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Improving Localization and Speech Reception in Noise for Bilateral Cochlear Implant Recipients

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Abstract

This study looked at different methods to preserve interaural level difference (ILD) cues for bilateral cochlear implant (BiCI) recipients. One possible distortion to ILD is from automatic gain control (AGC). Localization accuracy of BiCI recipients using default versus increased AGC threshold and linked AGCs versus independent AGCs was examined. In addition, speech reception in noise was assessed using linked versus independent AGCs and enabling and disabling Autosensitivity™ Control. Subjective information via a diary and questionnaire was also collected about maps with linked and independent AGCs during a take-home experience. Localization accuracy improved in the increased AGC threshold and the linked AGCs conditions. Increasing the AGC threshold resulted in a 4° improvement in root mean square error averaged across all speaker locations. Using linked AGCs, BiCI participants experienced an 8° improvement for all speaker locations and a 19° improvement at the speaker location most affected by the AGC. Speech reception threshold in noise improved by an average of 2.5 dB when using linked AGCs versus independent AGCs. In addition, the effect of linked AGCs on speech in noise was compared with that of Autosensitivity™ Control. The Speech, Spatial, and Qualities of Hearing Scale-12 question comparative survey showed an improvement when using maps with linked AGCs. These findings support the hypothesis that ILD cues may be preserved by increasing the AGC threshold or linking AGCs.

Keywords

interaural level difference, automatic gain control, kneepoint, AGC threshold, autosensitivity

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Introduction

Bilateral cochlear implants (BiCIs) have proven advantageous over unilateral CIs to localize sounds and enhance speech understanding in noise (Dunn et al., 2010; Dunn, Tyler, Oakley, Gantz, & Noble, 2008; Seeber, Baumann, & Fastl, 2004; van Hoesel, Ramsden, & O'Driscoll, 2002; van Hoesel & Tyler, 2003), but there are still opportunities to improve binaural cues with two CIs. When compared with normal-hearing listeners, BiCI users still demonstrate large deficits in spatial hearing performance (Dorman et al., 2014; Jones, Kan, & Litovsky, 2014; Seeber & Fastl, 2008) and speech understanding in noise (Bronkhorst, 2000; Hawley, Litovsky, & Colburn, 1999; Loizou et al., 2009; van Hoesel & Tyler, 2003; Wilson & Dorman, 2008). For example, Dorman et al. (2014) found that on a localization task, BiCI users averaged 19.6° of root mean square (RMS) error, while normal-hearing listeners averaged only 8.3° of RMS error in the same stimulus condition.

Normal-hearing listeners use both interaural level difference (ILD) and interaural time difference (ITD) cues to localize sound in the horizontal plane. However, BiCI listeners primarily use ILD cues rather than ITD cues for localization (Bronkhorst, 2000; Laback, Pok, Baumgartner, Deutsch, & Schmid, 2004; van Hoesel, Böhm, & Pesch, 2008; van Hoesel et al.,

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2002; van Hoesel & Tyler, 2003). ITD cues are variable for CI recipients as electrode pulses are unsynchronized between ears (Seeber et al., 2004). In addition, most BiCI users demonstrate large ITD just noticeable differences (van Hoesel, 2004). In contrast, ILD detection is consistently good on most electrodes for most participants. Aronoff et al. (2010) compared RMS error for ILD and ITD cues for BiCI recipients using head-related transfer function-processed signals presented via a cable directly connected to the auxiliary ports of the sound processors. Three conditions were tested (ITD + ILD, ITD only, ILD only), and the same average RMS error was measured for ITD + ILD and the ILD-only conditions. Significantly poorer performance was found in the ITD-only condition. These results confirmed Seeber's and Fastl's (2008) findings using direct measurements of ITD and ILD cues in a BiCI listener. ILD cues had a primary role in localization, with no evidence of a secondary role for ITD cues. This sensitivity to ILDs across many electrodes is more likely to provide the binaural system with a reliable, consistent localization cue, therefore making ILDs the most important cue for localization by BiCI users.

Presently, ILD magnitudes are smaller for BiCI listeners than for normal-hearing listeners due to CI processing. Using MED-EL sound processors, Dorman et al. (2014) examined ILD magnitude before and after automatic gain control (AGC) processing and found that ILDs were greatly reduced after CI signal processing. Wideband, high-pass, and low-pass noise signals that were filtered by head-related transfer functions were used to calculate ILDs in a cochlear implant simulation. The ILD magnitudes were reduced for all noise signals (wideband and high-pass signal ILDs were reduced from an average of 15.5 dB to 3.4 dB, and low-pass signal ILDs were reduced from 5.4 dB to 1.8 dB). Localization accuracy was also affected by the magnitude of ILDs available to the listener.

Sound sources farther to the right or left are more impacted by ILD distortion via compression because the level differences between the sides are greater. Many researchers have shown that compression of ILDs for azimuths between 60° and 90° causes sound sources from the sides to be localized more toward the center, which they attribute to a reduction in ILDs (Kerber & Seeber, 2012; Seeber & Fastl, 2008; van Hoesel & Tyler, 2003). In particular, Dorman et al. (2014) examined localization error patterns and reported that regions beyond 45° azimuth showed larger degrees of error.

ILD reduction in response to compression is compounded by independent operation of BiCI sound processors, meaning that one device may go into compression while the other may not (Dorman et al., 2014; Kerber & Seeber, 2012; Seeber & Fastl, 2008; van Hoesel et al., 2002). van Hoesel et al. (2002) verified on a Knowles Electronic Manikin for Acoustic Research (KEMAR) that AGC was not activated at 60 dB sound pressure level (SPL) presentation levels, but AGC was active for either ear when the signal was 70 dB SPL or greater. The mean localization response error at the 70 dB SPL presentation level was 16°. However, when the presentation level was reduced to 60 dB SPL, the mean localization response error decreased to 8°. To accurately preserve ILD cues, van Hoesel suggested making equal automatic gain adjustments in both sound processors used in a bilateral system.

Another common preprocessing scheme, sensitivity control, may also exacerbate these issues. As defined by Wolfe and Schafer (2015), the sensitivity control setting determines the gain of the sound processor microphone for input sounds and directly interacts with the input dynamic range (IDR) to change the level of the quietest sounds picked up by the microphone and the AGC threshold. An increase in sensitivity will lower the acoustic input needed for perception of quiet sounds as well as lower the acoustic input level required to engage the AGC. Unlike with AGC, CI recipients can directly manipulate sensitivity control. A common sound processor sensitivity setting used by Cochlear™ recipients is 12, but there are 20 discrete steps from which to choose on the sound processor sensitivity scale. The lowest AGC threshold is at sensitivity setting 0, and each step increases the threshold by 1.5 dB.

Kerber and Seeber (2012) found that the sensitivity control setting impacted localization accuracy. They quantified the AGC threshold of the sensitivity setting 12. The ILD of a single CI channel was measured using a sinusoid with a frequency corresponding to the center frequency of the measurement channel from a source at 60° at sensitivity setting 12 on a Cochlear Nucleus® Freedom™ sound processor. With the Freedom devices on a KEMAR acoustic mannequin, they presented narrowband sounds from 0° azimuth and recorded the compressor threshold. When the stimulus reached 50 dB SPL, compression began to reduce ILD cues. For stimulus levels exceeding 62 dB SPL, ILD cues were absent. They then assessed sound localization with bilateral CI users in diffuse background noise. Compression from a higher sensitivity setting was significantly correlated to decreased localization accuracy. To avoid this ILD compression completely, the AGC threshold needed to be shifted upward by nearly 8 dB, (i.e., the sensitivity setting needed to be decreased less than 6). Kerber and Seeber warned that different sensitivity settings at the two ears might exacerbate the negative effects on ILDs and suggested a communication link between the sound processors to preserve equal sensitivity settings. Patrick, Busby, and Gibson (2006) noted that differences in sensitivity can also arise from independent Autosensitivity™

Controls (ASCs) that automatically adjusts the sensitivity setting when the input noise level exceeds the default activation threshold of 57 dB SPL in each sound processor.

Currently, literature on the real-world benefit of linked AGCs in addition to the effect of ASC in actual CI patients is scarce. However, some studies in CI patients and normal-hearing simulations show promise. Linked AGCs have been shown to improve speech understanding in noise as tested on normal-hearing listeners through a hearing aid simulation (Wiggins & Seeber, 2013). In addition, an ear-to-ear link based on medial olivocochlear efferents has been shown to improve spatial release from masking relative to a standard condition in MED-EL users (Lopez-Poveda et al., 2017).

In this study, 2 AGC variations intended to reduce ILD distortions were examined in BiCI listeners on laboratory tests of localization and speech reception in noise. Subjective impressions were also collected throughout a take-home experience with one of the AGC variations. BiCI participants traveled to the Denver Research and Technology Labs at Cochlear Americas in Centennial, CO for laboratory testing. They received payment for their time participating in the study and were reimbursed for all travel-related costs. Testing was performed under protocols approved by the Western institutional review board, and an informed consent was obtained for all participants prior to participation.

Examination of the two AGC variations was accomplished in two experiments (see Tables 2, 4, and 5 for an overview of the testing in each experiment). In the first experiment, the AGC threshold was increased above Cochlear's default setting, but the BiCI users' devices were allowed to operate with independent AGCs. In the second experiment, default AGC thresholds were retained, but the devices operated with either linked AGCs or independent AGCs. Autosensitivity control was enabled for portions of the second experiment. SmartSound® options (e.g., ASC, adaptive dynamic range optimization [ADRO], Zoom, Beam, Whisper) were turned off to eliminate influence on the testing and isolate the contribution of the AGC variation during laboratory testing unless otherwise noted.

Experiment 1

Methods

The first AGC variation was produced by raising the level at which the AGC is triggered (i.e., the AGC threshold) by 10 dB (increasing the CSPL to 75 dB). CSPL is a parameter in the Cochlear™ programming software, Custom Sound™, which defines the top of the instantaneous IDR (IIDR) boundary and therefore sets the threshold for AGC activation. The bottom of the IIDR boundary is defined by the threshold SPL (TSPL) and defaulted to 25 dB SPL. Typical acoustic inputs between 25 and 65 dB SPL receive electrical stimulation between the T- and C-levels in the recipient's map without compression. Input sounds higher than 65 dB SPL will activate the AGC although the degree depends on the peaks in the signal. Increasing the CSPL to 75 dB reduces the chance that the AGC will be activated by a given sound, thereby preserving ILD cues. Increases to CSPL also require a reduction to the Q value to compensate for the change in slope of the loudness growth function produced through the increased IIDR (change to CSPL) and electrical dynamic range (increased C-levels for loudness balance). Changing the Q value from 20 (the default value) to 16 in coordination with the CSPL change to 75 dB preserves the loudness growth function at levels lower than 65 dB SPL.

This experiment is composed of one session for testing.

Participants. This experiment included eight adult bilateral Nucleus® cochlear implant recipients using the Advanced Combination Encoder (ACE™) strategy. Table 1 includes details related to the participants' age at the time of the study, etiology of hearing loss, duration of deafness in each ear prior to implantation, and years of CI use in each ear. The average duration of deafness prior to implantation was 10.5 years for the right ear and 10.1 years for the left ear. Years of CI usage ranged from 3 to 13 years with an average of 7.5 years in the right ear and 8.5 years in the left. All participants had a minimum of 6 months of experience with bilateral implants and routinely used their bilateral CIs. Etiologies included Meniere's disease (12.5%), autoimmune (12.5%), genetic (12.5%), and unknown (62.5%).

Experimental map settings. The experiments were conducted with cochlear implant signal processing implementation in real time on Mathworks xPC target. Settings were as in a Nucleus 6 sound processor with a fast-acting compression limiter (i.e., an AGC with infinite compression ratio with time constant of milliseconds).

Default AGC threshold map. A default AGC map was created with independent AGCs. Map parameters ensured that CSPL was set to 65 dB SPL (CSPL-65), and Q value was set to 20. SmartSound® features (e.g., ASC, ADRO, Zoom, Beam, Whisper) were disabled.

Modified AGC threshold map. For the modified AGC threshold map, CSPL was increased to 75 dB SPL (CSPL-75), Q value was decreased to 16 to preserve the loudness growth function, and C-levels were increased by

Table 1. Experiment 1—Subject Demographics.

Subject	Age (years)[a]	Etiology	Duration of sev/prof HL before CI—right[b]	Duration of sev/prof HL before CI—left[b]	Years of CI right[c]	Years of CI left[c]
R45	48	Cogan's syndrome (autoimmune)	0.7	0.4	11	13
R47	54	Meniere's	2.5	0.5	9	11
R51	37	Unknown	4.5	2	9	12
R68	45	Unknown	15	17	9	8
R78	76	Unknown	10	8	10	8
R86	41	Unknown	4	3	4	5
R93	73	Genetic	3	6	3	5
R104	66	Unknown	44	44	5	6
AVE	55.0		10.5	10.1	7.5	8.5

Note. HL = hearing loss; CI = cochlear implant.
[a]Age at time of testing.
[b]Duration of severe/profound hearing loss at candidacy evaluation.
[c]Years of use at the time of testing.

a percentage of the default map's dynamic range (between 10% and 20%) to ensure that speech was perceived at a comfortable loudness level. SmartSound features were disabled.

Localization. The Iowa Environmental Sounds (Dunn, Tyler, & Witt, 2005; 16 tokens including alarm, bell, glass shattering, etc.) were used with an 8-speaker array at 20° spacing (−70° to +70°). The loudspeakers were located at head height for a seated subject (reference point). The distance from the loudspeaker to the reference point was approximately 1 m (Figure 1). The participants were instructed to keep their heads oriented toward a marker placed at 0° azimuth and to indicate the speaker number (1 to 8) of the perceived location of each environmental sound. Head movement away from 0° azimuth was monitored by the experimenter.

A baseline condition using the default map with independent AGCs and default AGC threshold (CSPL-65) was measured first at 64 dB SPL for reduced AGC activation ("CSPL-65/64"). The presentation level at an average of 64 dB SPL is 5 dB which is less than the AGC threshold for CSPL-65.

Two test conditions with independent AGCs were measured at 79 dB SPL. Condition "CSPL-65/79" used the map with the default AGC threshold (CSPL-65). Condition "CSPL-75/79" used the map with the modified AGC threshold (CSPL-75). The stimuli for the test conditions were presented at an average of 79 dB SPL, near the AGC threshold for CSPL-75 and 10 dB above the AGC threshold for CSPL-65. The order of the test conditions at 79 dB SPL were randomized and balanced across the set for each subject. See Table 2 for conditions of testing and associated codes.

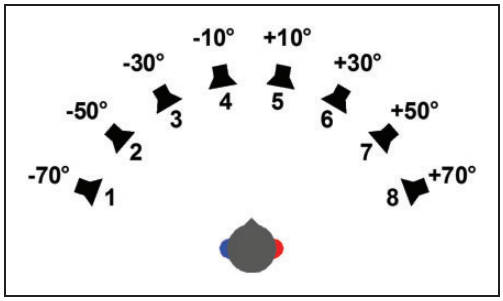

Figure 1. Schematic representation of the eight-speaker system. Speakers 1 and 8 were placed at −70° and +70° to the left and right of the straight-ahead (0°) position. Speakers 2 to 7 were placed at 20° spacing between Speakers 1 and 8. Each speaker was 1 m from the subject and at the level of the subject's ears when seated.

Table 2. Experiment 1—Localization Test Conditions.

Condition	AGC threshold	Q value	ASC	Independent or linked AGC	Stimulus level
CSPL-65/64	CSPL-65	20	OFF	Independent	64 dB SPL
CSPL-65/79	CSPL-65	20	OFF	Independent	79 dB SPL
CSPL-75/79	CSPL-75	16	OFF	Independent	79 dB SPL

Note. AGC = automatic gain control; ASC = Autosensitivity™ Control; SPL = sound pressure level.

A familiarization of speaker location to allow acclimation was performed prior to each of the three conditions (the baseline condition and two test conditions): The "alarm" token was presented once sequentially at each speaker location at the level and with the map

settings used in the associated condition. For each condition, three sets were completed. The first set presented 1 repetition of the 16 tokens, and no feedback was given. The second set presented 3 repetitions of the tokens (48 tokens) with feedback. During the third set, 3 repetitions of each token (48 tokens) were presented, and no feedback was given.

Results

Localization. The localization results for each condition were based on responses to a total of 96 tokens, half with feedback and half without feedback. This pooling was done because there was no significant difference between the "with feedback" and "without feedback" sets. The average difference in RMS error between sets "with feedback" and "without feedback" was 0.17° (compared with an average RMS error in the "without feedback" condition of 25°). An analysis of variance showed no significant effect of feedback in Experiment 1, $F(1, 7) = 0.13$; $p = .73$, or in Experiment 2, $F(1, 11) = 0.00$, $p = .96$, which also used this same test sequence to measure localization.

To calculate the RMS error, the speaker numbers were expressed as their degrees along the medial-lateral axis in space. The error in degrees between the correct answer and the given answer was calculated per trial, and the RMS of all the errors was calculated to obtain the RMS error.

In a linear repeated measures mixed effects model via maximum likelihood with a compound symmetric covariance matrix, there was a main effect of condition, $F(2, 14) = 8.07$, $p = .0047$). For the comparison of interest between conditions CSPL-65/79 and CSPL75/79, a significant improvement of 4° was observed in favor of the experimental, modified AGC CSPL-75 map after correction for multiple comparisons, $t(14) = 3.52$, adjusted $p = .009$. A Tukey–Kramer correction for three comparisons was applied. Conditions are shown in Table 2, and results are shown in Figure 2.

Experiment 2

Methods

The second AGC variation introduced a linked gain across sides of the right and left AGCs. This approach

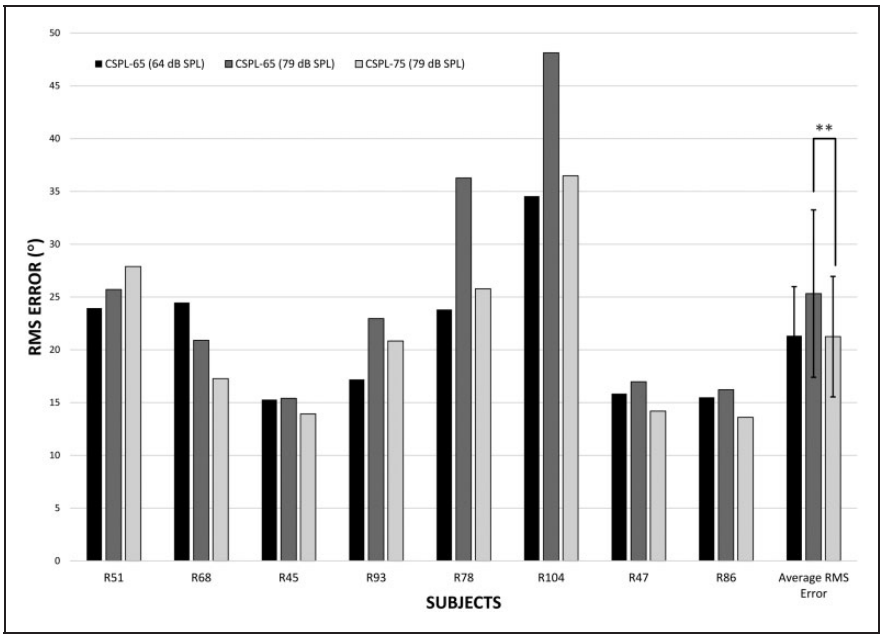

Figure 2. Experiment 1 localization RMS error for CSPL-65 versus CSPL-75. Localization ability of bilateral cochlear implant users was tested comparing increased AGC thresholds (CSPL of 75 dB) to the default (CSPL of 65 dB). A baseline condition using default AGC threshold was measured first at 64 dB SPL to minimize AGC circuit activation. Two test conditions were measured at 79 dB SPL: (a) default AGC thresholds (CSPL-65) and (b) increased AGC threshold (CSPL-75). AGC for all conditions was independent. There were 96 trials per subject per condition. There was a significant 4° improvement in the CSPL-75 degrees of error over the CSPL-65 degrees of error (**$p < .01$) in the 79 dB SPL test condition. Error bars indicate 95% confidence intervals. Each error bar demonstrates the variability across subjects. The experimental analysis is within-subjects, and this variability is often much less than shown by 95% confidence interval per condition.
RMS = root mean square; SPL = sound pressure level.

is similar to that proposed for hearing aids (Kates, 2004, 2008). This variation was tested with and without ASC which can be thought of as a slow (8 second time constant), low threshold (54 dB SPL) AGC component and is by default enabled in Cochlear device maps. The default Cochlear AGC threshold of CSPL-65 was used in this variation. Other SmartSound® features were turned off.

This experiment was composed of two testing sessions. All participants completed the first session. Participation in the second session was optional and varied as described in Table 3.

Participants. This experiment included 12 adult bilateral Nucleus® cochlear implant recipients who were users of the Advanced Combination Encoder (ACE™) strategy on Nucleus 5 (CP810) or Nucleus 6 (CP910) sound processors. Five participants from Experiment 1 completed Experiment 2. Table 3 includes details related to the participants' age at the time of the study, etiology of hearing loss, duration of deafness in each ear prior to implantation, and years of CI use in each ear. The average duration of deafness prior to implantation was 10.6 years for the right ear and 9.2 years for the left ear. Years of CI usage ranged from 2 to 16 years with an average of 8.0 years in the right ear and 7.4 years in the left. All participants had a minimum of 6 months of experience with bilateral implants and routinely used their bilateral CIs. Etiologies included Meniere's disease (8%), barometric fistula (8%), otosclerosis (17%), autoimmune (25%), and unknown (50%).

Experimental maps. Clinical maps were modified to the experimental settings as outlined in the following and presented to the participants via CP810 sound processors.

Independent AGC map. A map was created with independent AGCs. Map parameters ensured that CSPL was set to 65 dB SPL (CSPL-65) and Q value was set to 20. SmartSound features (e.g., ASC, ADRO, Zoom, Beam, Whisper) were disabled. For speech reception testing, ASC was enabled for some test conditions (as noted).

Linked AGC map. The map was modified only to link the AGCs. Other map parameters were confirmed as CSPL-65, Q value of 20, and SmartSound features disabled. For speech reception testing, ASC was enabled for some test conditions (as noted). Data exchanged between

Table 3. Experiment 2—Subject Demographics and Session Participation.

Subject	Age (years)[a]	Etiology	Duration of sev/prof hl before CI—right[b]	Duration of sev/prof HL before CI—left[b]	Years of CI right[c]	Years of CI left[c]	Participation—localization Session 1	Participation—SRT Session 1	Participation—take home	Participation—SRT Session 2
R04	69	Otosclerosis	1	1	12	16	Yes	Yes	Yes	Yes
R40	42	Unknown	12	12	3	6	Yes	Yes	No	Yes
R45	53	Cogan's syndrome (autoimmune)	0.75	0.5	11	13	Yes	Yes	No	Yes
R47	61	Meniere's	6	0.5	9	11	Yes	Yes	Yes	Yes
R51	45	Unknown	4	2	9	12	Yes	Yes	No	Yes
R64	65	Otosclerosis	20	24	9	5	Yes	Yes	Yes	Yes
R68	51	Unknown	15	17	9	8	Yes	Yes	No	Yes
R78	82	Unknown	10	8	10	8	Yes	Yes	Yes	No
R110	57	Barometric fistula right Autoimmune left	19	19	5	2	Yes	Yes	Yes	No
R115	78	Autoimmune	25	4	10	3	Yes	Yes	No	No
R116	83	Unknown	5	5	5	2	Yes	Yes	Yes	Yes
R127	53	Unknown—possibly hereditary or childhood mumps	10	17	4	3	Yes	Yes	No	No
	Average		Average	Average	Average	Average	# of Participants	# of Participants	# of Participants	# of Participants
	61.6		10.6	9.2	8.0	7.4	12	12	6	8

Note. HL = hearing loss; CI = cochlear implant; SRT = speech reception threshold.
[a]Age at time of testing.
[b]Duration of severe/profound hearing loss at candidacy evaluation.
[c]Years of use at the time of testing.

the two CP810 sound processors in a bilateral setup were facilitated by a custom bidirectional accessory cable plugged into the right and left accessory ports as shown in Figure 3. The CP810 sound processors were programmed with modified firmware, which allowed each device to send and receive full audio data to and from the other side. All modes of audio mixing were disabled in the modified firmware. Each device processed the accessory signal through a parallel AGC module to determine the gain applied at the contralateral ear. The minimum of the two gain calculations, $G_B = \min(\{G_{Left}, G_{Right}\})$, was used by both sound processors. The AGC coefficients table was updated in the firmware to match the parameters used on a CP910. Gains were processed using a 1 ms update rate. Each pair of sound processors was calibrated for a given cable before use with a subject.

Localization. The speaker and subject instructions, setup, and stimuli for localization testing in Experiment 2 were the same as in Experiment 1 (see Methods subsection in Experiment 1 section). All 12 participants completed this set of measures during Session 1.

A baseline condition using the independent AGC map (''Ind-AGC/60'') was measured first at 60 dB SPL to minimize AGC circuit activation.

Two test conditions were measured at 75 dB SPL. Condition ''Ind-AGC/75'' used the map with independent AGCs. Condition ''Link-AGC/75'' used the map with linked AGCs. The order of the test conditions at 75 dB SPL was randomized and balanced across the set for each subject. See Table 4 for conditions of testing and associated codes.

Figure 3. Picture of the wired link. The bidirectional accessory cable was plugged into the right and left accessory ports of the CP810 sound processors.

The familiarization of the speaker location and the three sets of localization tests per condition were the same as in Experiment 1 (see Methods subsection in Experiment 1 section).

Speech reception threshold (SRT) in noise. Speech understanding in babble noise was assessed using the Bamford–Kowal–Bench (BKB) sentences (Bench, Kowal, & Bamford, 1979). BKB sentences were presented in the sound field with the target talker at the $+10^\circ$ speaker location and four-talker babble at the -70° speaker location. The level of the noise remained at 70 dB SPL, and the level of the talker was adapted to find the signal-to-noise ratio (SNR) in dB which would provide 50% intelligibility. The initial SNR was +14 dB. Sixteen sentences, which were selected from one of two lists designated as practice, were presented for familiarization prior to each test condition. Thirty-six sentences, chosen from one pair of the 18 paired lists which were equated for difficulty, were presented for testing.

The following test conditions were assessed (Table 5): independent AGCs or linked AGCs, ASC enabled or disabled and intermittent or continuous four-talker babble. In the intermittent noise condition, the duration of babble before the token was 3 second. The babble continued during the token and was then silent at the completion of the token for approximately 3 to 5 seconds during the subject's response and clinician scoring. The

Table 4. Experiment 2—Localization Test Conditions.

Condition	AGC threshold	Q value	ASC	Independent or linked AGC	Stimulus level
Ind-AGC/60	CSPL-65	20	OFF	Independent	60 dB SPL
Ind-AGC/75	CSPL-65	20	OFF	Independent	75 dB SPL
Link-AGC/75	CSPL-65	20	OFF	Linked	75 dB SPL

Note. AGC = automatic gain control; ASC = Autosensitivity™ Control; SPL = sound pressure level.

Table 5. Experiment 2—Speech Reception Threshold Test Conditions.

Condition	Independent or linked AGC	ASC	Noise type
1	Independent	No	Intermittent
2	Linked	No	Intermittent
3	Independent	No	Continuous
4	Linked	No	Continuous
5	Independent	Yes	Continuous
6	Linked	Yes	Continuous

Note. AGC = automatic gain control; ASC = Autosensitivity™ Control.

exact duration of silence was dependent on the time needed for the subject to respond and the clinician to score. Once scoring was completed, the noise restarted for the next token. For continuous noise, the babble was present during the entire test run, including 3 seconds prior to the first token, during the token, and after the token for the subject response and the scoring. Continuous noise activates the ASC (when enabled) and simulates certain real-world noisy environments (e.g., a noisy restaurant).

Session 1 SRT testing included conditions 1 to 4, comparing independent AGCs to linked AGCs without ASC enabled in both intermittent and continuous noise conditions. Session 2 SRT testing comprised Conditions 5 and 6 to determine the effect of ASC in continuous noise in independent versus linked AGCs. Twelve participants completed Session 1 SRT testing, and eight participants completed Session 2 SRT testing.

Results

Localization. Calculation of RMS error as described in Experiment 1 was the same in Experiment 2 (see Results subsection in Experiment 1 section).

In a linear repeated measures mixed effects model via maximum likelihood with a compound symmetric covariance matrix, there was a main effect of condition, $F(2, 22) = 31.66$, $p < .001$. For the comparison of interest between when the AGCs operated independently (Ind-AGC/75) and linked AGCs (Link-AGC/75), there was a significant 8° benefit from linking AGCs after correction for multiple comparisons, $t(22) = 7.16$, adjusted $p < .001$. A Tukey–Kramer correction for three comparisons was applied. All 12 participants showed improved localization with linked AGCs when compared with independent AGCs. Test conditions are shown in Table 4, and results are shown in Figure 4.

At the most challenging location (−70°), the average RMS error was 46° for Ind-AGC/75 and was significantly improved to 27°, $t(154) = 6.05$, adj $p < .001$, with linked AGCs (Link-AGC/75) as shown in Figure 5. This analysis included a parameter for speaker and a Tukey–Kramer correction for all possible pairwise comparisons.

The absolute value of the broadband ILD from speaker 1 (−70°) was 7 dB. Due to asymmetries in the room acoustics, the absolute value of ILDs from speaker 1 to 8 was not symmetric (7 dB, 7.6 dB, 5.4 dB, 2.3 dB, 1.0 dB, 4.5 dB, 5.2 dB, 5.0 dB, respectively). The RMS errors with the independent AGCs (Ind-AGC/75) were lower for all other speakers as shown in Table 6. For instance, the average error in the independent AGC condition at +70° was not significantly improved with the linked AGCs after Tukey–Kramer correction, $t(154) = 2.20$, adj $p = .86$, when examined separately.

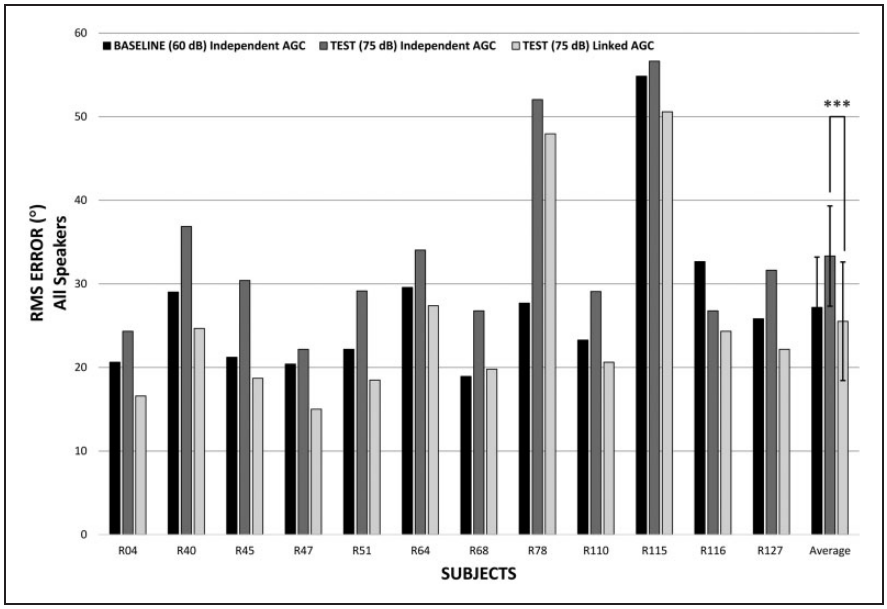

Figure 4. Experiment 2 localization RMS error for independent versus linked AGCs for all speaker locations. Localization ability of bilateral cochlear implant users was tested comparing independent AGCs to linked AGCs. A baseline condition using independent AGCs was measured first at 60 dB SPL to minimize AGC circuit activation. Two test conditions were measured at 75 dB SPL: (a) independent AGCs and (b) linked AGCs. There were 96 trials per subject per condition. An 8° benefit was found for the linked AGCs when compared with the independent AGCs (***$p < .001$) in the 75 dB SPL test condition. Error bars indicate 95% confidence intervals across subjects. AGC = automatic gain control; RMS = root mean square.

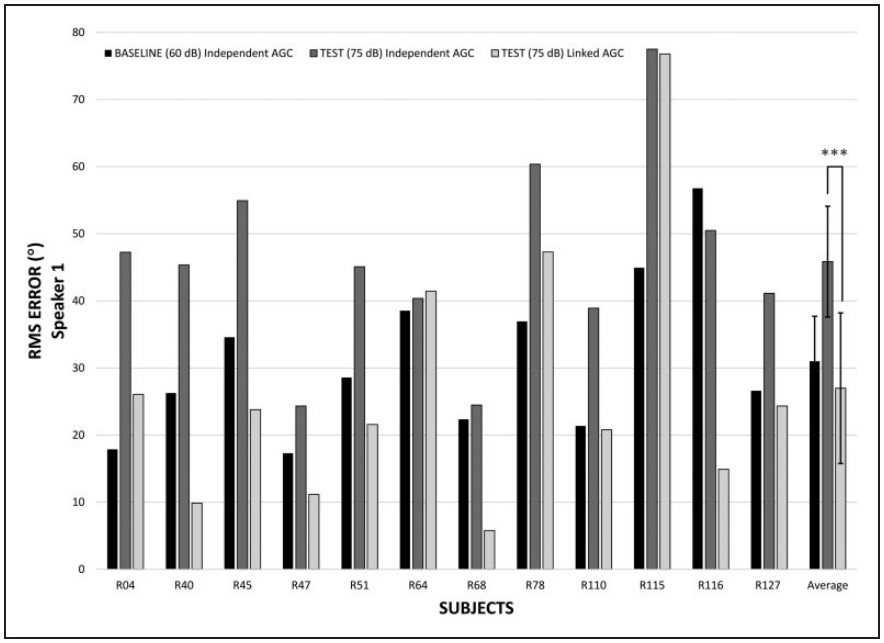

Figure 5. Experiment 2 localization RMS error for independent versus linked AGCs for Speaker 1. The largest ILDs were at Speaker 1 (−70°), which made it the most difficult location to correctly localize. There were 12 trials per subject per condition at Speaker 1. There was a significant 19° improvement in the linked AGC degrees of error over the independent AGC degrees of error (***$p < .001$) in the 75 dB SPL test condition. Error bars indicate 95% confidence intervals across subjects.
AGC = automatic gain control; RMS = root mean square.

Table 6. Average RMS Error per Speaker.

Speaker	Speaker position in degrees	Independent AGC RMS error	Linked AGC RMS error
1	−70°	45.9	27.0
2	−50°	31.1	20.3
3	−30°	31.9	26.9
4	−10°	32.4	22.0
5	+10°	25.3	22.3
6	+30°	26.1	22.8
7	+50°	23.8	17.6
8	+70°	36.9	30.0

Note. AGC = automatic gain control; RMS = root mean square.

SRT in noise. In SRT testing, data from four conditions (Table 5) were collected in one session with 12 participants without ASC enabled: linked AGCs and independent AGCs in both intermittent and continuous noise. In a linear repeated measures mixed effects model via maximum likelihood with a compound symmetric covariance matrix, there was a main effect of AGC condition, $F(1, 9) = 29.0$, $p = .0004$. The effect of noise type was insignificant, $F(1, 9) = 0.21$, $p = .65$. In intermittent noise, linking the AGCs reduced the SRT by 2.0 dB and was marginally significant after correction for multiple comparisons, $t(9) = 3$, $p = .0598$ after Tukey–Kramer adjustment). In continuous noise, the benefit of linking the AGCs was 3.1 dB and significant after correction for multiple comparisons, $t(9) = 4.61$, $p = .0057$ after Tukey–Kramer adjustment. The SRT values are shown in Figure 6.

In a second session, data from two additional conditions with a subset of the eight participants who took part in the first session were collected with ASC enabled in continuous noise with independent and linked AGCs. Performance with the link was not significantly different from performance with independent AGCs (Figure 7) when ASC was enabled in continuous noise, $F(1, 7) = 0.18$, $p = .68$.

Others have shown significant, multiple dB benefit to SRT due to ASC (Brockmeyer & Potts, 2011; Gifford, Olund, & DeJong, 2011; Gifford & Revit, 2010; Wolfe, Schafer, John, & Hudson, 2011) with a range of reported improvement from 2.5 dB to 6 dB. This is consistent with the large difference seen here in the eight participants with data in both sessions (Figure 8). In continuous babble with independent AGCs, the average SRT with ASC off (Session 1) was 3.8 dB and with ASC on (Session 2) was 0 dB. This comparison across sessions must be viewed with caution due to the different dates and post hoc nature of the comparison. Concerns about across session comparisons are ameliorated by research showing only a very small improvement (0.2 dB) due to

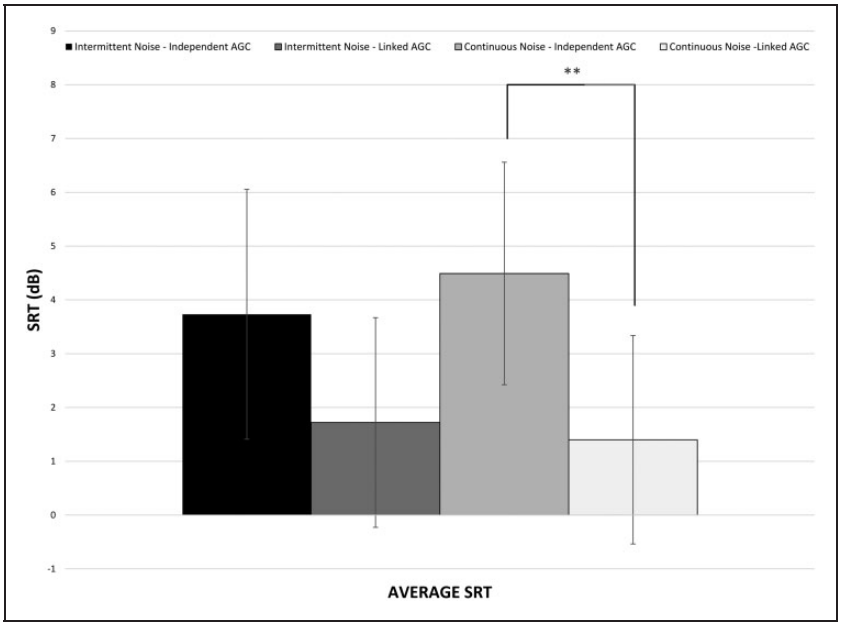

Figure 6. Experiment 2 SRT for independent versus linked AGCs in intermittent noise and continuous noise with Autosensitivity™ disabled. In Session 1 with 12 participants, independent AGCs were compared with linked AGCs without ASC enabled in both intermittent and continuous noise. In intermittent noise with ASC off, a marginally significant improvement of 2 dB ($p = .0598$) was found for the linked AGC SRT over the independent AGC SRT in intermittent noise. A significant improvement of 3 dB ($^{**}p < .01$) was found for the linked AGC SRT over the independent AGC SRT in the continuous noise condition with ASC off. Error bars indicate 95% confidence intervals across subjects.
AGC = automatic gain control; SRT = speech reception threshold.

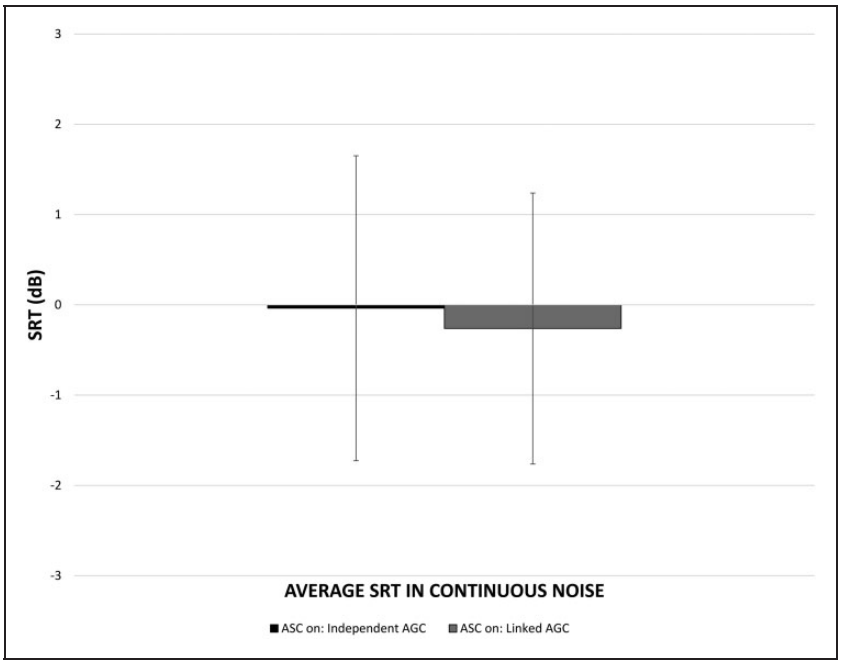

Figure 7. Experiment 2 SRT in continuous noise for independent AGCs versus linked AGCs with Autosensitivity™ enabled. In Session 2, the effect of ASC in continuous noise with independent and linked AGCs was determined. Eight of the 12 participants from Session 1 completed this testing. The 8 participants' performance in Session 1 was used to compare with their performance in Session 2. There was no significant difference in the linked AGC SRT and the independent AGC SRT with ASC enabled in continuous babble ($p > .05$). Error bars indicate 95% confidence intervals across subjects.
AGC = automatic gain control; ASC = Autosensitivity™ Control; SRT = speech reception threshold.

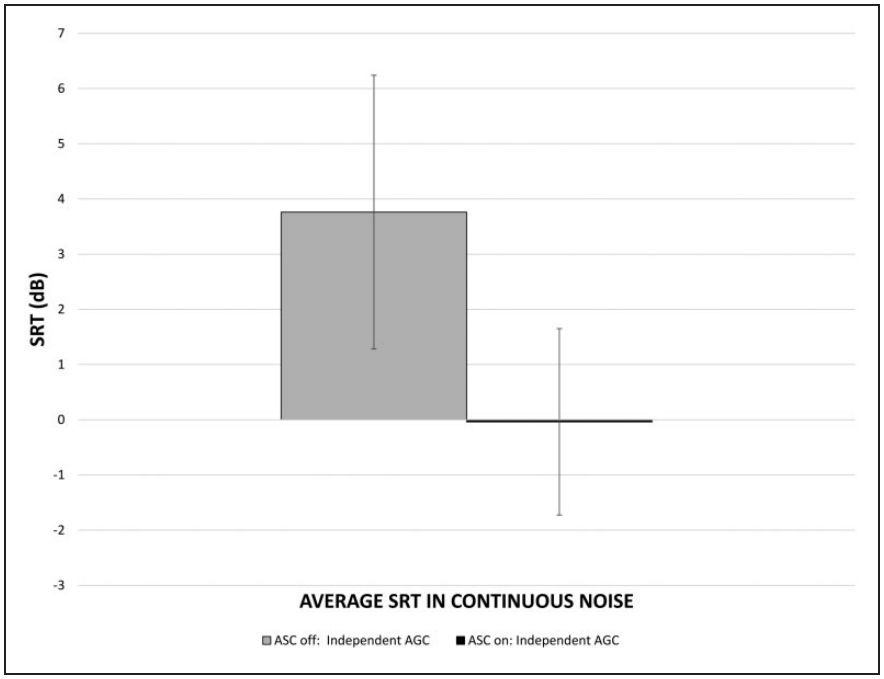

Figure 8. Experiment 2 SRT in continuous noise for independent AGCs with Autosensitivity™ disabled versus enabled. In Session 2, the effect of ASC in continuous noise with independent AGCs was determined. Eight of the 12 participants from Session 1 participated in this testing. The 8 participants' performance in Session 1 was used to compare with their performance in Session 2. Error bars indicate 95% confidence intervals across subjects.
AGC = automatic gain control; ASC = Autosensitivity™ Control; SRT = speech reception threshold.

learning from test sessions to subsequent retest session on BKB SRT (Dawson, Hersbach, & Swanson, 2013). It is also worth noting that the mean 3.8 dB effect manifested in same direction for all 8 subjects (ranging from 0.5 to 7.3 dB benefit).

The most parsimonious interpretation of the data from the sessions is that in situations in which the ASC is either disabled or inactive due to the nature of the auditory environment, the linked AGC provides a significant benefit. When ASC is enabled and activated by continuous noise, the ASC can provide a similar benefit that the linked AGC does not hinder nor add to.

Table 7. Take-Home Maps.

Program	Independent or linked AGC	SmartSound features
P1	Linked	"Everyday" (ADRO and ASC)
P2	Independent	"Everyday" (ADRO and ASC)
P3	Independent	"Focus" (ADRO, ASC, Beam)
P4	Independent	"Music" (ADRO, Whisper)

Note. AGC = automatic gain control; ASC = Autosensitivity™ Control.

Subjective Information

Methods

Subjective information was gathered with a small number of participants to gain insight into the linked AGC implementation in real-world settings and identify subjective benefits, directions for future testing, and issues with the implementation. Questionnaires were completed before and after a 4-week long take home with a linked AGC map, and participants kept a diary to document their experiences.

Participation in the take-home experience was optional, and subject participation varied as described in Table 3 due to time constraints and willingness to wear the experimental setup at home.

Participants. A subset of participants (Table 3) from Experiment 2 completed questionnaires, participated in the take-home experience, and contributed diary entries.

Experimental maps. Clinical maps were modified to the settings as outlined in the following (and shown in Table 7) and programmed to CP810 sound processors that the participants wore for the take-home experience.

Independent AGC maps. Take-home maps were created with independent AGCs. Map parameters ensured that CSPL was set to 65 dB SPL (CSPL-65) and Q value was set to 20. SmartSound® features (e.g., ASC, ADRO, Zoom, Beam, Whisper) were enabled depending on the map. The right and left sound processors were programmed with an "Everyday" (ADRO and ASC) map in P2, "Focus" (ADRO, ASC, Beam) map in P3, and a "Music" (ADRO, Whisper) map in P4.

Linked AGC map. The "Everyday" map was modified only to link the AGCs using the method as described in Experiment 2. This map was programmed in P1.

Questionnaires, take-home experience, and diary. Prior to the take-home experience, six participants (see Table 3) completed the short form of the Speech, Spatial, and Qualities of Hearing Scale-12 (SSQ12; Noble, Jensen, Naylor, Bhullar, & Akeroyd, 2013) to rate their level of performance with their clinical map settings. The SSQ12 is a questionnaire designed to measure self-reported auditory disability with a number between 0 and 10 on a visual analog scale across diverse listening situations, reflecting everyday hearing performance. Participants rated their performance hearing speech in a variety of contexts. For spatial hearing, the directional, distance, and movement components of sound were evaluated. Also, segregation of sounds and attending to simultaneous speech streams were evaluated. For the qualities of hearing, the naturalness, clarity, and identifiability of different speakers, music and everyday sounds were rated.

The six participants took part in a take-home experience for an average of 4 weeks. The wired link was plugged in to the right and left accessory ports of the CP810 sound processors at all times (Figure 3), but depending on the program selected, the AGCs were linked (the wire connection was active) or independent (the wire connection was inactive). Participants were asked to try the linked AGC map (in P1) and compare it with the independent AGC maps (in P2, P3, and P4) in the same listening environments. Their instruction was to compare, contrast, and rate performance of P1 against the other maps.

Five of the participants kept a diary of their experiences with the linked AGC during the take-home portion of the study. The diary was completed online or on paper, and each entry was for 1 day. The daily entries included questions on length of use in hours of the linked AGC map (P1), which other independent AGC maps were used (P2-P4), what environments the subject encountered, and open-ended questions to describe experiences with the linked AGC map. A rating scale comparing the linked AGC map in P1 with the independent AGC map in P2 was also included in the daily diary entry. Ratings from −5 (indicating P1 was much worse) to +5 (indicating P1 was much better) were obtained.

After completion of the take-home experience, the abbreviated comparison version of the Speech, Spatial, and Qualities of Hearing Scale-12 question comparative survey (SSQ12C; Jensen, Akeroyd, Noble, & Naylor, 2009) was administered to compare P1 with the other maps in P2 to P4 during the take home. Five participants completed the SSQ12C. One subject withdrew early due to personal reasons and did not participate in the SSQ12C; however, she completed the SSQ12 and created diary entries of her take-home experience before she withdrew. Both the SSQ12 and SSQ12C were presented to participants online.

In a 2012 article, Demeester et al. compared the results of a modified full-length version of the SSQ (Gatehouse & Noble, 2004), a 50-item questionnaire with the 5 hearing aid-related questions removed, administered to normal-hearing young listeners, normal-hearing older listeners, and older listeners with hearing loss. From this, they determined the SSQ disability cutoff point to be 2 standard deviations from the mean SSQ disability scores of the normal-hearing young listeners' group. Significant hearing disability was determined if the subject scores were less than the SSQ disability cutoff points for the various categories of questions. Noble et al. (2013) described a transformation between a full-length SSQ (49 questions) to the SSQ12 (12 questions), and we have applied this transformation to the Demeester approach to derive a set of cutoffs relevant to the SSQ12. SSQSPEECH scores less than 6.2, SSQSPATIAL scores less than 5.4, SSQQUALITY scores less than 7.8, and Total SSQ scores less than 6.6 indicate a significant degree of speech, spatial, quality, or overall disability, respectively. These cutoff points will be used as context for the SSQ12 data collected for the present study.

Results

Questionnaires, take-home experience, and diary. Due to the small number of participants who completed the questionnaires and diary, the power of this portion of the study was low, and the results should be interpreted with caution. In addition, a potential bias toward the investigational map in P1 was present during the take-home experience given that P1 was identified for comparison against other maps. The results are intriguing in that to the authors' knowledge, linked AGCs have not been tested in a real-world environment, and there was consistency in diary entries between participants regarding the perceived benefits of the linked AGC map. Other diary entries noted better performance in certain listening situations by the independent AGC maps. This feedback provided by the participants will inform future directions of linked AGC implementations.

SSQ12. The SSQ12 was administered before the take-home experience. Participants were asked to rate their level of performance (e.g., *Not at All* [0] to *Perfectly* [10]) with their current clinical map and sound processor settings with independent AGCs for the 12 different listening scenarios.

Questions 1 through 5 of the SSQ12 assessed the Speech domain of hearing. The Spatial domain of hearing was assessed by questions 6 to 8 of the SSQ12. The final four questions on the SSQ12 assessed the Quality domain of hearing. SSQ Total results are found in Figure 9, and SSQ12 results are shown per subject in Table 8. Overall, before the intervention, half the participants were below the disability cutoff thresholds for the SSQ12.

SSQ12C. After completion of the take-home portion, the SSQ12C was administered to the participants. They were asked to compare P1 (linked AGCs) with P2 to P4 (independent AGCs) for the same 12 scenarios presented in the SSQ12. Participants marked on the scale from −5 (P1 much worse) to +5 (P1 much better). The zero point on the scale indicated no difference.

Performance with the linked AGCs was rated significantly better than with the independent AGCs (Table 9) as shown by the positive average rating (0.9) of all SSQ12C questions, $t(4) = 3.17$, $p = .034$, two-tailed t test.

Diary. Although six BiCI users participated in the take-home experience, only five participants kept a diary of their experiences with the linked AGC during the take-home portion of the study. These participants were asked to use P1 in all types of listening environments. Participants were instructed to change programs to compare with P2 and rate the performance of P1 against P2. They were also encouraged to use P3 and P4 in the same listening situation to P1 and report subjective comments. Map settings are found in Table 7.

A comparative question, "How did P1 (with wire present) perform today compared with the nonlinked case (either P2 or P1 without the wire present)?" as well as open-ended questions to allow subjective descriptions were included in each diary entry. An average of 20 diary entries was completed per subject.

The five participants gave a positive rating on the comparative question administered in the diary (average score of +1.1), indicating that the participants rated P1 more favorably, $t(4) = 2.78$, $p = .049$ on two-tailed, pairwise t test.

Four participants indicated in diary entries that it was easier to locate things while on P1 (linked AGC map) with specific comments made about localization of sounds. R110 specifically tested her localization skills by having her family hide her cell phone and she searched for it using audition only. She indicated that her localization ability improved when using the linked

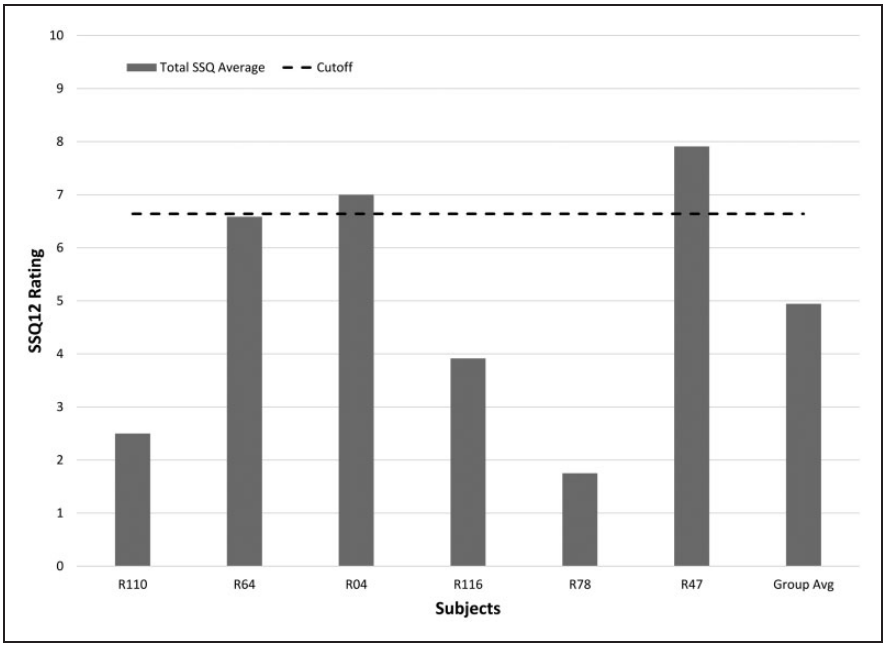

Figure 9. SSQ12 average ratings for the Total SSQ12 when compared with the adjusted SSQ12 disability cutoff. The dotted line indicates the disability cutoff threshold. Before the intervention, the participants' Total SSQ12 ratings on average were below the disability cutoff threshold.
SSQ12 = Speech, Spatial and Qualities of Hearing scale-12.

Table 8. SSQ12 Ratings per Subject.

Question	R110	R64	R04	R116	R78	R47	Group average
SSQ12 domain							
Q1	6	7	7	1	3	7	5.2
Q2	2	6	7	1	3	N/A	3.8
Q3	5	7	8	1	3	6	5.0
Q4	3	7	8	3	0	8	4.8
Q5	3	7	8	7	1	7	5.5
Speech average	3.8	6.8	7.6	2.6	2.0	7.0	5.0
Q6	0	6	5	5	0	9	4.2
Q7	0	6	5	3	0	9	3.8
Q8	0	7	6	5	0	9	4.5
Spatial average	0.0	6.3	5.3	4.3	0.0	9.0	4.2
Q9	0	6	7	8	0	8	4.8
Q10	3	5	8	1	0	6	3.8
Q11	5	7	8	5	8	9	7.0
Q12	3	8	7	7	3	9	6.2
Quality average	2.8	6.5	7.5	5.3	2.8	8.0	5.5
Total SSQ average	2.5	6.6	7.0	3.9	1.8	7.9	5.0

Note. SSQ = Speech, Spatial and Qualities of Hearing scale. Entries with "N/A" indicate that the subject answered "not applicable" for that question.

Table 9. SSQ12C Ratings per Subject.

Question	R110	R64	R04	R116	R47	Group average
SSQ12C domain						
Q1	2	3	1	0	N/A	1.5
Q2	N/A	1	0	0	N/A	0.3
Q3	2	2	1	0	1	1.2
Q4	2	−1	1	0	1	0.6
Q5	0	2	1	0	1	0.8
Speech average	1.5	1.4	0.8	0.0	1.0	0.9
Q6	2	3	1	0	1	1.4
Q7	0	3	1	0	1	1.0
Q8	0	3	1	0	1	1.0
Spatial average	0.7	3.0	1.0	0.0	1.0	1.1
Q9	3	−1	1	0	0	0.6
Q10	0	0	0	0	0	0.0
Q11	2	0	1	0	0	0.6
Q12	3	2	1	0	0	1.2
Quality average	2.0	0.3	0.8	0.0	0.0	0.6
Total SSQ average	1.45	1.42	0.83	0.00	0.60	0.9*

Note. SSQ12C = Speech, Spatial, and Qualities of Hearing Scale-12 question comparative survey. Entries with "N/A" indicate that the subject answered "not applicable" for that question. Total SSQ average for the group was significantly different than zero (*$p < .05$).

AGC map. R04 described accurately locating a helicopter even though he could not visually locate the helicopter at the time as it was behind a tree. R64 noted improved localization of geese at her neighbor's house. R47 reported that in a quiet kitchen with an electric teapot on his left, the direction of the teapot was more precise in the linked AGC condition. He attended a concert and noted that the soloist's position was more tightly focused.

Improved performance in speech in noise with P1 was also described in diary entries. Specifically, R110 reported improved clarity and ability to identify conversation out of the background noise in church, while watching movies at the cinema, and in a busy supermarket. R110 also reported on several dates in her diary that clarity and volume in general improved. R04 noted that the public address system at the baseball stadium was easier to hear, and he was able to have an easier conversation with his neighbor at the baseball game.

One subject, R47, reported a mixed review of the linked AGC condition in noise. He noted that using the linked AGC reduced noise more effectively, but it also reduced the target signal. P1 was the best map in a noisy restaurant; however, R47 noted a perception of sound "fading in and out" when in a noisy environment. It is possible that linked compressors create a more robust, singular percept of compression than two independent processors.

Benefits to other listening conditions when using the linked AGC map were noted in diary entries. Clarity of the radio in the car for both music and speech was noted by all five participants. Speech understanding on the phone with use of linked AGCs was reported as the biggest improvement for R110. She noted this several times in her diary, in six separate entries.

In diary entries pertaining to performance in group settings, participants preferred the "Focus" program to the linked AGC condition. The "Focus" program uses an adaptive beamformer to improve the SNR. The linked AGC map was only available in "Everyday" map settings, which uses an omnidirectional directivity pattern at all times. This situation demonstrates the benefit of directional microphones rather than the impact of linked or independent AGCs.

Discussion

Disruption to ILDs caused by independent AGCs reduces the perceived spatial separation between target and background. Access to ITD cues may compensate for this degradation in ILDs (Wiggins & Seeber, 2013). However, BiCI users do not have adequate perception of ITDs and therefore require accurate ILD cues to achieve best performance (Aronoff et al., 2010; Bronkhorst, 2000; Laback et al., 2004; Seeber & Fastl, 2008; van

Hoesel et al., 2002, 2008; van Hoesel & Tyler, 2003). In this study, ILD preservation was accomplished in two ways: (a) increasing the CSPL to 75 dB and (b) linking the AGCs between right and left devices. In addition, the effect of linked AGCs on speech in noise was compared with that of ASC.

van Hoesel et al. (2002) found that sounds at a higher level than 70 dB SPL activated the AGC and resulted in RMS errors of 16°. Therefore, in the present study, baseline conditions were used at lower levels to minimize AGC activation and testing conditions at 75 dB SPL or higher to assess localization performance with the influence of active AGCs.

Cochlear^{TM} sound processors have a 40 dB IDR and signals higher than 65 dB SPL are subjected to compression by the fast AGC. In Experiment 1, the AGC threshold was increased by 10 dB to minimize AGC activation for stimuli. This resulted in an overall improvement of 4° and an improvement of 9° in the most difficult location to localize. Raising the AGC threshold is simple to implement and could be used immediately in current clinical practice to improve ILD cues. Situations in which the stimulus is at a higher level than 75 dB SPL will occur in everyday listening situations, so this approach simply reduces the prevalence of the ILD distortion.

There are programming considerations with higher CSPL including an increase in C-levels and a reduction in Q value to compensate for the change in slope of the loudness growth function. This increase in C-levels requires mapping procedures to reduce the risk of (a) channels reaching the limits of voltage compliance, (b) channels exceeding the loudness discomfort levels, (c) facial nerve stimulation, and (d) change to sound quality. To address these issues, recipients may be allowed volume control to ensure comfortable loudness in various listening environments or the CSPL can be reduced to 70 dB SPL. CSPL-75 may also lead to reduced battery life for the recipient.

Linked gains have been shown to improve ILDs for hearing aids. Ernst et al. (2018) assessed ILDs for an independent compression versus a binaurally linked, model-based, fast-acting dynamic compression algorithm. ILD preservation for binaurally synchronized algorithms was better than for the independent compression. Linking gains in hearing aids has also been beneficial to localization performance (Ibrahim et al., 2013; Sockalingam, Holmberg, Eneroth, & Shulte, 2009) especially if ITD cues are unavailable (Keidser, Convery, & Hamacher, 2011). In the present study, linked AGCs proved advantageous to localization and SRT testing. In Experiment 2, linking AGCs provided BiCI users with an average improvement of 8° on localization error and a large 19° advantage at the most difficult speaker location. While localization skills are better for BiCI users than unilateral CI users, there continues to be a gap in performance with normal-hearing listeners. This overall improvement from linking the AGCs helps to close the gap in performance and could be even more critical to closing the gap in performance at the extreme lateral locations where ILDs are most impacted by compression (Dorman et al., 2014).

Linking AGCs afforded an average gain of 2.5 dB on SRT testing in intermittent and continuous babble. The literature on linked AGCs for hearing aids provides a context for speech performance with such a link. Wiggins and Seeber (2013) modeled speech intelligibility in spatially separated noise for linked versus independent AGCs for bilateral moderate sensorineural hearing loss. The predicted intelligibility was found to be higher for linked compression over independent compression for all SNRs tested, even with reduced audibility from the lower gain provided by the linked compression in the model. Kreisman, Mazevski, Schum, and Sockalingam (2010) reported a significant improvement in speech understanding in noise (smaller SNR loss and lower receptive threshold for sentences) using hearing aids with wireless synchrony versus without synchrony. Ernst et al. (2018) also found a preference for linked compression on a paired comparison with independent compression.

In clinical sound processors, ASC is another preprocessing feature that may be enabled in CI programs that changes the effective AGC activation threshold and corresponding gain based on the listening environment. In this study, enabling ASC in processors with independent AGCs provided a benefit to speech perception in noise consistent with findings from previous studies (Brockmeyer & Potts, 2011; Gifford et al., 2011; Gifford & Revit, 2010; Wolfe et al., 2011). Linked AGCs did not provide an added benefit to SRT in the lab when ASC was enabled but maintained the benefit already achieved with ASC alone. Enabling ASC can be implemented in the clinic simply and immediately, although not all patients report liking the effect of ASC (Vaerenberg et al., 2014).

The advantages found for speech in noise performance with linked gains and with ASC are consistent with the known effects of compression parameters. Pittman et al. (2014) processed speech and environmental stimuli using parameters for slow- and a fast-acting compression. The slow compression maintained the amplitude variations within the waveform, while fast compression reduced the amplitude variations. ASC attenuates both peaks and troughs greater than 54 dB SPL as well as reduces the levels relative to the fast AGC threshold, both of which serve to preserve the peak-to-trough ratio. Wiggins and Seeber (2013) showed that an unlinked AGC reduced the peak-to-trough ratio in the better ear when there was a fast AGC that responded predominantly to the signal, not the noise. Linking the AGCs preserved

the original peak-to-trough ratio by reducing the troughs caused by contralateral noise. The earlier findings are consistent with the pattern of speech results obtained for linked AGCs versus independent AGCs with ASC on and ASC off.

A small number of participants used linked AGCs plus ASC enabled in an investigational map they wore at home for a period of 4 weeks. They were instructed to compare this investigational map to standard clinical maps. A take-home experience of linked AGCs has not been done to the authors' knowledge prior to this experiment, and while there is a potential for bias toward the investigational map, the information collected during this take-home experience has given insight into potential benefits in real-world situations and demonstrated areas of need for further testing.

Participants were in agreement on both the SSQ12C and in diary entries that it was easier to localize using the linked AGCs when compared with the clinical, independent AGC maps. Four out of five participants reported specific examples of increased localization accuracy with the linked AGCs in real-life listening situations in diary entries. Localization with ASC enabled was not tested in laboratory. Because ASC was enabled on take-home maps and localization was one of the main benefits mentioned by participants in the take-home experience, this needs to be studied further.

When considering performance on speech in noise, all participants engaging in the take-home experience rated the linked AGC map positively in the SSQ12C and in diary entries when compared with independent AGCs. Three participants reported examples of increased intelligibility for speech in noise in real-life listening situations. The positive outcomes for speech in noise are consistent with the link adding benefit beyond ASC alone. A limitation with ASC is that it takes 8 s before it is fully activated in noisy environments. In contrast, there is no required build up to full activation with linked AGCs. Given this delay with ASC, the linked AGCs may provide better speech understanding in a wider variety of situations. In addition, speech understanding in noise has also been shown to benefit from localization cues when lip-reading cues are available. van Hoesel (2015) showed a 9-dB benefit to speech understanding in noise when both lip-reading and localization cues were available, so anything that improves localization is expected to enhance speech understanding in many common, multimodal listening situations. These are areas to examine further to determine the nature and magnitude of the benefit of linked AGC plus ASC as well as comparing performance with linked AGCs to performance with independent AGCs with all SmartSound options.

The AGC modifications in this study resulted in improved localization of higher level lateral sounds, without a negative impact on perception of other sounds (either at more central locations or lower levels). Participants over the entire observed range of baseline performance were aided by AGC modifications.

Conclusions

In our implementation, all gain modifications including increasing the AGC kneepoint to CSPL-75 and linking the left and right AGCs preserved ILD cues, which resulted in improved localization. Linked AGCs also resulted in improved performance for speech in noise. For speech in continuous noise, ASC also produced similar benefits as linked AGCs. Two of these approaches (increasing CSPL to 75 dB and enabling ASC) are available commercially and could be implemented immediately in the clinic.

The linked AGC implementation studied here was a simple one. Further testing is needed to explore the functional gains shown during the take-home experience and determine the contributions to localization and speech in noise from AGCs, ASC, other mapping parameters, and SmartSound® options.

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Declaration of Conflicting Interests

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