Beam can be beneficial in moderate noise levels (Brockmeyer & Potts, 2011). Beam is not a typically recommended pre-processing strategy for children since it affects the microphone polar plot and creates nulls around the CI user where sound is not amplified. Due to constant opportunities for incidental language learning in the environment, children are typically set to have the microphones of their external speech processors programmed to pick up sound in a 360° polar plot.

Kolb (2011) completed a follow up study to Brockmeyer & Potts (2011), which examined the effectiveness of pre-processing strategies in the R-SPACE for 32 adult CI users ranging in age from 36 to 92 years. In this study a CP810 processor was used for all testing. HINT sentences were presented to the participants with an adaptive presentation level in the presence of a constant noise level of 70 dB SPL for eight different pre-processing conditions: Beam only, Beam+ASC, Beam+ADRO, Beam+ASC+ADRO, Zoom only, Zoom+ASC, Zoom+ADRO, and Zoom+ASC+ADRO. The Zoom+ASC condition yielded the lowest (best) Reception Threshold for Sentences (RTS) while the Zoom only condition yielded the highest RTS (worst). Also, ADRO was shown to significantly increase RTS (indicating poorer performance) when it was added to another pre-processing condition. Kolb (2011) suggests that ADRO may be detrimental for the participants in the study due to the mapping protocol used (Skinner, 2003). For the participants in this study, T levels were set at either 100% detection or above, allowing for access to more soft sounds. The C levels were set at a "loud but comfortable" perceptual level for each participant. With these higher T levels, it may be expected that soft sounds are perceived as medium soft to medium as opposed to very soft to soft, and the electrical dynamic range is narrower. The electrical dynamic range for these participants was carefully measured with possibly higher T levels than those used in other studies. Since ADRO works to optimally place the input sound within the upper portion of the electrical dynamic range, it may have made detrimental adjustments by introducing more compression to the sound based on the four statistical rules that it follows (Kolb, 2011).

The purpose of the present study was to compare pediatric speech perception performance across various pre-processing strategies (no pre-processing active, ADRO, ASC, or ASC+ADRO). The population in this study had standardized programming techniques similar to those used in the Brockmeyer & Potts (2011) and Kolb (2011) articles. These techniques include behavioral programming to set counted Ts at 100% accuracy and scaled Cs set to a loud but comfortable level, along with using loudness balancing. When the maximum output (C levels) of the electrodes in the array are perceived to be equally loud, speech perception and production are believed to benefit (Shapiro, 2006). After these mapping procedures were applied, aided soundfield thresholds were measured and electrical T levels were increased as needed until the detection of frequency modulated (FM) tones were optimized between 20 to 30 dB Hearing Level (HL) from 250-6000 Hertz (Hz), often leading to T levels that were increased above the counted levels, closer to a perception of a medium loudness. Firszt et al. (2004) found that aided thresholds less than 30 dB HL led to better speech recognition.

METHODS

Design

This was a prospective, cross-sectional, observational study. All participants performed several speech perception tasks in different pre-processing conditions: no pre-processing, ADRO, ASC, ASC+ADRO. This research had approval from the Human Research Protection Office at Washington University School of Medicine (#201210075).

Participants

Eleven pediatric cochlear implant participants ranging in age from 8.08 to 17.33 years (mean 12.62 years, SD 3.40) were recruited for the study. Participants included five females and six males. Six participants used a CI on both ears (bilateral), one used a CI on only one ear (unilateral), and four participants used a CI on one ear and a hearing aid on the opposite ear (bimodal). For those with bilateral CIs, testing was completed wearing both processors. The participant with a unilateral CI had no hearing at the opposite ear and was tested with the CI alone. The bimodal users were tested with only the CI processor on, using a plug and muff at the non-implanted ear. Demographic information is specified in Table 1.

Each participant used a Cochlear Corporation CI24R, CI24RE, CI512, or CI422 internal system with either a Freedom or CP810 external speech processor for daily use. Seven of the participants used a Freedom external speech processor and four participants used a CP810 external speech processor. Of the 11 participants, two were using no pre-processing in his or her everyday program, six were using ADRO, and three were using ASC+ADRO. The age at implantation of the participants' first CI ranged from 1.25 to 8.33 years (mean 4.37 years, SD 2.06). This average age reflects the fact that several participants were implanted after 2 years of age due to progressive hearing losses. At the time of testing, the participants had a range of 2 to 12.5 years (mean 8.18 years, SD 3.12) of implant use. Information about CI use is reported in Table 2.

Participants were recruited from the clinical population at St. Louis Children's Hospital (SLCH). Only CI users who were able to clinically score at least 50% on a CNC word list at an average intensity level (60 dB SPL) in quiet were recruited. Letters were mailed to participants' families followed by a phone call to participants' guardians. If the guardian and child were interested, a test session was scheduled. Participants' guardians signed informed consent documents and each participant received a token amount of remuneration for participation.

All participants had their CI processor(s) mapped within 6 months of the research testing by the managing SLCH clinician using a specific protocol. Ts are obtained using a process called "counted Ts" where the CI user was instructed to count the number of soft beeps he or she heard through the CI programming software (Skinner, 2003). A tone stimulus was presented at very soft levels using a modified Hughson-Westlake approach (Carhart & Jerger, 1959). T levels were set at the softest presentation level the CI user could consistently identify the correct number of presented beeps with 100% accuracy (Shapiro, 2006). Cs were obtained using a process called "loudness scaling", where the CI user was instructed to identify how loud a stimulus was when presented through the computer using at least a five point scale: first hearing, soft, medium, loud but comfortable, too loud. C levels were set at "loud but comfortable". Loudness balancing was also performed. This was completed to ensure that adjacent electrode C levels were perceived to be equally loud. Following mapping, aided soundfield threshold testing was conducted in a soundtreated booth. Typically, Ts set at counted yield aided soundfield thresholds between 20 and 30 dB HL (Skinner, Binzer, Potts, Holden, & Aaron, 2002). If aided thresholds are greater than 30 dB HL the electrical T levels are increased above the counted level to allow access to softer sounds. This technique has been found to improve audibility of both soft and average speech levels (Skinner et al., 2002).

Equipment/Test Environment

During testing, all participants were tested with consignment CP810 external speech processors. The processors were preprogrammed with each participant's current, optimized everyday map. For the seven participants that used a Freedom speech processor, his or her map was converted to an equivalent CP810 map before being downloaded to the speech processor. Four programs, with the same map, were set in the processor for each participant with different pre-processing strategies applied: no pre-processing, ADRO, ASC, and ASC+ADRO in programs one through four, respectively. All participants used the speech processor with volume set at 10 and sensitivity set at 12.

Testing for this study was performed at the Washington University School of Medicine Department of Otolaryngology. The participants completed testing in one, three-hour session. All testing was performed in a double-walled soundtreated booth (8’3” x 8’11”). Aided soundfield testing and word recognition in quiet were obtained with the participant facing the loudspeaker at 0° azimuth while sitting approximately one meter away. Testing in noise was conducted in the R-SPACE, a specific setup where eight speakers are positioned 360° around the participant (Revit, Schulein, & Julstrom, 2002; Revit, Killion, & Compton-Conley, 2007). The eight speakers are set apart by 45°, with a speaker set at 0, 45, 90, 135, 180, 225, 270, and 315°. The participant is seated and centered in the middle, with each speaker 24 inches away (Compton-Conley, Neuman, Killion, & Levitt, 2004). See Figure 1 for a schematic of the configuration. With this setup, a real-world recording of background noise (R-SPACE) from a neighborhood restaurant is presented out of the speaker array with the stimulus presented from the speaker 0° azimuth to the participant, which creates a realistic noisy listening environment (Compton-Conley et al., 2004).

A Dell personal computer with a sound card, power amplifier, and Urei 809 loudspeaker was used for soundfield thresholds and CNC testing. To present FM tones for the aided soundfield thresholds, a custom designed mixing and amplifying network was used. To present CNC word lists, recorded stimuli were presented at 50 and 70 dB SPL while the participant was seated 0° azimuth to the loudspeaker.

An Apple iMac 17 personal computer using a MAC OS X operating system was used to run the R-SPACE. Professional audio mixing software (MOTU Digital Performer 5) and an audio interface (MOTU 828mkII, 96 kHz firewire interface) was used to execute the R-SPACE. The audio output was sent to four amplifiers (ART SLA-1, two-channel stereo linear power amp with 100 W per channel) then onto eight loudspeakers (Boston Acoustic CR67) positioned in a circular array around the participant.

Test Stimuli

FM tones at 250, 500, 750, 1000, 2000, 3000, 4000, and 6000 Hz were used for aided soundfield testing. The CNC word lists (Peterson & Lehiste, 1962) were used for testing word recognition in quiet. These lists are comprised of 50 monosyllabic words recorded by a male talker. The HINT sentences are comprised of sets of two phonetically balanced lists with 10 sentences each, presented by a recorded male talker (Nilsson, Soli, & Sullivan, 1994). These sentences were used for testing in noise.

Test Procedures

Aided thresholds were obtained utilizing a modified Hughson-Westlake procedure with a +4/-2 dB step size (Carhart & Jerger, 1959) for each participant in the CI alone condition with no pre-processing active using conventional audiometry. For bilateral participants, each CI was tested individually to ensure optimal aided threshold levels for each CI. After ear specific aided thresholds were obtained, bilateral CI participants were tested wearing both CIs together for the remainder of the test conditions. For bimodal participants, the hearing aid was removed and the unaided ear was plugged and muffed throughout all testing, including aided soundfield thresholds. Although bimodal participants were not tested in their optimal device configuration; the CI alone was tested in order for results to reflect pre-processing effects without introducing complex interactions with hearing aid noise reduction algorithms. See Figure 2 for mean aided threshold results. Participants' thresholds fell between 6 and 32 dB HL. Within the group there was only one threshold (at 6000 Hz) that was higher than 30 dB HL. Programming manipulations for this individual had previously been attempted to improve this particular threshold without success. Therefore, no programming changes were necessary for any participant after thresholds were obtained for the study.

The CNC monosyllabic word list recordings were presented in quiet at a soft level of 50 dB SPL and loud level of 70 dB SPL in each of the four conditions: no pre-processing active, ADRO, ASC, and ASC+ADRO. One word list was randomly selected for each presentation level and presented for each pre-processing condition, which were also randomly ordered. CNCs were scored as percent words correct.

The Adaptive HINT sentences were presented in the R-SPACE from the speaker 0° azimuth to the participant and the real-world restaurant noise was presented through all seven speakers at each constant noise level, 60 and 70 dB SPL (Gifford & Revit, 2010). Two randomized lists were used per test condition and each randomly ordered pre-processing strategy was tested at each presentation level. The presentation level of the HINT sentences adapted as the test proceeded (i.e. a correct response caused the following sentence stimuli to get softer; an incorrect response caused the following sentence stimuli to get louder). For the 70 dB SPL conditions the noise remained constant at 70 dB SPL and the first sentence was presented at +14 dB and the next three sentences presented were adjusted in +/- 4 dB steps for acclimatization purposes. The following 16 sentences were adjusted in +/- 2 dB step sizes. This same method was used for the 60 dB SPL conditions, but the initial SNR was +16 dB. The level at which the participant can correctly repeat the sentence back in its entirety is used to establish his or her score as a SNR which indicates the difference between the intensity level of the sentences compared to the noise (a lower score would be better as the child could perceive the sentences with more noise present). In total, each participant completed 16 test conditions. See Table 3 for protocol information.

Data Analysis

When comparing each pre-processing strategy for the average group data, a repeated-measures analysis of variance (ANOVA) was used. If the data violates the assumption of sphericity, Greenhouse-Geisser values are reported. After significance was determined, a post-hoc analysis using the Bonferroni correction was performed to see which conditions were different. The effects of possible demographic variables that are known to affect outcome measures in children with CIs were examined using correlational analyses.

For each individual participant, scores obtained with each pre-processing strategy were compared to the baseline condition of no preprocessing on each measure. In order to evaluate significant differences in an individual's scores between conditions for the CNC scores, the critical difference tables published by Carney and Schlauch were used (Carney & Schlauch, 2007). The critical differences are the 95% confidence around the mean percent correct score for the baseline condition for a given list length, based on the binomial distribution. For HINT sentence SNR scores in the R-SPACE, a 95% confidence interval was used to identify a critical difference of 1.4 dB as significant (Compton-Conley et al., 2004).

RESULTS

CNC Words

Figure 3 displays results of the CNC words presented at 50 dB SPL in quiet. For the average group data of the CNC words presented at 50 dB SPL, results from the ANOVA revealed a significant effect for pre-processing condition [$F(1.5,15.4) = 11.47$, $p<.01$]. ASC+ADRO had the highest (best) average percentage correct (71.5%) followed by ADRO (66.5%) then no pre-processing (60.4%). ASC had the lowest (worst) average score (59.6%). Bonferroni post-hoc comparisons revealed that scores for ASC+ADRO were significantly better than all other conditions ($p<.05$). ASC resulted in significantly worse scores than ADRO or ASC+ADRO ($p\leq.001$). Individual participant data was analyzed based on the binomial model. Two participants performed significantly better with ASC+ADRO than no pre-processing; participant 5 (P5) performed significantly better with ASC+ADRO when compared to no pre-processing (70% compared to 48%, respectively), and participant 7 (P7) performed significantly better with ADRO (68%) and ASC+ADRO (72%) than with no pre-processing (44%). Nine participants did not show a significant advantage for one pre-processing condition over another.

Figure 4 displays results of the CNC words presented at 70 dB SPL in quiet. For the average group data of the CNC words presented at 70 dB SPL, the overall repeated measures ANOVA result was marginally significant ($p<.05$), however, post-hoc tests did not show any differences in group average scores for the different pre-processing strategies. All conditions for group averages had percent words correct in the 77-82% range. Individual participant data showed that the pre-processing strategy that yielded the highest percent words correct varied across participants with significance based on the binomial model. One participant (P10) showed a significant decrease in percent words correct when using ASC (84%) compared to no pre-processing (96%). Ten participants did not show a statistically significant difference in scores between pre-processing conditions.

Adaptive HINT Sentences

Figure 5 displays results of the Adaptive HINT sentences in the R-SPACE with 60 dB SPL of noise. For the average group data, no significant results were seen. ADRO had the lowest (best) average score (4.99 dB) followed by ASC+ADRO (6.13 dB) then ASC (6.64 dB). No pre-processing had the highest (worst) score (7.47 dB). When comparing average scores, only a difference of 1.14 dB existed between the two best strategies, ADRO and ASC+ADRO. Individual participant data showed that the pre-processing strategy that yielded the lowest SNR varied across participants with significance based on the 95% confidence interval. Two participants (P3 and P6) had significantly better scores with no pre-processing. Three participants (P5, P7, and P11) had significantly better scores with ADRO. Two participants (P1 and P9) had significantly better scores with ASC. Three participants (P4, P8, and P10) had significantly better scores with ASC+ADRO. One participant (P2) had significantly better scores with both no pre-processing and ADRO (equal performance between these conditions).

Figure 6 displays results of the Adaptive HINT sentences in the R-SPACE with 70 dB SPL of noise. For the average group data, results from the ANOVA revealed a significant effect for pre-processing condition [$F(3,10) = 10.07$, $p<.001$]. ASC+ADRO had the lowest (best) average scores (3.47 dB) followed by ASC (4.78 dB) then ADRO (5.65 dB). No pre-processing had the highest (worst) average scores (7.56 dB). ASC ($p=.003$) and ASC+ADRO ($p=.002$) were significantly better than no pre-processing. ASC+ADRO ($p=.028$) was significantly better than ADRO. Individual participant data showed that the pre-processing strategy that yielded the lowest SNR varied across participants. One participant (P8) obtained significantly better scores with no pre-processing activated. Five participants (P1, P3, P4, P7, and P10) obtained significantly better scores with ASC. Five participants (P2, P5, P6, P9, and P11) obtained significantly better scores with ASC+ADRO.

Predictor Variables

Correlational analyses between possible demographic predictor variables and outcomes were completed. Predictor variables examined were age at test and duration of CI use. No significant correlations were seen between duration of CI use and participants' average scores on test conditions or age of participant and test condition. See Table 4 for the correlation table. Additionally, a pattern with participants' previously used pre-processing strategy and their best pre-processing condition was not observed. Table 5 shows participants previously used pre-processing and their best pre-processing condition per test condition. Variability was seen between previously used pre-processing and best pre-processing condition. Also, variability was seen across and within individuals for the best pre-processing strategy in each test condition.

DISCUSSION

The aim of this study was to determine which pre-processing strategy should be used for pediatric CI users whose everyday maps are programmed with behaviorally set Ts between a soft to medium level, and Cs set at a loud, but comfortable level with aided soundfield thresholds between 20 – 30 dB HL as measured through the CI with FM tones.

For this population group data revealed that when CNC words were presented at a loud level of 70 dB SPL in quiet, participants did not show a statistical advantage or disadvantage for one pre-processing strategy over another. Similarly, sentence recognition of Adaptive HINT sentences in 60 dB SPL of noise, did not yield statistical significance for any of the pre-processing conditions. However, participants performed significantly better with ASC+ADRO compared to any other pre-processing strategy for word recognition of CNC words at a soft presentation level of 50 dB SPL in quiet. For this test condition, participants performed significantly worse with ASC alone. Performance on the Adaptive HINT sentences in 70 dB SPL of noise revealed that, ASC+ADRO resulted in significantly better scores than no pre-processing or ADRO alone.

The results from this study are in agreement with results from Wolfe et al. (2011b) and Gifford et al. (2011) demonstrating an advantage for ASC+ADRO when listening to speech in background noise. Even though ASC+ADRO was not found to significantly benefit participants in each test condition (i.e. CNC words at 70 dB SPL and HINT sentences in 60 dB SPL of noise), ASC+ADRO did not significantly decrease scores in any condition.

Unlike findings from Kolb (2011), the addition of ADRO to another pre-processing strategy did not significantly decrease participants' speech recognition in noise. Notably ASC+ADRO benefited participants for listening to speech in higher levels of noise (70 dB SPL) and for listening to words at a soft presentation level (50 dB SPL). The adverse effects of adding ADRO to other pre-processing strategies for adult participants in the Kolb study were thought to be due to excessive compression leading to distortion of speech caused by the reduced dynamic range created by using a mapping protocol with higher T levels. However, studies have shown that children typically tolerate higher C levels than adults (Hughes, Brown, Abbas, Wolaver, & Gervais, 2000; Weberling, Firszt, Reeder, & Cadieux, 2011). Even though the same mapping protocol is used with higher T levels, the children prefer higher C levels than adults, allowing children to utilize a larger electrical dynamic range compared to adults. Thus, an excessive amount of compression would not be imposed when ADRO was applied to pediatric CI programs, resulting in less distortion of the speech signal.

Also, interesting to note, is that participants' everyday experience with pre-processing strategies did not seem to affect which pre-processing strategy they performed best with for the study. As there was no acclimatization period before testing the different pre-processing strategies, it might have been expected that the participants would achieve the best scores using the pre-processing strategy with which they had the most listening experience. There was no trend for the best pre-processing condition to be associated with the child's everyday pre-processing strategy. Furthermore, some participants performed best with pre-processing strategies that were different than what they previously used and their best pre-processing strategy often varied across test measures.

While group data showed significant improvement with ASC+ADRO on two of the four test measures with no detriment on any of the measures when ASC+ADRO was applied, individual data varied across measures and within subjects. Therefore, while this data supports the recommendation of ASC+ADRO to be the default everyday setting for children, a variety of pre-processing applications should be considered on an individual level.

CONCLUSION

Based on the results from this study, it is recommended that pediatric CI users utilize the ASC+ADRO pre-processing strategy for their everyday maps. Since ASC+ADRO was not seen to significantly degrade performance in any situation and was seen to significantly improve speech recognition in quiet at a soft level and in noise at a loud level, it would be advantageous to apply it to everyday situations. Due to the variability seen in the study, if a child is not achieving expected speech recognition performance, other pre-processing strategies should be assessed.

Possible future studies could investigate a larger population, explore additional pre-processing strategies within the pediatric population, examine how CI pre-processing interacts with hearing aid processing for bimodal users, and explore possible relationships between pre-processing and T level settings/electrical dynamic range. Further information may reveal predictive variables as to which pre-processing strategy may be most beneficial for specific individuals.

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Table 1: Participant demographic information
Female (F), Male (M), Left (L), Both (B), Right (R), Enlarged Vestibular Aqueduct (EVA)

Participant	Age at Test	Sex	Device Configuration	Implanted Ear	Etiology	Age at implant	Internal	Speech Processor
1	17.33	F	Bimodal	L	Unknown	6.08	CI24R	CP810
2	16.92	M	Bilateral	B	Unknown	L-4.42; R-11.21	L-CI24R; R-CI24RE	Freedom
3	9.42	F	Bimodal	L	EVA	4	CI24RE	Freedom
4	13.66	F	Bilateral	B	Unknown	L-2.83; R-8.5	L-CI24R; R-CI24RE	Freedom
5	12.25	M	Bilateral	B	Unknown	R-1.75; L-7.33	R-CI24R; L-CI24RE	Freedom
6	10.66	F	Bilateral	B	Unknown	4.17	R/L-CI24RE	CP810
7	17.08	M	Bimodal	L	EVA	8.33	CI24R	CP810
8	13.17	M	Unilateral	R	Unknown	3.75	CI24R	Freedom
9	11.92	M	Bimodal	L	Unknown	5.17	CI24RE	Freedom
10	8.33	F	Bilateral	B	EVA	L-6.33; R-7.92	L-CI512; R-CI422	CP810
11	8.08	M	Bilateral	B	Unknown	L-1.25; R-2.0	L-CI24RE; R-CI24RE	Freedom

Table 2: Device use information
No pre-processing (None), Automatic Dynamic Range Optimization (ADRO), Autosensitivity+Automatic Dynamic Range Optimization (ASC+ADRO), Advanced Combination Encoder (ACE), Cochlear Implant (CI), Consonant-Nucleus-Consonant word list (CNC).

Participant	Current Pre-processing Strategy	Speech Processing Strategy	Channel Rate	Maxima	Years of CI Use	CNC score presented at 60 dB SPL for CI(s)
1	None	ACE	900	12	10.5	72%
2	ADRO	ACE	900	8	12.5	92%
3	ASC+ADRO	ACE	900	10	6	78%
4	ADRO	ACE	900	12	10.92	84%
5	ADRO	ACE	900	8	10.5	80%
6	ADRO	ACE	1200	12	6.5	94%
7	None	ACE	900	9	9.5	80%
8	ADRO	ACE	900	12	9.42	74%
9	ADRO	ACE	1200	12	6.75	80%
10	ASC+ADRO	ACE	1200	10	3	72%
11	ASC+ADRO	ACE	1200	12	6.83	78%

Table 3: Test protocol table

Test Condition	Pre-processing Strategy
Sound Field Thresholds	No Pre-processing Active
CNC Words at 50 dB SPL	No Pre-processing Active
	ADRO
	ASC
	ASC+ADRO
CNC Words at 70 dB SPL	No Pre-processing Active
	ADRO
	ASC
	ASC+ADRO
HINT Sentences in R-SPACE in 60 dB SPL of noise	No Pre-processing Active
	ADRO
	ASC
	ASC+ADRO
HINT Sentences in R-SPACE in 70 dB SPL of noise	No Pre-processing Active
*Sound Field Threshold were obtained first for every participant. The order of all other test measures, stimuli, and pre-processing strategy were randomized per participant.	ADRO
	ASC
	ASC+ADRO

Table 4: Correlation table for duration of CI use and average scores per test condition.

		Age	AvgCNC50	AvgCNC70	AvgHINT60	AvgHINT70
Age	Pearson Correlation	1	.363	-.016	.225	.482
	Sig. (2-tailed)		.272	.963	.507	.133
	N	11	11	11	11	11

Table 5: Participants best pre-processing strategy in the study's test conditions

Participant	Everyday	CNC 50	CNC 70	HINT 60	HINT 70
1	None			ASC	ASC
2	ADRO			None/ADRO	ASC+ADRO
3	ASC+ADRO			None	ASC
4	ADRO			ASC+ADRO	ASC
5	ADRO	ASC+ADRO		ADRO	ASC+ADRO
6	ADRO			None	ASC+ADRO
7	None	ASC+ADRO		ADRO	ASC
8	ADRO			ASC+ADRO	None
9	ADRO			ASC	ASC+ADRO
10	ASC+ADRO		None	ASC+ADRO	ASC
11	ASC+ADRO			ADRO	ASC+ADRO

* Pre-processing Strategies reported in table were found to be statistically significant

Figure 1: Schematic of R-SPACE
An eight-speaker array is positioned in a 360-degree circle with speakers positioned 45 degrees apart. The participant is seated 24 inches away, in the center of each of the 8 speakers in the array (Compton-Conley et al., 2004).

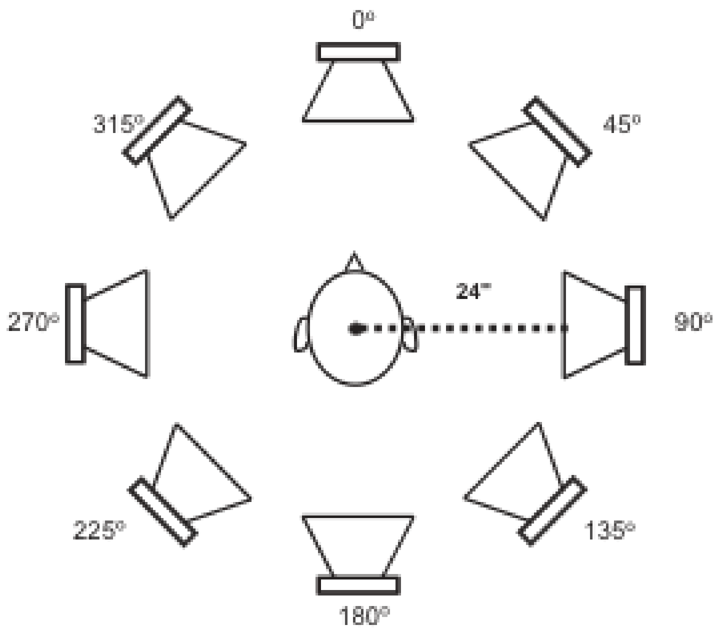

Figure 2: Aided mean soundfield audiogram (dB HL)
Includes +/- standard deviation error bars for every cochlear implant.

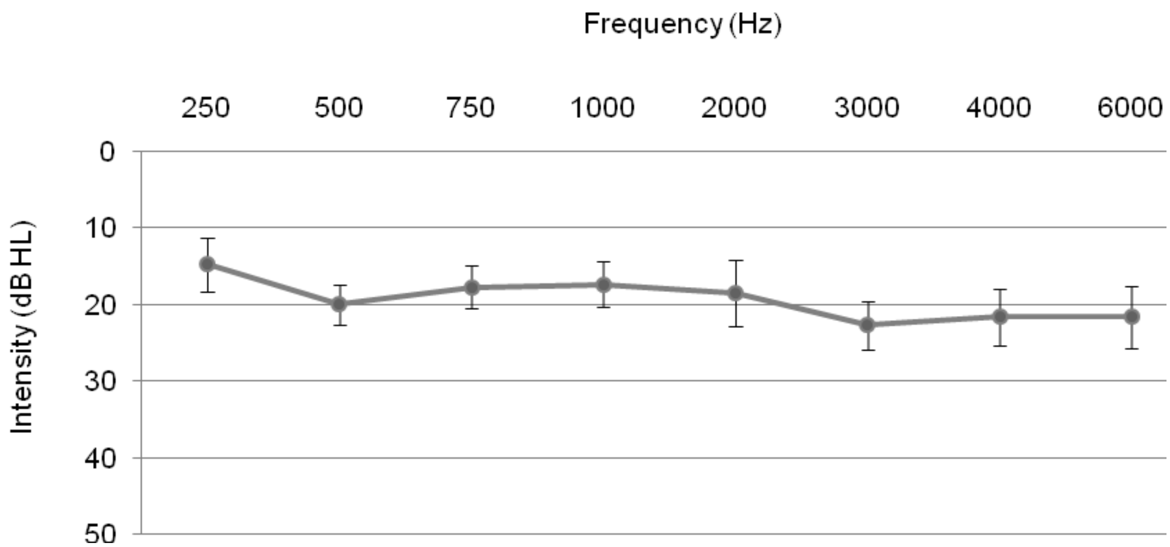

Figure 3: Results for CNC words at 50 dB SPL
Individual participants' and group mean percent correct scores for the CNC at 50 dB SPL for the four pre-processing conditions: no-processing (blue), ADRO (red), ASC (green) and ASC+ADRO (purple). The + symbol denotes a statistically significant difference in scores between conditions for a specific participant (p<.05). The asterisks denote a statistically significant difference between conditions for group scores (p<.05).

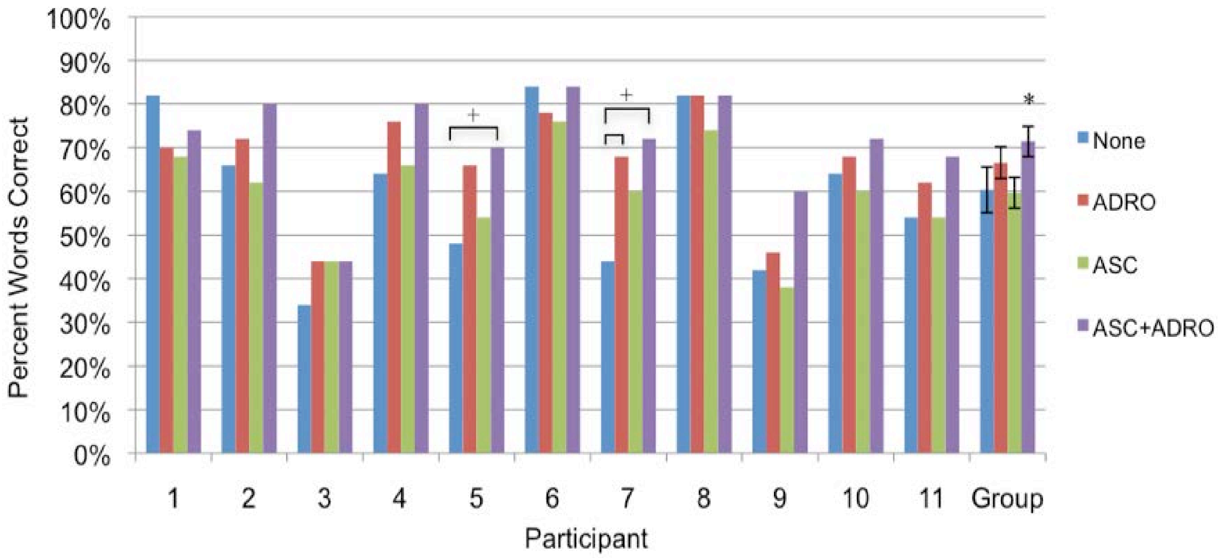

Figure 4: Results for CNC words at 70 dB SPL
Individual participants' and group mean percent correct scores for the CNC at 70 dB SPL for the four pre-processing conditions: no-processing (blue), ADRO (red), ASC (green) and ASC+ADRO (purple). The + symbol denotes a statistically significant difference in scores between conditions for a specific participant (p<.05). The asterisks denote a statistically significant difference between conditions for group scores (p<.05).

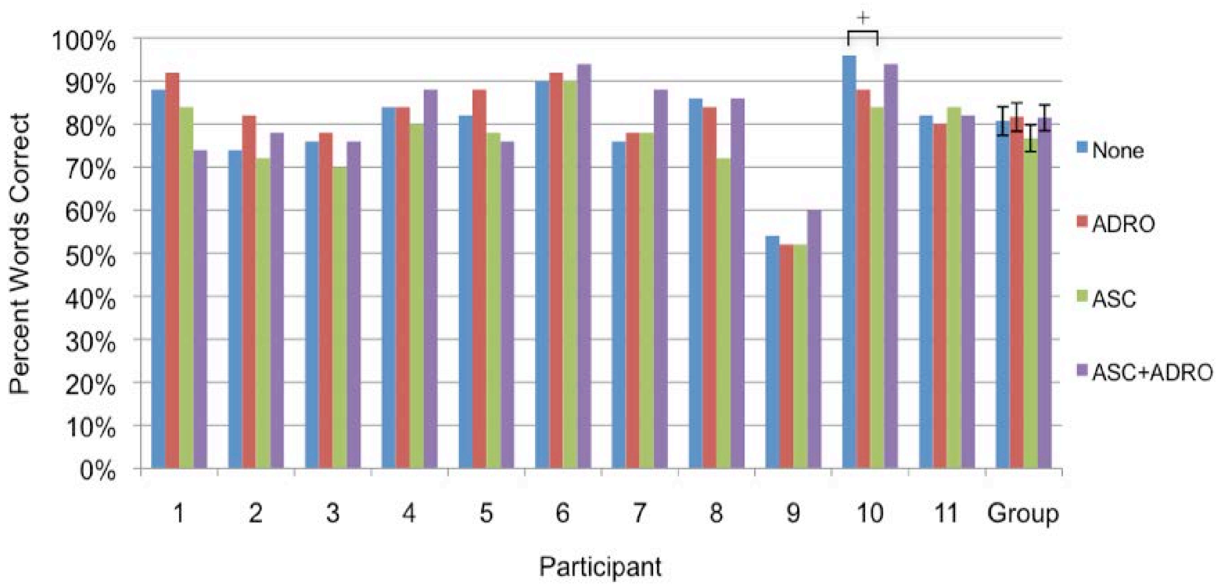

Figure 5: Results for HINT sentences in R-SPACE in 60 dB SPL of noise
Individual participants' and group mean HINT in R-SPACE SNR scores in 60 dB SPL noise for the four pre-processing conditions: no-processing (blue), ADRO (red), ASC (green) and ASC+ADRO (purple). The + symbol denotes a statistically significant difference in scores between conditions for a specific participant (>1.4 dB critical difference). The asterisks denote a statistically significant difference between conditions for group scores (p<.05).

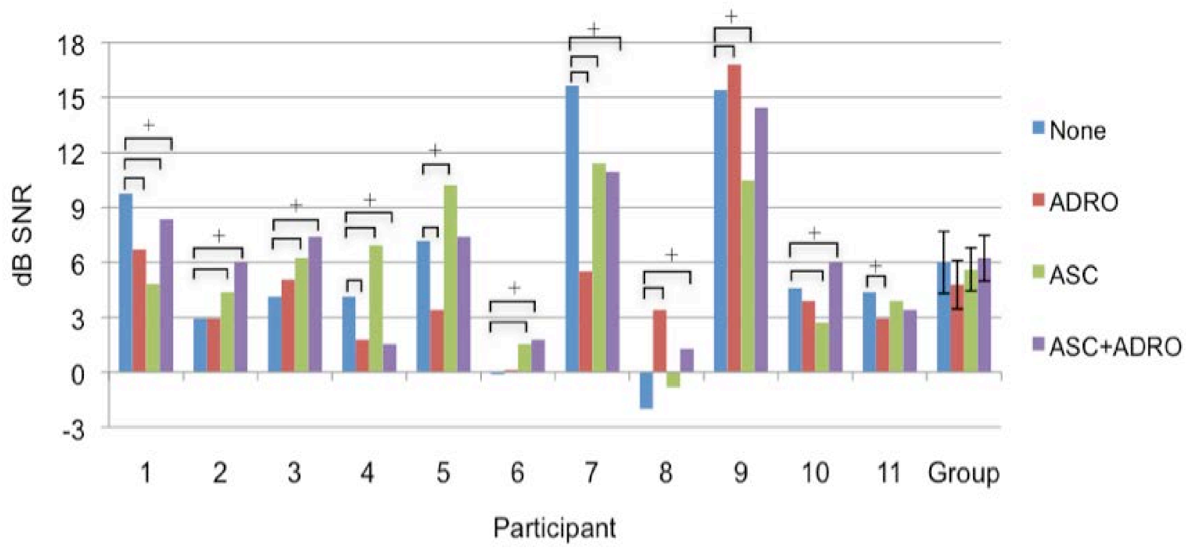

Figure 6: Results for HINT sentences in R-SPACE in 70 dB SPL of noise
Individual participants' and group mean HINT in R Space SNR scores in 70 dB SPL noise for the four pre-processing conditions: no-processing (blue), ADRO (red), ASC (green) and ASC+ADRO (purple). The + symbol denotes a statistically significant difference in scores between conditions for a specific participant (>1.4 dB critical difference). The asterisks denote a statistically significant difference between conditions for group scores (p<.05).