HHS Public Access
Author manuscript
*J Am Acad Audiol*. Author manuscript; available in PMC 2016 April 21.

Published in final edited form as:
*J Am Acad Audiol*. 2016 February ; 27(2): 85–102. doi:10.3766/jaaa.14058.

# The Effects of Pre-processing Strategies for Pediatric Cochlear Implant Recipients

**Bernadette Rakszawski**,
Program in Audiology and Communication Sciences, Washington University School of Medicine

**Rose Wright**,
St. Louis Children's Hospital

**Jamie H. Cadieux**,
St. Louis Children's Hospital

**Lisa S. Davidson**, and
Program in Audiology and Communication Sciences & Department of Otolaryngology, Washington University School of Medicine

**Christine Brenner**
Department of Otolaryngology, Washington University School of Medicine

## Abstract

**Background—**Cochlear implants (CIs) have been shown to improve children's speech recognition over traditional amplification when severe to profound sensorineural hearing loss is present. Despite improvements, understanding speech at low-level intensities or in the presence of background noise remains difficult. In an effort to improve speech understanding in challenging environments, Cochlear Ltd. offers pre-processing strategies that apply various algorithms prior to mapping the signal to the internal array. Two of these strategies include Autosensitivity Control™ (ASC) and Adaptive Dynamic Range Optimization (ADRO®). Based on previous research, the manufacturer's default pre-processing strategy for pediatrics' everyday programs combines ASC +ADRO®.

**Purpose—**The purpose of this study is to compare pediatric speech perception performance across various pre-processing strategies while applying a specific programming protocol utilizing increased threshold (T) levels to ensure access to very low-level sounds.

**Research Design—**This was a prospective, cross-sectional, observational study. Participants completed speech perception tasks in four pre-processing conditions: no pre-processing, ADRO®, ASC, ASC+ADRO®.

**Study Sample—**Eleven pediatric Cochlear Ltd. cochlear implant users were recruited: six bilateral, one unilateral, and four bimodal.

Bernadette Rakszawski: St. Louis Children's Hospital, 1 Children's Place, Room 3S23, St. Louis, MO 63110; Telephone: 314-454-2595; Fax: 314-454-4097; bxr0319@bjc.org.

**Intervention—**Four programs, with the participants' everyday map, were loaded into the processor with different pre-processing strategies applied in each of the four positions: no pre-processing, ADRO®, ASC, and ASC+ADRO®.

**Data Collection and Analysis—**Participants repeated CNC words presented at 50 and 70 dB SPL in quiet and HINT sentences presented adaptively with competing R-Space noise at 60 and 70 dB SPL. Each measure was completed as participants listened with each of the four pre-processing strategies listed above. Test order and condition were randomized. A repeated-measures analysis of variance (ANOVA) was used to compare each pre-processing strategy across group data. Critical differences were utilized to determine significant score differences between each pre-processing strategy for individual participants.

**Results—**For CNC words presented at 50 dB SPL, the group data revealed significantly better scores using ASC+ADRO® compared to all other pre-processing conditions while ASC resulted in poorer scores compared to ADRO® and ASC+ADRO®. Group data for HINT sentences presented in 70 dB SPL of R-Space noise revealed significantly improved scores using ASC and ASC +ADRO® compared to no pre-processing, with ASC+ADRO® scores being better than ADRO® alone scores. Group data for CNC words presented at 70 dB SPL and adaptive HINT sentences presented in 60 dB SPL of R-Space noise showed no significant difference among conditions. Individual data showed that the pre-processing strategy yielding the best scores varied across measures and participants.

**Conclusions—**Group data reveals an advantage with ASC+ADRO® for speech perception presented at lower levels and in higher levels of background noise. Individual data revealed that the optimal pre-processing strategy varied among participants; indicating that a variety of pre-processing strategies should be explored for each CI user considering his or her performance in challenging listening environments.

### Keywords

ADRO®; ASC; cochlear implant; pre-processing strategies; speech perception

---

Cochlear Implants (CIs) have been shown to vastly improve speech recognition over traditional amplification for adults and children with severe to profound sensorineural hearing loss (Skinner et al, 1997; Fetterman and Domico, 2002; Spahr and Dorman, 2004; Firszt et al, 2004). Despite notable improvements in speech recognition in quiet settings, understanding speech at low-level intensities and/or in the presence of background noise remains difficult for most CI users (Fetterman and Domico, 2002; Nelson et al, 2003; Spahr and Dorman, 2004; Firszt et al, 2004). An audiologist can apply a variety of programming options, such as altering stimulation levels, rate, pulse width, microphone directionality, and pre-processing strategy, 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. When programming the Cochlear Nucleus device the audiologist determines the amount of electrical current for threshold (T) levels and maximum comfort (C) levels for each electrode. The difference in clinical units between the T and C levels defines the CI users electrical dynamic range (EDR) for each electrode, thus the level of current that will be delivered for low through high level sounds to provide audibility and comfort. A variety of behavioral programming techniques are used to set T and C levels and may include setting T levels at or above the detection threshold along with using psychophysical loudness scaling and balancing to set C levels.

Clinically at St. Louis Children's Hospital (SLCH), a specific programming protocol is followed during routine visits as children become developmentally able to participate. First, T levels are measured at each electrode using a process called "counted Ts." A pulsed tone stimulus is presented through the CI programming software at a current level that is below the CI user's detectable hearing level using an ascending modified Hughson-Westlake approach (Carhart and Jerger, 1959) with a step size of approximately +2/−4 clinical units (Skinner, 2003). Once detection of the stimulus is reported, the CI user is instructed to count the number of presentations he or she hears (child is asked to "count the beeps"). The pulse tone stimulus is presented in a train of one, two, three, four, or five beeps. T levels are set at the softest presentation level that the CI user can consistently identify the correct number of presentations with 100% accuracy (Shapiro, 2006). Therefore, T levels are set at a current level that is higher than the level of first detection at each electrode. This provides the CI user with audibility of low-level speech cues (Skinner, 2003).

Aided thresholds are always measured to confirm that T levels have been set to allow aided thresholds in the desired target range (~20 dB HL) from 250–6000 Hertz (Hz) utilizing frequency modulated (FM) tones in the sound field. In the case of bilateral CI users, this is done for each CI device. Studies have shown the importance of including sound field thresholds as part of a fitting protocol that verifies the audibility, intelligibility, and comfort of speech at levels ranging from soft to loud (Skinner et al, 1997; Skinner et al, 1999; Holden et al, 2013). Better speech recognition for low and medium level speech has been correlated with sound field thresholds less than 30 decibel (dB) hearing level (HL) (Firszt et al, 2004; Davidson et al, 2009; Davidson et al, 2014). For many clinicians, aided thresholds are used to determine the minimum audibility of speech provided to cochlear implant recipients.

If aided thresholds are greater than the target of 15 to 30 dB HL, T levels are increased above the counted level in an attempt to achieve this target. Only the electrodes within the frequency ranges that do not yield sound field thresholds less than 30 dB HL are adjusted. A typical clinical unit increase of 2 to 5 is employed. The T level is set at the minimum level of increased current needed to achieve desirable sound field thresholds at the necessary frequencies. In all cases, this leads to T levels that are increased above 100% detection. This technique has been found to improve speech recognition at both low and average intensity levels (Skinner et al, 2002; Holden et al, 2013). When considering the Articulation Index (Pavlovic et al, 1985; Pavlovic, 1988) and "count-the-dot method" (Mueller and Killion, 1990), sound field thresholds less than 30 dB HL ensure audibility of acoustic cues present during normal conversational speech (Holden et al, 2013).

C levels for each electrode are then measured using a process called loudness scaling. Beginning at the T level the current is increased in steps of 3–5 clinical units and the CI user is instructed to rate the perceived loudness of the stimulus. Generally a five-point rating scale is used for this task: first hearing, soft, medium, loud but comfortable, too loud. C levels are set at the clinical unit that is perceived to be “loud but comfortable.”

After C levels are set at each electrode, loudness balancing across C levels is performed to ensure that adjacent C levels are perceived to be equally loud. Beginning with the most apical electrode, it’s C level is presented followed by the presentation of the C level on the adjacent electrode. This process continues along the array. The CI user determines if the stimuli are equal in perceived loudness. If so, the C levels are unchanged. If the C levels are not perceived to be equally loud, they are adjusted to match the perceived loudness of the previous electrode. When the maximum output (C levels) of each electrode in the array is perceived to be equally loud, speech perception and production are believed to benefit (Shapiro, 2006).

Once all programming manipulations are made, the CI users listen using the speech processor in live voice mode. Sound quality is assessed, specifically to ensure conversational speech is perceived to be comfortably loud, that loud sounds are not too loud, and that no static or humming noise is heard in quiet. If speech is perceived to be too loud, C levels are globally decreased in 2 clinical units until it is perceived to be comfortable. If static is perceived when listening in quiet, T levels are globally decreased in 2 clinical units until the static is eliminated.

A number of programming variables (i.e. microphone sensitivity control, volume control, automatic gain control (AGC), and pre-processing strategies) may also be manipulated to ensure that low to high level acoustic information in the environment is placed optimally in the EDR. Earlier studies (Wilson et al, 1991; Cosendai and Pelizzone, 2001; Zeng et al, 2002; Donaldson and Allen, 2003) used the term input dynamic range (IDR) to refer to the full range of acoustic input that when processed is mapped onto the CI users available EDR. They demonstrated that an IDR greater than 30 dB was needed for optimal speech perception, especially speech presented at soft levels. Later studies evaluating the Cochlear Nucleus CI system used the term instantaneous input dynamic range (IIDR) to refer to the range of acoustic input levels that are encoded by the CI system at any given point in time (James et al, 2003; Dawson et al, 2007).

Studies conducted with the Cochlear Nucleus CI system have demonstrated the benefits of increasing the IIDR from 30 dB to ~ 40 dB for adults and children citing lower sound field thresholds, better speech recognition when listening to low-level speech stimuli, along with no detriments to speech perception in the presence of background noise (Dawson et al, 2007; Holden et al, 2007; Davidson et al, 2009). Due to concerns that a wider IIDR would map low-level noise into the CI users EDR, participants in the Dawson study were tested with two programs/maps; one program/map with standard clinical T levels and another map where a global reduction across T levels was applied. The majority of the participants performed best with and preferred the wider IIDR with standard T levels. Participants in the Holden et al (2007) and Davidson et al (2009) studies had T levels set using the protocol outlined above (i.e. T levels set above 100% detection, usually counted T levels). Group data from both studies did not reveal any detriment for speech in noise when increasing the IIDR from 30–40 dB.

As mentioned, the Cochlear Ltd. device offers pre-processing strategies that allow the audiologist to customize a program in an effort to improve performance in challenging situations. These pre-processing strategies include Adaptive Dynamic Range Optimization (ADRO®), Autosensitivity Control™ (ASC), Whisper™, Beam®, and Zoom, which apply various algorithms adjusting electrode gains, sensitivity control, IIDR, microphone directionality, and noise reduction. Whisper, Beam®, and Zoom are not evaluated in the current study, so they will not be explained further in this manuscript. The remaining pre-processing strategies will be discussed below.

## Adaptive Dynamic Range Optimization (ADRO®)

ADRO® was developed to place the speech input for low to moderate level intensities within the CI user's EDR utilizing statistical rules, in an attempt to highlight the speech signal by keeping it audible and comfortable for the user (James et al, 2002; Dawson et al, 2004). These rules assess incoming stimuli based on overall input level, competing noise level, and the most intense input level (James et al, 2002; Wolfe et al, 2011a).

The gain rules for ADRO® are applied based on percentile estimates of the long-term output level in a given frequency band (Dawson et al, 2004). Percentile estimates are calculated approximately every 2 milli-seconds. The comfort rule applies when the 98$^{th}$ percentile level is greater than the C level stimulation amount for a channel. When this occurs, the gain is reduced in that channel to place the stimulus at a comfortable intensity within the dynamic range (Dawson et al, 2004; Blamey, 2005). The background noise rule reduces the level of noise by capping the maximum allowable gain in a processing channel. According to the audibility rule, an increase in the gain for a channel will occur if the 70$^{th}$ percentile level is lower than the audibility target, which is 15 dB below the upper end of the IIDR for that channel. In addition, a maximum gain rule is in effect so that noise does not exceed a defaulted gain limit for a channel (James et al, 2002; Dawson et al, 2004).

By utilizing these rules, ADRO® keeps the stimulus output within the EDR on a channel-by-channel basis (Blamey, 2005). Sounds are processed with ADRO® to allow for comfort and enhanced audibility of low to medium level inputs while providing comfort and clear speech intelligibility of high level sound stimuli (James et al, 2002; Blamey et al, 2004; Dawson et al, 2004; Blamey, 2005).

ADRO® has been documented to improve sound quality in quiet conditions, without degrading speech perception in noise (James et al, 2002; Dawson et al, 2004). James et al (2002) used three different speech perception tests in quiet: closed-set spondee words, City University of New York (CUNY) sentences, and Consonant-Nucleus-Consonant (CNC) words, to compare scores obtained when adult participants listened with ADRO® versus no pre-processing. The authors found that with the implementation of ADRO®, participants performed significantly better for the spondee words presented at a low level of 40 dB sound pressure level (SPL), for CUNY sentences presented at 50 and 60 dB SPL, and for CNC words presented at 60 dB SPL. Also, when testing participants in noise using the CUNY sentences, there was no significant difference in scores obtained using ADRO® or no pre-processing (James et al, 2002). Dawson et al (2004) compared children's speech perception scores in two conditions, ADRO® and no pre-processing, using the Bamford-Kowal-Bench (BKB) sentences presented at 50 dB SPL in quiet and at 65 dB SPL in noise. The authors report significantly better scores obtained when participants listened with ADRO® than no pre-processing for both quiet and noise conditions (Dawson et al, 2004).

## Autosensitivity Control™ (ASC)

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 Ltd, 2010).

The microphone sensitivity determines the amount of sound in the environment that the microphone will amplify and deliver to the CI user's EDR. If the sensitivity is increased, the microphones will detect lower level sounds in the environment, allowing the user to hear sounds that are farther away. If the sensitivity is decreased, the microphones will detect only higher sound levels in the environment, therefore capturing sounds that are closer to the user (assuming those are the loudest in intensity). Increasing or decreasing sensitivity will increase or decrease the AGC kneepoint, the input level above which compression occurs. The sensitivity and AGC kneepoint are inversely related (Patrick et al, 2006). If the microphone sensitivity is decreased, the AGC kneepoint is increased and the IIDR is shifted upwards. Thus low-level acoustic sounds falling below the kneepoint will not be mapped onto the CI user's EDR and will likely be inaudible. If the microphone sensitivity is increased, the AGC kneepoint is decreased and the IIDR shifts downwards. This allows low-level input to be mapped to the EDR resulting in better access to low-level sounds (Patrick et al, 2006).

Without ASC (and with the speech processor sensitivity set at the manufacturer default of 12), the microphones pick up acoustic stimuli between 25 and 65 dB SPL, mapping those sounds to the CI user's EDR in a linear manner (Dillon, 2001; Gifford et al, 2011). If the intensity of the sound exceeds 65 dB SPL, the sound is compressed (i.e. amplification becomes non-linear) to allow higher level sounds to be mapped in the CI user's EDR without being amplified to an uncomfortable listening level. 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). Low-level sounds below 25 dB SPL are not mapped to the CI user's EDR.

With ASC, the input noise level and the signal-to-noise ratio (SNR) are assessed and then used to manipulate the speech processor's microphone sensitivity (Cochlear Limited, 2010; Gifford et al, 2011). Unlike ADRO®, which adjusts the output on a channel-by-channel basis, ASC affects the entire frequency range captured by the microphones (Gifford et al, 2011). When ASC is enabled, the sensitivity of the speech processor microphones are automatically decreased when the sound in the environment surpasses 57 dB SPL (the manufacturer default). As the sound level in an environment increases above 57 dB SPL, the sensitivity continues to decreases incrementally. This allows the spectral peaks of speech to surpass the long-term average speech spectrum by 15 dB SPL before they are affected by infinite compression (Cochlear Ltd, 2009). However, in unfavorable SNRs this cannot be guaranteed. In quiet conditions (below 57 dB SPL) ASC is inactive (Wolfe et al, 2011a). The purpose of ASC is to allow the desirable speech signal to be captured while avoiding infinite compression in the presence of moderate to high-level background noise (Wolfe et al, 2009).

## Utilizing Pre-Processing Strategies

Recent research has supported the default pre-processing setting for pediatric CI programming as ASC+ADRO® (Gifford et al, 2011; Wolfe et al, 2011b). In combination, ASC works to improve speech intelligibility and comfort in background noise while ADRO® works to position low and moderate level speech stimuli into a CI user's audible range.

Wolfe et al (2011b) examined the use of ADRO® only and ASC+ADRO® as pre-processing strategies for 11 children ranging in age from 4.4 to 12.0 years and using the Freedom or CP810 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) using list pairs at 75 dB SPL to compare the two different pre-processing conditions. Wolfe et al (2011b) reported 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® with twenty-two participants ranging in age from 5.6 to 16.8 years who used Freedom or CP810 external speech processors. Participants completed the adaptive Hearing in Noise Test (HINT) sentences in the R-Space with noise at 72 dB A. The results of this study showed that participants performed significantly better when using ASC+ADRO® versus ADRO® alone, with a mean improvement in SNR of 3.5 dB achieved when tested in the ASC+ADRO® condition compared to the ADRO® condition (Gifford et al, 2011).

Based on these results, ASC+ADRO® is the recommended setting for the everyday program in children's speech processors (Gifford et al, 2011; Wolfe et al, 2011b). However, these studies did not include information about how the participants' processors were programmed regarding T and C levels and did not report on audibility, as measured through the cochlear implant in the sound field. It is possible that different programming protocols could affect the benefit of pre-processing strategies for individual CI users.

Results from a recent study in adults, detailing programming techniques that focused on optimizing audibility, has provided differing recommendations for the application of ADRO®. Brockmeyer and Potts (2011) tested 30 adults. All participants were tested with the adaptive HINT sentences in the R-Space (noise at 60 and 70 dB SPL) using the Freedom speech processor in four pre-processing conditions: no pre-processing active, ADRO®, ASC, and Beam®. The study found that the ASC condition resulted in the best speech recognition in the presence of high level (70 dB SPL) background noise (mean reception threshold for sentences (RTS) 9.5 dB). No significant difference was seen between the mean RTS of ASC and Beam in the high-level background noise condition. Participants performed best with Beam® (mean RTS 8.3 dB) in the moderate noise condition (60 dB SPL); however, no statistical difference was observed between Beam® and ASC in the moderate level background noise condition. The authors suggest that ASC should be used when the CI user is in high or moderate level background noise to allow for the greatest speech understanding and that Beam® can be beneficial in moderate noise levels. ADRO® was not recommended based on a poorer RTS results for this pre-processing strategy (mean RTS 12.8 dB) (Brockmeyer and Potts, 2011).

Of note, Beam® is not typically a recommended pre-processing strategy for children's everyday maps due to the attenuation of sounds from behind and to the sides of the CI user. Due to constant opportunities for incidental language learning and over hearing in the environment, children are typically set with omnidirectional microphones.

As Brockmeyer and Potts (2011) did not apply combinations of pre-processing strategies, Potts and Kolb (2014) completed a follow up study examining the effectiveness of pre-processing strategy combinations for adaptive HINT Sentences in the R-Space for 32 adult CI users, again detailing a specific programming protocol focused on optimization of audibility. In this study a CP810 processor was used for all testing. HINT sentences were presented in the R-Space to participants with an adaptive presentation level in the presence of a constant restaurant 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) RTS while the Zoom only condition yielded the highest (worst) RTS.

Notably, when ADRO® was used in combination with other pre-processing conditions, it revealed significantly poorer performance (increased RTS). In previous studies the poorest scores were seen when ADRO® alone was utilized compared to ASC or ASC+ADRO® (Gifford and Revit, 2010; Brockmeyer and Potts, 2011; Wolfe et al, 2011b). Potts and Kolb (2014) suggest that ADRO® may be detrimental for participants in their study due to the programming protocol used (i.e. Skinner, 2003). For participants in this study, EDRs were carefully established by setting T levels at either 100% detection or above and setting well defined Cs at a "loud but comfortable" perceptual level. With the T levels set to provide maximum audibility of low-level sounds and ADRO® working to optimally place low and moderate level sounds in the upper range of the CI user's EDR, implementation of ADRO® with this programming method may have made detrimental adjustments by introducing more compression to the stimuli based on the statistical rules that it follows (Potts and Kolb, 2014). Also, it is possible that when both loud levels of noise and speech are present, ADRO® applies over-compression resulting in a comfortable perceived volume for the CI user, but with degraded speech understanding (Potts and Kolb, 2014). These studies provide contradictory recommendations compared to those of Wolfe et al (2011b) and Gifford et al (2011).

The purpose of the present study is to compare pediatric speech perception performance across various pre-processing strategies (no pre-processing active, ADRO®, ASC, or ASC +ADRO®). The results of this study will provide evidence to support current default pre-processing selections for pediatric CI users programmed following the protocol outlined above.

## MATERIALS AND METHODS

This is a prospective, cross-sectional, observational study and is approved by the Human Research Protection Office at Washington University School of Medicine (#201210075).

### Participants

Eleven pediatric CI users ranging in age from 8.08 to 17.33 years (mean 12.62 years, standard deviation (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). Demographic information is specified in Table 1. For those with bilateral CIs, speech perception 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. Although bimodal participants were not tested in their everyday device configuration, the CI ear was tested alone in order for results to reflect pre-processing effects without introducing complex interactions with hearing aid noise reduction algorithms.

Each participant used a Cochlear Ltd. CI24R, CI24RE, CI512, or CI422 internal system with either a Freedom (7 of 11 participants) or CP810 (4 of 11 participants) external speech processor for daily use. 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®. All participants used the Advanced Combination Encoder (ACE) speech coding strategy. Participants' mean EDRs ranged from 25.00 to 61.29 clinical units (mean 41.36 clinical units, SD 10.93). 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 mean 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. Participants' clinically measured CNC scores for stimuli presented at 60 dB SPL ranged from 72–94%. Information about CI programming parameters and usage are reported in Table 2.

Participants were recruited from the clinical population at SLCH and must have scored at least 50% on a CNC word list at an average conversational intensity level (60 dB SPL) in quiet. All SLCH patients using a Cochlear Ltd. device that met this requirement were contacted via a letter mailed to their residence and a phone call. Interested patients and families were then scheduled for the test session. All participants had their CI processor(s) programmed within 6 months of the research testing by their managing SLCH audiologist using the specific programming protocol that was previously described.

## Procedures

All participants were tested with consignment CP810 speech processors. The processors were preloaded with each participant's current optimized everyday program. For the seven participants that used a Freedom speech processor, his or her program was converted to maps with the same T and C Levels for a CP810 processor before being downloaded to the consignment processor. Four equivalent programs were set in the processor for each participant with the different pre-processing strategies applied: no pre-processing, ADRO®, ASC, and ASC+ADRO® in positions one through four, respectively. All participants used the speech processor with volume set at 10 and sensitivity set at 12. No programming changes were made for any participants.

All testing was completed in one, three-hour test session in a double-walled sound treated booth (8′3″ × 8′11″). Test measures included aided CI sound field thresholds, CNC words in quiet presented at 50 and 70 dB SPL, and adaptive HINT Sentences (Nilsson et al, 1994) in 60 and 70 dB SPL of R-Space noise. Randomization was applied across the test protocol for speech perception measures in addition to the order of pre-processing conditions. In total, each participant completed 16 test conditions. Although participants were blinded to which pre-processing strategy was applied during the test conditions, the examiners were aware, as they were in control of changing the processor programs.

Aided sound field thresholds were obtained with the participant facing the loudspeaker (Urei Model 809) at 0° azimuth while sitting approximately one meter away listening for FM tones at 250, 500, 750, 1000, 2000, 3000, 4000, and 6000 Hz. These were obtained utilizing a modified Hughson-Westlake procedure with a +2/−4 dB step size (Carhart and 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 appropriate aided threshold levels for each CI. See Figure 1 for mean aided sound field threshold results. Participants' thresholds fell between 6 and 32 dB HL. Within the group there was only one individual with 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.

The Consonant-Nucleus-Consonant (CNC) monosyllabic word list recordings are comprised of 50 monosyllabic words recorded by a male talker (Peterson and Lehiste, 1962). These lists were presented in quiet at of 50 dB SPL and 70 dB SPL with the participant facing the loudspeaker at 0° azimuth while sitting approximately one meter away in each of the four conditions: no pre-processing, ADRO®, ASC, and ASC+ADRO®. Word lists were randomized for each presentation level and each pre-processing condition. The participant repeated the word that was perceived after each presentation and the score was calculated as percent words correct.

Testing in noise was conducted by presenting HINT sentences adaptively in the R-Space, a specific setup where eight speakers are positioned 360° around the participant (Revit et al, 2002; Revit et al, 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 was seated and centered in the middle, with each speaker 24 inches away (Compton-Conley et al, 2004). 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. This creates a realistic, diffuse, uncorrelated noisy listening environment consisting of people talking, dishes clanking, and other sounds typically heard in a restaurant (Compton-Conley et al, 2004).

The HINT sentences are comprised of sets of two phonetically balanced lists with 10 sentences each, presented by a recorded male talker (Nilsson et al, 1994). The HINT sentences were presented adaptively at 0° azimuth to the participant and the restaurant noise was presented through all speakers at a fixed level of 60 and 70 dB SPL. 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 lower in intensity level; an incorrect response caused the following sentence stimuli to get higher in intensity level).

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 initial SNR was set at the easiest SNR for each condition (70 versus 60 dB SPL) that was available with the given software parameters. The lowest level at which the participant can correctly repeat the sentence back in its entirety is used to establish his or her score as an 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).

### Data Analysis

When comparing each pre-processing strategy for the group data, a repeated-measures analysis of variance (ANOVA) was used. If the data violated the assumption of sphericity, Greenhouse-Geisser values are reported. After significance was determined, a post-hoc analysis using the Bonferroni correction was performed to determine which conditions were different. Due to the relatively small number of participants (11), effect size and precision of estimate for the significant results were then calculated. A raw score mean difference and the 95% Confidence Interval, with Bonferroni correction is provided.

For each individual participant, scores obtained with each pre-processing strategy were compared to the baseline condition of no pre-processing 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 (2007) were used. The critical differences are the 95% confidence intervals around the mean percent correct score for the baseline condition for a given list length, based on the binomial distribution.

For adaptive 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).

The effects of possible demographic variables that are known to affect outcome measures in children with CIs, i.e. age at test and duration of CI use (Nicholas and Geers, 2006; Nicholas and Geers, 2007; Holt and Svirsky, 2008) were examined using correlational analyses.

## RESULTS

Figure 2 displays results of the CNC words presented at 50 dB SPL in quiet for which analysis of group data revealed a significant effect for pre-processing condition [$F(1.5,15.4) = 11.47$, $p<.01$]. The ASC+ADRO® condition resulted in the best speech perception scores with a mean percentage correct of 71.5%. The ADRO® condition followed with a mean percent correct of 66.5%. The no pre-processing and ASC conditions yielded the lowest speech perception results with scores of 60.4 and 59.6%, respectively. Bonferroni post-hoc comparisons revealed that scores for ASC+ADRO® were significantly better than all other conditions ($p<.05$). ASC resulted in significantly poorer scores than ADRO® ($p=.001$) and ASC+ADRO® ($p<.001$). Effect size and precision of estimate for the perception of mean CNC word lists presented at 50 dB SPL improves by 11% (1–21%) when using ASC +ADRO® as opposed to no pre-processing.

Individual participant data for CNC words presented at 50 dB SPL is shown in Figure 3. This data was analyzed based on the binomial model (Carney and Schlauch, 2007). Nine participants did not show a significant advantage for one pre-processing condition over another. Two participants performed significantly better with ASC+ADRO® compared to no pre-processing; participant 5 (P5) performed significantly better with ASC+ADRO® when compared to no pre-processing (70% compared to 48%, respectively), and P7 performed significantly better with ADRO® (68%) and ASC+ADRO® (72%) than with no pre-processing (44%).

Figure 4 displays group results of the CNC words presented at 70 dB SPL in quiet. Post-hoc tests for group data did not show any significant differences between pre-processing. All conditions for group means had percent words correct in the 77–82% range.

Individual participant data, seen in Figure 5, again showed that the pre-processing strategy that yielded the highest percent words correct varied across participants. Ten participants did not show a statistically significant difference in scores between pre-processing conditions. Only one participant (P10) showed a significant decrease in percent words correct when using ASC (84%) compared to no pre-processing (96%).

Figure 6 displays group results of the adaptive HINT sentences in the R-Space with 60 dB SPL of noise. A lower SNR indicates better speech perception in noise. Mean SNRs ranged from 4.78 to 6.24 dB, with ADRO® yielding the lowest mean SNR and ASC+ADRO® yielding the highest SNR. ASC and no pre-processing had SNRs of 5.61 and 6.00 dB, respectively. For the mean group data no significant differences were seen.

Individual participant data, seen in Figure 7, showed that the pre-processing strategy that yielded the lowest SNR varied across participants. All participants had at least one significantly different score within the pre-processing conditions tested. 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 8 displays group results of the adaptive HINT sentences in the R-Space with 70 dB SPL of noise. For the group data, results from the ANOVA revealed a significant effect for pre-processing condition [$F(3,30) = 10.99$, $p<.001$]. ASC+ADRO® had the lowest (best) mean score (3.47 dB) followed by ASC (4.78 dB) then ADRO® (5.65 dB). The condition with no pre-processing had the highest (worst) mean score (7.56 dB). Bonferroni post-hoc comparisons revealed that scores for ASC ($p=.003$) and ASC+ADRO® ($p=.002$) were significantly better than no pre-processing. ASC+ADRO® ($p=.028$) was significantly better than ADRO®. Effect size and precision for the significant differences were calculated for this test condition and revealed that mean SNRs for this test condition improved by 4.2 dB (1.9 – 6.5 dB) when using ASC+ADRO® as opposed to no pre-processing. Also, mean SNRs improve by 3.0 dB (1.5 – 4.6 dB) when using ASC as opposed to no pre-processing.

Individual participant data, seen in Figure 9, showed that the pre-processing strategy that yielded the lowest SNR varied across participants. All participants yielded scores that were significantly different from one or more of their other pre-processing conditions. 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®.

No significant correlations were seen between duration of CI use and participants' average scores on test conditions or age of participants at time of testing and test condition. Additionally, a pattern with participants' previously used pre-processing strategy and their best pre-processing condition was not observed. Table 3 shows the participants' previously used pre-processing strategy and their best pre-processing condition per test measure. All participants demonstrated discrepancies between the pre-processing strategy they utilized prior to the study compared to which pre-processing strategy they performed best with for the different test conditions. Individual variability was seen when comparing all participants' best pre-processing strategies. Also, individual participants varied in regards to which pre-processing strategy they performed best with for the different test conditions.

## DISCUSSION

The aim of this study was to determine if the current default pre-processing strategy combination of ASC+ ADRO® is appropriate for pediatric CI users with T levels set at or above 100% detection in order to obtain aided CI sound field thresholds better than 30 dB HL. Supporting evidence for using this default combination with these programming techniques is necessary given that a group of adults mapped using the same counted T level programming protocol performed more poorly when ADRO® was used with combinations of pre-processing strategies (Potts and Kolb, 2014). The authors discuss the possibility that the EDR obtained using counted T levels may interact negatively with the audibility and comfort rules implemented by ADRO®. Additionally, the pediatric studies supporting the use of ASC+ADRO® did not specify the exact fitting protocol used for obtaining T and C levels.

For this population, group data revealed that when CNC words were presented at a high intensity level of 70 dB SPL in quiet, participants did not show a statistical advantage or disadvantage for one pre-processing strategy over another. This is not surprising given that group scores for all pre-processing conditions resulted in high levels of speech understanding in quiet.

Similarly, sentence recognition in noise measured via adaptive HINT sentences in 60 dB SPL of R-Space noise did not yield statistical significance among any of the pre-processing conditions. Although not statistically significant, it is interesting to note that SNRs obtained with ADRO® were better than those obtained with ASC+ADRO®. As ASC is implemented to help with speech understanding in the presence of background noise, it is notable that ASC+ADRO® did not result in better speech perception on this measure. It is possible that with a larger number of participants, the group mean scores for this test condition may have reached significance.

Participants performed significantly better with ASC+ADRO® compared to any other pre-processing strategy for recognition of CNC words at a low presentation level of 50 dB SPL in quiet. For this test condition, participants performed significantly worse with ASC compared to ADRO® or ASC+ADRO®. As previously stated, ASC works to improve speech perception in noise (Wolfe et al, 2009). Since this test condition was performed in quiet, background noise likely never exceeded 57 dB SPL. Therefore ASC was not active and the microphone sensitivity may never have changed. The ASC only condition acted more like the no pre-processing condition. In fact, group mean scores for ASC and for no pre-processing were not significantly different. Also, in the ASC only condition, ADRO® was not active to better place the low-level stimuli in the CI users EDR.

Performance on adaptive HINT sentences in 70 dB SPL of noise revealed that ASC +ADRO® resulted in significantly better scores than no pre-processing or ADRO®. This is likely due to the constant microphone sensitivity setting in the no pre-processing and ADRO® conditions. Without ASC active, the microphone sensitivity never adjusted to the high level of background noise that was presented. ASC yielded significantly better SNRs than no pre-processing. This may be explained due to the benefits seen when ASC is active in the presence of background noise. It is likely that with no pre-processing active in this condition that the noise and the sentence stimuli were infinitely compressed into the CI users EDR. This results in difficulty with speech perception.

Interesting to note, individual participant scores for CNC word lists presented in quiet yielded far fewer significant results than adaptive HINT sentences presented in diffuse background noise. This may be attributed to the increased difficulty of listening in noise. Results from adult and pediatric CI studies have demonstrated that listening in background noise produces a greater degradation in speech perception scores compared to listening at low levels (Firszt et al, 2004; Davidson et al, 2011). The mean word recognition score for a group of 112 pediatric CI participants from the Davidson et al (2011) study decreased 13 percentage points (60% to 47%) when testing at 70 dB SPL versus 50 dB SPL respectively. However the group mean sentence score decreased from 28 percentage points (80% to 52%) for sentences presented in quiet versus multi-talker background noise presented at +8 dB SNR. For the current study, the adaptive HINT sentences in the R-Space presented a more challenging task compared to listening in quiet, even at low presentation levels. It is also possible that the different analyses were a factor. Significant differences in CNC word scores are determined based off of the binomial distribution model. Significant differences for HINT sentences are established by a set critical difference.

Another interesting finding from this study is that for the adaptive HINT sentences in the R-Space, ASC+ADRO® resulted in the best SNR when the noise was presented at 70 dB SPL, in contrast with no significant difference among pre-processing strategies when the noise was presented at 60 dB SPL. One could speculate that this is related to the fact that while ASC was activated in each scenario it was most restrictive when 70 dB SPL of noise was presented. This would allow for less of the R-Space noise to be captured (as there are peaks and valleys to the intensity of the various sounds captured in that noise signal). Additionally, with the same SNR, the speech signal is 10 dB louder when noise is presented at 70 dB SPL versus 60 dB SPL (i.e. +6 dB SNR for R-Space noise presented at 60 dB SPL puts the sentence stimuli at 66 dB SPL and a +6 dB SNR for R-Space noise presented at 70 dB SPL puts the sentence stimuli at 76 dB SPL). With the combination of more noise restriction from ASC and higher speech signal intensity when R-Space noise is at 70 dB SPL, the users may have been able to gain more benefit from ASC+ADRO® compared to when noise was at a lower level of 60 dB SPL for this same measure. Other factors affecting this outcome could include statistical limitations due to the small sample size and variability in this study and relative difficulty of the task. Listening in 70 dB SPL is more difficult than listening in 60 dB SPL of noise. The participants may have relied on the effects of the pre-processing strategies more during the 70 dB SPL noise conditions.

For the most difficult measures in quiet and in noise, ASC+ADRO® improved group performance compared to the no pre-processing and ADRO® only conditions. The results from this study are in agreement with results from Gifford et al (2011) and Wolfe et al (2011b) demonstrating an advantage for ASC+ADRO® when listening to speech in background noise. Gifford et al (2011) and Wolfe et al (2011b) reported that participants performed significantly better in noise in the ASC+ADRO® condition than the ADRO® alone condition. In the current study, even though ASC+ADRO® was not found to significantly benefit participants in each test condition (i.e. CNC words at 70 dB SPL and adaptive HINT sentences in 60 dB SPL of noise), ASC+ADRO® did not significantly decrease scores in any condition.

Brockmeyer and Potts (2011) and Potts and Kolb (2014) programmed adult participants using a similar programming protocol to the one followed in the current study. Brockmeyer and Potts (2010) tested adults using adaptive HINT sentences in the R-Space in 60 and 70 dB SPL of noise. The authors found that adult participants performed best with ASC at 70 dB SPL of R-Space noise. In the current study, similar results were found: ASC yielded significantly better SNRs than no pre-processing in the same test condition. The combination of ASC+ADRO® was not evaluated in the Brockmeyer and Potts (2011) study.

In the subsequent study, the findings from Potts and Kolb (2014) stated that the combination of Zoom+ASC yielded the best RTS (measured as SNR) for adaptive HINT sentences presented in 70 dB SPL of R-Space noise. Also, the authors found that the addition of ADRO® to another pre-processing strategy significantly decreased participants' speech recognition in noise. This detriment seen with the addition of ADRO® was not replicated in the current study. Notably ASC+ADRO® benefited the pediatric participants listening to speech in higher levels of noise (70 dB SPL) and to words at a low presentation level (50 dB SPL). Potts and Kolb (2014) attributed the adverse effects seen when ADRO® was added to other pre-processing strategies to excessive compression due to a reduced EDR (higher T levels). Adult participants in that study had T levels programmed at or above 100% detection, which mirrors the T levels applied to the pediatric population in the current study. In theory, these higher T level settings led to distortion of the speech signal when the ADRO® rules were active. This discrepancy between study results may be explained by research that has shown that children typically utilize higher C levels than adults (Hughes et al, 2000; Weberling et al, 2011). Even though a similar programming protocol was used, the children likely preferred higher C levels than the adults, allowing them to utilize a larger EDR despite having raised T levels. 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. This difference in study results highlights the importance of studies completed with both the adult and pediatric population.

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 this 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.

For this study, individual data varied across measures and within participants. Therefore, while this data supports the recommendation of ASC+ADRO® as the default everyday setting for children, a variety of pre-processing strategies should be considered on an individual level. If a CI user is not achieving the expected progress or complains of difficulty understanding speech at low levels or in the presence of background noise, an alternative pre-processing strategy should be evaluated. In addition to speech perception testing in the clinic, this evaluation could include a trial period for several programs employing different pre-processing strategies to be used in the child's everyday environments. Patient report should be considered regarding pre-processing preference and sound quality. It should also be noted that even if a CI user performs better with ASC+ADRO®, if he or she was previously using a different pre-processing strategy, the CI user may be reluctant to change pre-processing strategies due to differences in sound quality. The CI user may need to be strongly counseled towards accepting an acclimatization period.

The main limitation to the current study is the small sample size. Conducting the study with a greater number of participants may reveal differences between pre-processing strategies that were not detected with this smaller sample size. Also, the test measures in this study, such as sentence recognition in R-Space noise, attempt to replicate real-world situations; however these measures were performed in a controlled laboratory setting. Therefore, there may be differences in performance with these pre-processing strategies encountered in the real-world that could not be replicated in this study.

## CONCLUSION

Based on the results from this study, it is recommended that pediatric CI recipients 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 found to significantly improve speech recognition in difficult listening situations, i.e. in quiet at a low intensity level and in noise at a high intensity level, it would be advantageous to apply it to everyday situations.

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/EDR. Further information may reveal predictive variables as to which pre-processing strategy may be most beneficial for specific individuals.

## Acknowledgments

We acknowledge Dorina Kallogjeri, MD, MPH for her statistical support and the support of the P30 Research Center for Auditory and Vestibular Studies and the National Institutes of Health (NIDCD Grant no. P30DC04665)

## Abbreviations

| | |
|---|---|
| **A** | A-weighting |
| **ADRO®** | Adaptive Dynamic Range Optimization |
| **AGC** | automatic gain control |
| **ANOVA** | analysis of variance |
| **ASC** | Autosensitivity Control |
| **C** | comfort level |
| **CI** | cochlear implant |
| **CNC** | Consonant-Nucleus-Consonant |
| **CUNY** | City University of New York |
| **dB** | decibel |

| | |
|---|---|
| **EDR** | electrical dynamic range |
| **FM** | frequency modulated |
| **HINT** | Hearing in Noise Test |
| **HL** | hearing level |
| **Hz** | hertz |
| **IIDR** | instantaneous input dynamic range |
| **IDR** | input dynamic range |
| **P** | participant |
| **RTS** | reception threshold for sentences |
| **SD** | standard deviation |
| **SLCH** | St. Louis Children's Hospital |
| **SNR** | signal-to-noise ratio |
| **SPL** | sound pressure level |
| **T** | threshold level |

## References


Blamey PJ, Martin FLA, Fiket HJ. A digital processing strategy to optimize hearing aid outputs directly. J Am Acad Audiol. 2004; 15:716–728. [PubMed: 15646669]

Blamey P. Adaptive dynamic range optimization (ADRO): a digital amplification strategy for hearing aids and cochlear implants. Trend Amplif. 2005; 9:77–98.

Brockmeyer A, Potts L. Evaluation of different signal processing options in unilateral and bilateral cochlear freedom implant recipients using R-space background noise. J Am Acad Audiol. 2011; 22:65–80. [PubMed: 21463562]

Carhart R, Jerger JJ. Preferred method for clinical determination of pure-tone thresholds. J Speech Hear Disord. 1959; 24:330–345.

Carney E, Schlauch RS. Critical difference table for word recognition testing derived using computer simulation. J Speech Lang Hear Res. 2007; 50:1203–1209. [PubMed: 17905906]

Cochlear Ltd. Custom Sounds 3.0. Sydney: Cochlear Limited; 2009.

Cochlear Ltd. Dual omni-directional microphone technology. Sydney, Australia: 2010. Cochlear N34480F ISS1 MAY10

Compton-Conley CL, Neuman AC, Killion MC, Levitt H. Performance of directional microphones for hearing aids: real-world versus simulation. J Am Acad Audiol. 2004; 15:440–455. [PubMed: 15341225]

Cosendai G, Pelizzone M. Effects of acoustical dynamic range on speech recognition with cochlear implants. Int J Audiol. 2001; 40:272–281.

Davidson LS, Skinner MW, Holstad BA, et al. The effect of instantaneous input dynamic range on the speech perception of children with the Nucleus 24 implant. Ear Hearing. 2009; 30:340–349. [PubMed: 19322085]

Davidson LS, Geers AE, Blamey PJ, Tobey EA, Brenner CA. Factors contributing to speech perception scores in long-term pediatric cochlear implant users. Ear Hear. 2011; 32:19S–26S. [PubMed: 21832887]

Davidson LS, Geers AE, Nicholas JG. The effects of audibility and novel word learning ability on vocabulary level in children with cochlear implants. Cochlear Implants Int. 2014; 15:211–221. [PubMed: 23998324]

Dawson PW, Decker JA, Psarros CE. Optimizing dynamic range in children using the Nucleus cochlear implant. Ear Hear. 2004; 25:230–241. [PubMed: 15179114]

Dawson PW, Vandali AE, Knight MR, Heasman JM. Clinical evaluation of expanded input dynamic range in Nucleus cochlear implants. Ear Hear. 2007; 28:163–176. [PubMed: 17496668]

Dillon, H. Hearing Aids. New York: Theime Medical Publishers; 2001.

Donaldson GS, Allen SL. Effects of presentation level on phonemes and sentence recognition in quiet by cochlear implant listeners. Ear Hear. 2003; 24:392–405. [PubMed: 14534410]

Fetterman BL, Domico EH. Speech recognition in background noise of cochlear implant patients. Otolaryngol Head Neck Surg. 2002; 26:257–263. [PubMed: 11956533]

Firszt JB, Holden LK, Skinner MW, et al. Recognition of speech presented at soft to loud levels by adult cochlear implant recipients of three cochlear implant systems. Ear Hear. 2004; 25:375–387. [PubMed: 15292777]

Gifford RH, Revit L. Speech perception for adult cochlear implant recipients in realistic background noise: effectiveness of preprocessing strategies and external options for improving speech recognition in noise. J Am Acad Audiol. 2010; 21:441–451. [PubMed: 20807480]

Gifford RH, Olund AP, DeJong M. Improving speech perception in noise for children with cochlear implants. J Am Acad Audiol. 2011; 22:623–632. [PubMed: 22192607]

Holden LK, Skinner MW, Fourakis MS, Holden RA. Effect of increased IIDR in the Nucleus Freedom cochlear implant system. J Am Acad Audiol. 2007; 18:777–793. [PubMed: 18354886]

Holden LK, Finley CC, Firszt JB, et al. Factors affecting open-set word recognition in adults with cochlear implants. Ear Hear. 2013; 34:342–360. [PubMed: 23348845]

Holt RF, Svirsky MA. An exploratory look at pediatric cochlear implantation: Is earliest always best? Ear Hear. 2008; 29:492–511. [PubMed: 18382374]

Hughes ML, Brown CJ, Abba PJ, Wolaver AA, Gervais JP. Comparison of EAP thresholds with MAP levels in the Nucleus 24 cochlear implant: data from children. Ear Hear. 2000; 21:164–174. [PubMed: 10777023]

James CJ, Blamey PJ, Martin L, Swanson B, Just Y, Macfarlane D. Adaptive dynamic range optimization for cochlear implants: a preliminary study. Ear Hear. 2002; 23:49S–58S. [PubMed: 11883767]

James CJ, Skinner MW, Martin LFA, Holden LK, Galvin KL, Holden TA, Whitford L. An investigation of input level range for the Nucleus 24 cochlear implant system: Speech perception performance, program preference, and loudness comfort ratings. Ear Hear. 2003; 24:157–173. [PubMed: 12677112]

Mueller HG, Killion MC. An easy method for calculating the articulation index. Hear J. 1990; 43:14–17.

Nelson PB, Jin S, Carney AE, Nelson P. Understanding speech in modulated interference: cochlear implant users and normal-hearing listeners. J Acoust Soc Amer. 2003; 113:961–968. [PubMed: 12597189]

Nicholas JG, Geers AE. Effects of early auditory experience of the spoken language of deaf children at 3 years of age. Ear Hear. 2006; 27:286–298. [PubMed: 16672797]

Nicholas JG, Geers AE. Will they catch up? The role of age at cochlear implantation in the spoken language development of children with severe to profound hearing loss. J Speech Lang Hear Res. 2007; 50:1048–1062. [PubMed: 17675604]

Nilsson M, Soli SD, Sullivan JA. Development of the hearing in noise test for the measurement of speech reception thresholds in quiet and in noise. J Acoust Soc Amer. 1994; 95:1085–1099. [PubMed: 8132902]

Patrick JF, Bugsby PA, Gibson PJ. The development of the Nucleus Freedom cochlear implant system. Trends Amplif. 2006; 10:175–200. [PubMed: 17172547]

Pavlovic CV, Studebaker GA, Sherbecoe RL. An articulation index based procedure for predicting the speech recognition performance of hearing-impaired individual. J Acoust Soc Amer. 1985; 80:50–57. [PubMed: 3745665]

Pavlovic CV. Articulation index prediction of speech intelligibility in hearing aid selection. ASHA. 1988; 20:63–65. [PubMed: 3401281]

Peterson GE, Lehiste I. Revised CNC lists for auditory tests. J Speech Hear Disord. 1962; 27:62–70. [PubMed: 14485785]

Potts LG, Kolb KA. Effect of different signal-processing options on speech-in-noise recognition for cochlear implant recipients with the Cochlear CP810 speech processor. J Am Acad Audiol. 2014; 25:367–379. [PubMed: 25126684]

Revit LJ, Schulein RB, Julstrom SD. Toward accurate assessment of real-world hearing aid benefit. Hear Rev. 2002; 9:34–38. 51.

Revit LJ, Killion MC, Compton-Conley CL. Developing and testing a laboratory sound system that yields accurate real-world results. Hear Rev. 2007; 4:54–62.

Skinner MW, Holden LK, Holden TA, Demorest ME, Fourakis MS. Speech recognition at simulated soft, conversational, and raised-to-loud vocal efforts by adults with cochlear implants. J Acoust Soc Amer. 1997; 101:3766–3782. [PubMed: 9193063]

Skinner MW, Holden LK, Holden TA, Demorest ME. Comparison of two methods for selecting minimum stimulation levels used in programming the Nucleus 22 cochlear implant. J Speech Lang Hear Res. 1999; 42:814–828. [PubMed: 10450903]

Skinner, MW.; Binzer, SB.; Potts, LG.; Holden, LK.; Aaron, RJ. Hearing rehabilitation for individuals with severe and profound hearing impairment: hearing aids, cochlear implants, and counseling. In: Valente, M., editor. Strategies for Selecting and Verifying Hearing Aid Fittings. New York: Thieme; 2002. p. 311-344.

Skinner MW. Optimizing cochlear implant speech performance. Ann Otol Rhinol Laryngol. 2003; 112:4–13.

Spahr AJ, Dorman MF. Performance of subjects fit with the Advanced Bionics CII and Nucleus 3G cochlear implant devices. Arch Otolaryngol Head Neck Surg. 2004; 130:624–628. [PubMed: 15148187]

Shapiro, WH. Device programming. In: Waltzman, SB.; Roland, JT., editors. Cochlear Implants. 2. New York: Theime; 2006. p. 133-144.

Weberling, LW.; Firszt, JB.; Reeder, RM.; Cadieux, J. Speech processor programs in children and adults with bilateral implants. Poster presented at the 13th Symposium on Cochlear Implants in Children for the International cochlear Implant Professional meeting; Chicago, Illinois. 2011 Jul 14–16.

Wilson BS, Finley CC, Lawson DT, Wolford RD, Eddington DK, Rabinowitz WM. Better speech recognition with cochlear implants. Nature. 1991; 352:236–238. [PubMed: 1857418]

Wolfe J, Schafer EC, Heldner B, Mülder H, Ward E, Vincent B. Evaluation of speech recognition in noise with cochlear implants and dynamic FM. J Am Acad Audiol. 2009; 20:409–421. [PubMed: 19928395]

Wolfe J, Hudson M, John A, Schafer EC. Evaluation of noise reduction technologies in a contemporary cochlear implant system. Hear J. 2011a; 64:36–43.

Wolfe J, Schafer EC, John A, Hudson M. The effect of front-end processing on cochlear implant performance of children. Otol Neurotol. 2011b; 32:533–538. [PubMed: 21436756]

Zeng FG, Grant G, Niparko J, et al. Speech dynamic range and its effect on cochlear implant performance. J Acoust Soc Am. 2002; 111:377–386. [PubMed: 11831811]

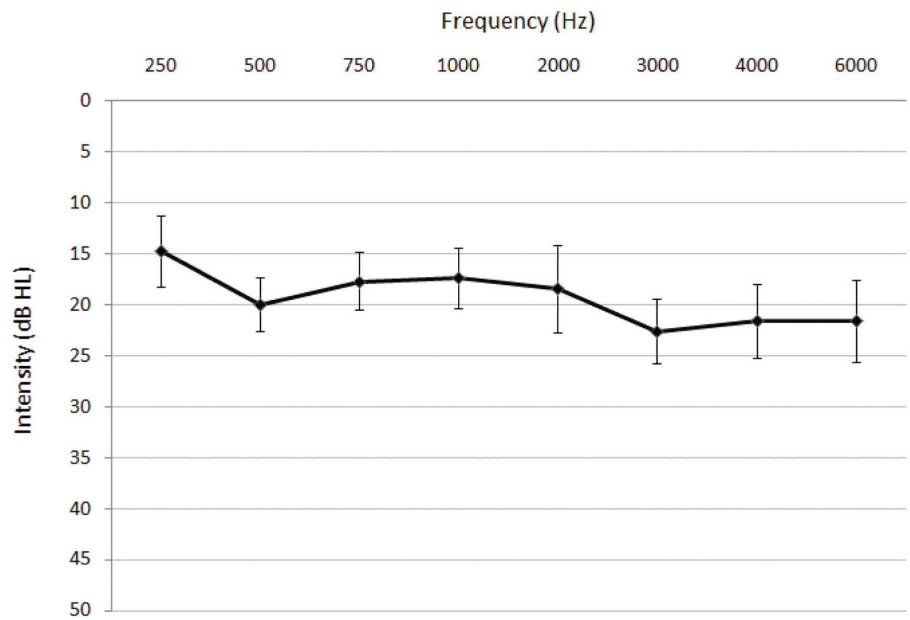


**Figure 1.**

Mean sound field thresholds (dB HL) for CI with no pre-processing active Includes +/− 1 standard deviation bars for group mean thresholds.

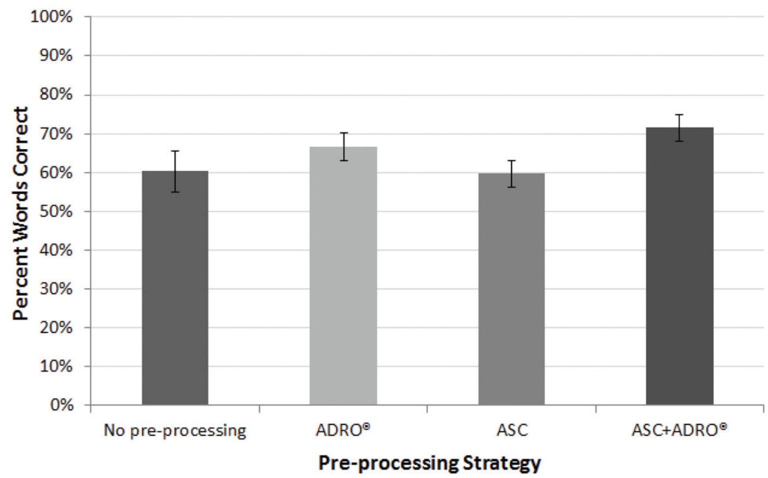


**Figure 2.**

Group results for CNC word lists presented at 50 dB SPL

Group mean percent correct scores for the CNC word lists presented at 50 dB SPL for the four pre-processing conditions: No pre-processing, ADRO®, ASC, and ASC+ADRO®. The asterisk denotes a statistically significant difference between conditions for group scores ($p<.05$). The - symbol denotes significantly worse results between conditions for group scores ($p\leq.001$). Group mean scores include standard error bars.

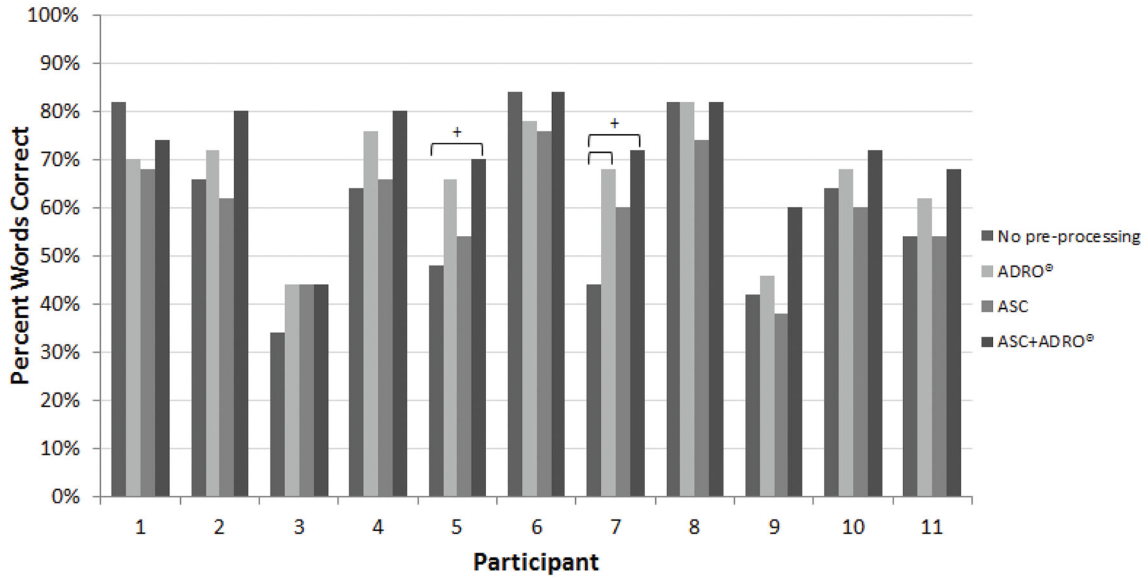


**Figure 3.**

Individual participant results for CNC word lists presented at 50 dB SPL

Individual participants' percent correct scores for the CNC word lists presented at 50 dB SPL for the four pre-processing conditions: No pre-processing, ADRO®, ASC, and ASC +ADRO®. The + symbol denotes a statistically significant difference in scores between conditions for a specific participant (p<.05).

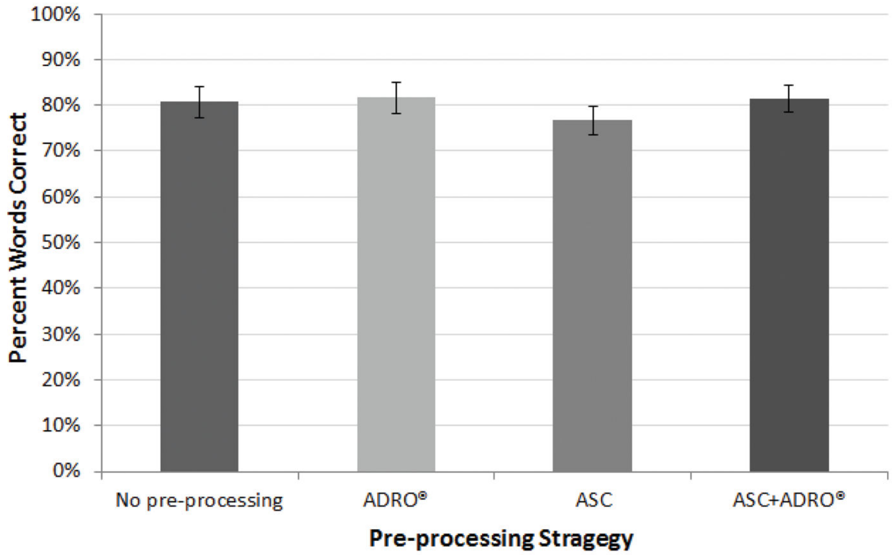


**Figure 4.**

Group results for CNC word lists presented at 70 dB SPL

Group mean percent correct scores for the CNC word lists presented at 70 dB SPL for the four pre-processing conditions: No pre-processing, ADRO®, ASC, and ASC+ADRO®. Group mean scores include standard error bars.

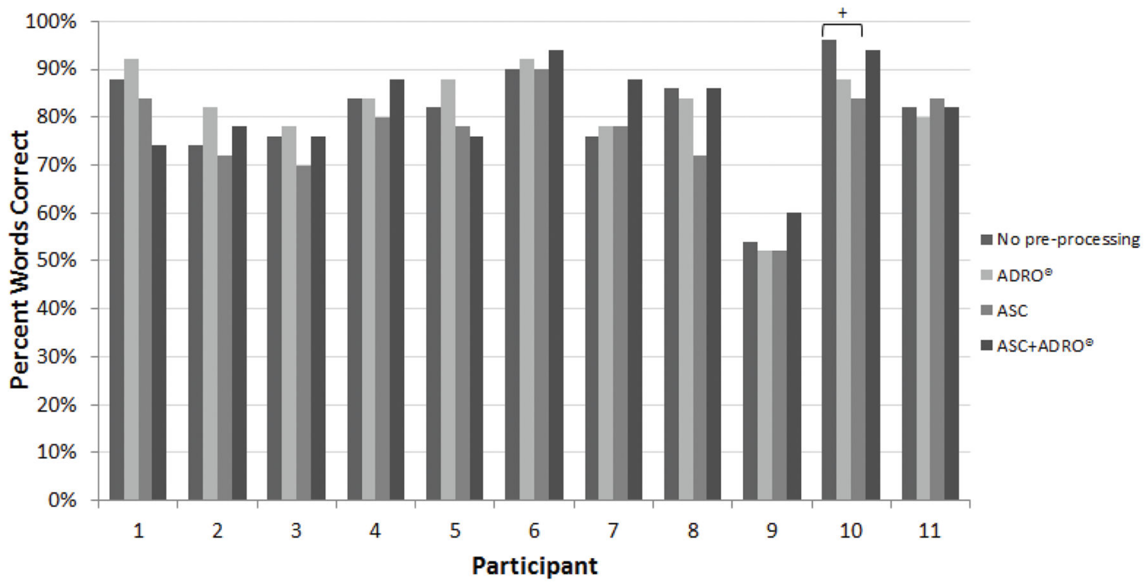


**Figure 5.**

Individual participant results for CNC word lists presented at 70 dB SPL

Individual participants' percent correct scores for the CNC word lists presented at 70 dB SPL for the four pre-processing conditions: No pre-processing, ADRO®, ASC, and ASC +ADRO®. The + symbol denotes a statistically significant difference in scores between conditions for a specific participant (p<.05).

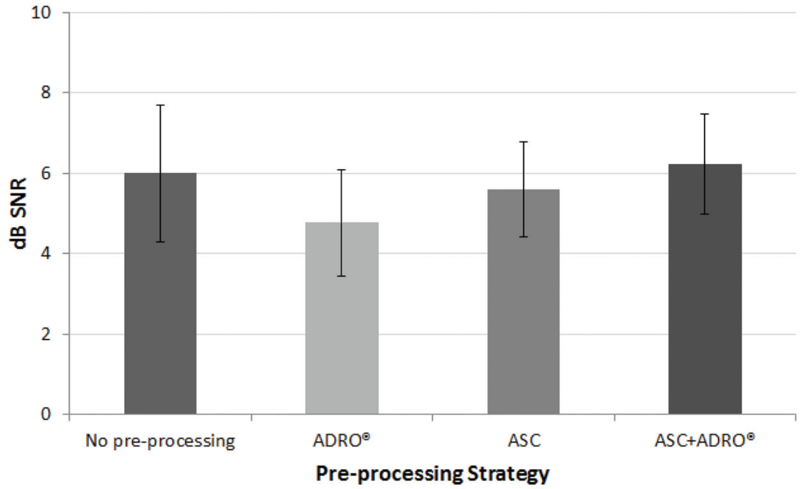


**Figure 6.**

Group results for HINT sentences presented adaptively in R-Space noise at 60 dB SPL Group mean SNR scores for the four pre-processing conditions: No pre-processing, ADRO®, ASC, and ASC+ADRO®. Group mean scores include standard error bars.

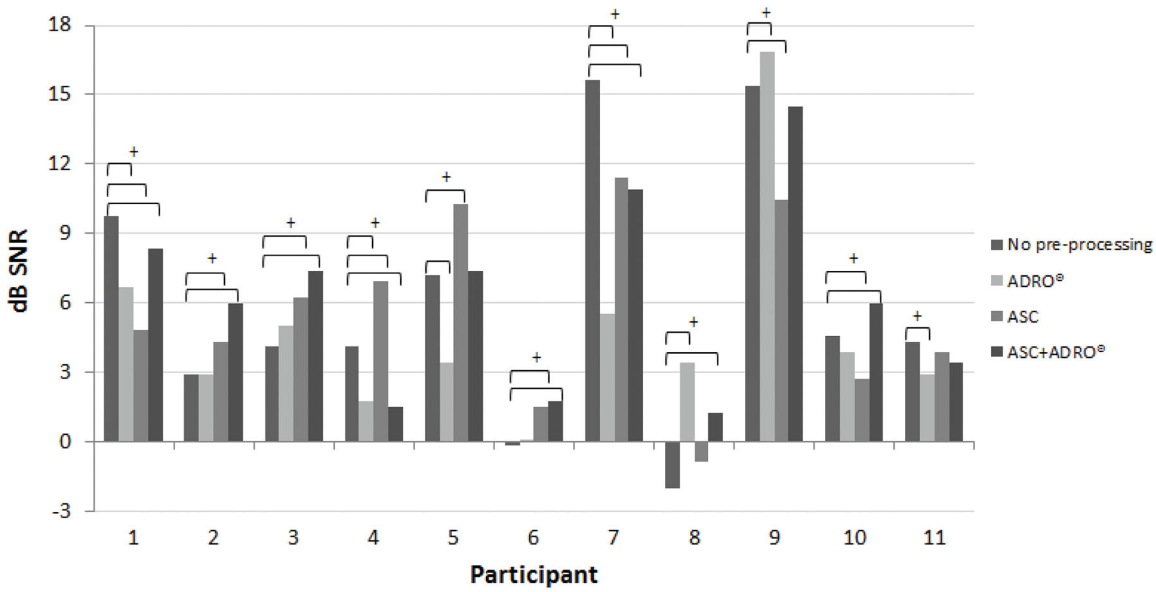


**Figure 7.**

Individual participant results for HINT sentences presented adaptively in R-Space noise at 60 dB SPL

Individual participants' SNR scores for the four pre-processing conditions: No pre-processing, ADRO®, ASC, and ASC+ADRO®. The + symbol denotes a statistically significant difference in scores between conditions for a specific participant (>1.4 dB critical difference).

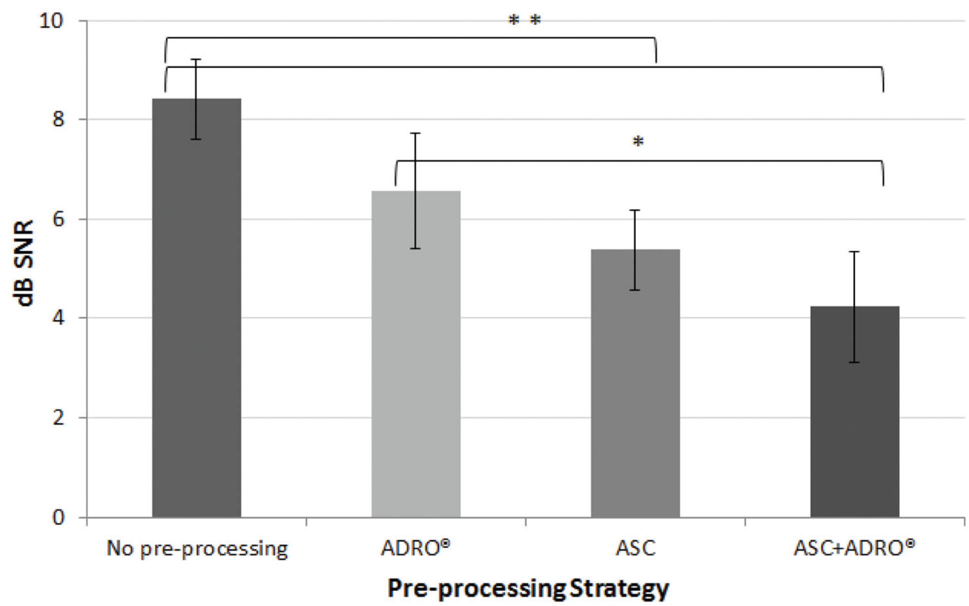


**Figure 8.**

Group results for HINT sentences presented adaptively in R-Space noise at 70 dB SPL Group mean SNR scores for the four pre-processing conditions: No pre-processing, ADRO®, ASC, and ASC+ADRO®. The asterisk denotes a statistically significant difference between conditions for group scores (p<.05). The double asterisks denote a statistically significant difference between conditions for group scores (p<.005). Group mean scores include standard error bars.

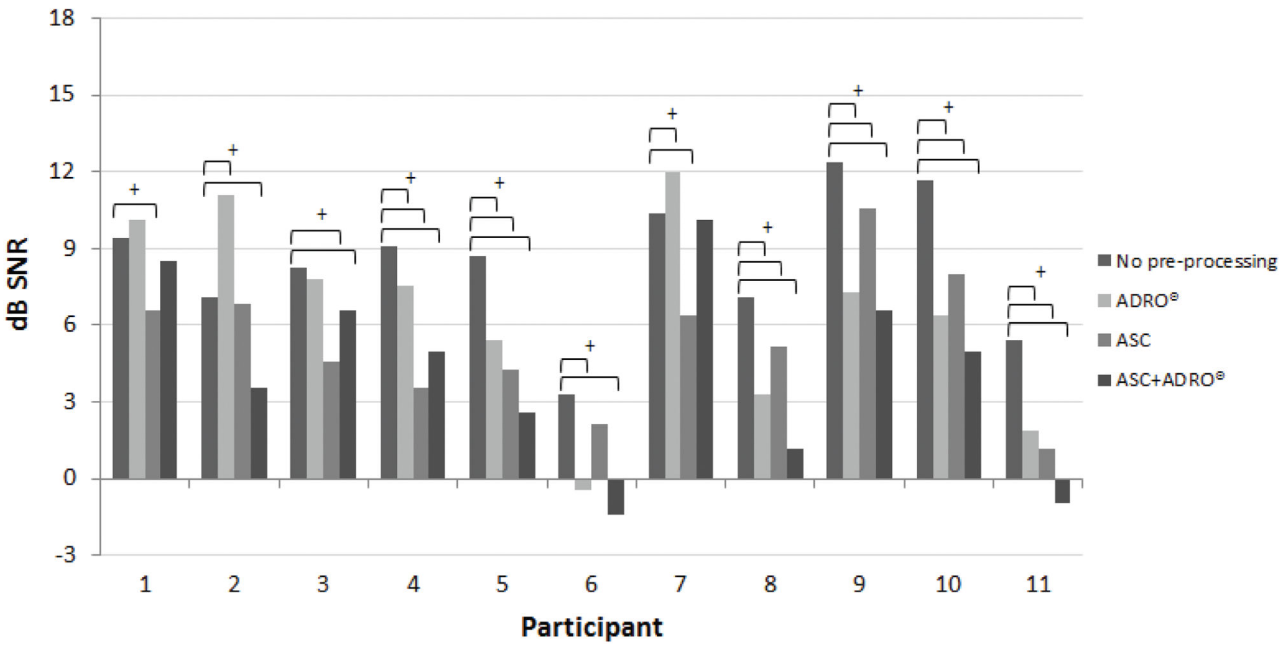


**Figure 9.**

Individual participant results for HINT sentences presented adaptively in R-Space noise at 70 dB SPL

Individual participants' SNR scores for the four pre-processing conditions: No pre-processing, ADRO®, ASC, and ASC+ADRO®. The + symbol denotes a statistically significant difference in scores between conditions for a specific participant (>1.4 dB critical difference).

## Table 1

Participant demographic information

| Participant | Age at Test (y) | Device Configuration | Implanted Ear | Etiology | Age at Implant (y) | Internal Device | Speech Processor |
|---|---|---|---|---|---|---|---|
| 1 | 17.33 | Bimodal | L | Unknown | 6.08 | CI24R | CP810 |
| 2 | 16.92 | Bilateral | B | Unknown | L-4.42; R-11.21 | L-CI24R; R-CI24RE | Freedom |
| 3 | 9.42 | Bimodal | L | EVA | 4.00 | CI24RE | Freedom |
| 4 | 13.66 | Bilateral | B | Unknown | L-2.83; R-8.50 | L-CI24R; R-CI24RE | Freedom |
| 5 | 12.25 | Bilateral | B | Unknown | R-1.75; L-7.33 | R-CI24R; L-CI24RE | Freedom |
| 6 | 10.66 | Bilateral | B | Unknown | 4.17 | R/L-CI24RE | CP810 |
| 7 | 17.08 | Bimodal | L | EVA | 8.33 | CI24R | CP810 |
| 8 | 13.17 | Unilateral | R | Unknown | 3.75 | CI24R | Freedom |
| 9 | 11.92 | Bimodal | L | Unknown | 5.17 | CI24RE | Freedom |
| 10 | 8.33 | Bilateral | B | EVA | L-6.33; R-7.92 | L-CI512; R-CI422 | CP810 |
| 11 | 8.08 | Bilateral | B | Unknown | L-1.25; R-2.00 | L/R-CI24RE | Freedom |

Note: y = years; L = Left; B = Both; R = Right; EVA = Enlarged Vestibular Aqueduct

## Table 2

Cochlear implant programming parameters and usage

| Participant | Current Pre-processing Strategy | Channel Rate | Maxima | Years of CI use since initial stimulation | Mean EDR in clinical units (1st ear stimulated) | Mean EDR in clinical units (2nd ear stimulated) |
|---|---|---|---|---|---|---|
| 1 | No pre-processing | 900 | 12 | 10.50 | 31.35 | |
| 2 | ADRO® | 900 | 8 | 12.50 | 32.36 | 25.00 |
| 3 | ASC+ADRO® | 900 | 10 | 6.00 | 44.95 | |
| 4 | ADRO® | 900 | 12 | 10.92 | 53.14 | 35.91 |
| 5 | ADRO® | 900 | 8 | 10.50 | 43.75 | 43.59 |
| 6 | ADRO® | 1200 | 12 | 6.50 | 27.14 | 25.00 |
| 7 | No pre-processing | 900 | 9 | 9.50 | 36.20 | |
| 8 | ADRO® | 900 | 12 | 9.42 | 50.18 | |
| 9 | ADRO® | 1200 | 12 | 6.75 | 47.77 | |
| 10 | ASC+ADRO® | 1200 | 10 | 3.00 | 49.77 | 40.77 |
| 11 | ASC+ADRO® | 1200 | 12 | 6.83 | 61.29 | 55.00 |

Note: ADRO® = Automatic Dynamic Range Optimization; ASC+ADRO® = Autosensitivity control and Automatic Dynamic Range Optimization; CI = Cochlear Implant; EDR = Electrical Dynamic Range

**Table 3**

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

| Participant | Everyday pre-processing (prior to study) | CNC at 50 dB SPL | CNC at 70 dB SPL | HINT at 60 dB SPL | HINT at 70 dB SPL |
|---|---|---|---|---|---|
| 1 | No pre-processing | No pre-processing | ADRO® | **ASC** | **ASC** |
| 2 | ADRO® | ASC+ADRO® | ADRO® | **No pre-processing, ADRO®** | **ASC+ADRO®** |
| 3 | ASC+ADRO® | ADRO®, ASC, ASC+ADRO® | ADRO® | **No pre-processing** | **ASC** |
| 4 | ADRO® | ASC+ADRO® | ASC+ADRO® | **ASC+ADRO®** | **ASC** |
| 5 | ADRO® | **ASC+ADRO®** | ADRO® | **ADRO®** | **ASC+ADRO®** |
| 6 | ADRO® | No pre-processing, ASC+ADRO® | ASC+ADRO® | **No pre-processing** | **ASC+ADRO®** |
| 7 | No pre-processing | **ASC+ADRO®** | ASC+ADRO® | **ADRO®** | **ASC** |
| 8 | ADRO® | No pre-processing, ADRO®, ASC+ADRO® | No pre-processing, ASC+ADRO® | **ASC+ADRO®** | **No pre-processing** |
| 9 | ADRO® | ASC+ADRO® | ASC+ADRO® | **ASC** | **ASC+ADRO®** |
| 10 | ASC+ADRO® | ASC+ADRO® | **No pre-processing** | **ASC+ADRO®** | **ASC** |
| 11 | ASC+ADRO® | ASC+ADRO® | ASC | **ADRO®** | **ASC+ADRO®** |

Note: Best pre-processing strategies (in bold) were found to be statistically significant at the individual level. Grey font indicates no significant differences among pre-processing strategies for that individual on that test measure. When two or more different pre-processing conditions are listed (i.e. P2 for HINT at 60 dB SPL) it means that both were significantly better than the others, but not different from one another. ADRO® = Automatic Dynamic Range Optimization; ASC+ADRO® = Autosensitivity control and Automatic Dynamic Range Optimization; CNC = Consonant-Nucleus-Consonant word list; ASC = Autosensitivity control; HINT = Hearing in Noise Test adaptively presented in the R-Space; dB SPL = decibels in sound pressure level