The Relationship Between Spatial Release From Masking and Listening Effort Among Cochlear Implant Users With Single-Sided Deafness

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Objectives: To examine speech intelligibility and listening effort in a group of patients with single-sided deafness (SSD) who received a cochlear implant (CI). There is limited knowledge on how effectively SSD-CI users can integrate electric and acoustic inputs to obtain spatial hearing benefits that are important for navigating everyday noisy environments. The present study examined speech intelligibility in quiet and noise simultaneously with measuring listening effort using pupillometry in individuals with SSD before, and 1 year after, CI activation. The study was designed to examine whether spatial separation between target and interfering speech leads to improved speech understanding (spatial release from masking [SRM]), and is associated with a decreased effort (spatial release from listening effort [SRE]) measured with pupil dilation (PPD).

Design: Eight listeners with adult-onset SSD participated in two visits: (1) pre-CI and (2) post-CI (1 year after activation). Target speech consisted of Electrical and Electronics Engineers sentences and masker speech consisted of AzBio sentences. Outcomes were measured in three target-masker configurations with the target fixed at 0° azimuth: (1) quiet, (2) co-located target/maskers, and (3) spatially separated (±90° azimuth) target/maskers. Listening effort was quantified as change in peak proportional PPD on the task relative to baseline dilation. Participants were tested in three listening modes: acoustic-only, CI-only, and SSD-CI (both ears). At visit 1, the acoustic-only mode was tested in all three target-masker configurations. At visit 2, the acoustic-only and CI-only modes were tested in quiet, and the SSD-CI listening mode was tested in all three target-masker configurations.

Results: Speech intelligibility scores in quiet were at the ceiling for the acoustic-only mode at both visits, and in the SSD-CI listening mode at visit 2. In quiet, at visit 2, speech intelligibility scores were significantly worse in the CI-only listening modes than in all other listening modes. Comparing SSD-CI listening at visit 2 with pre-CI acoustic-only listening at visit 1, speech intelligibility scores for co-located and spatially separated configurations showed a trend toward improvement (higher scores) that was not significant. However, speech intelligibility was significantly higher in the separated compared with the co-located configuration in acoustic-only and SSD-CI listening modes, indicating SRM. PPD evoked by speech presented in quiet was significantly higher with CI-only listening at visit 2 compared with acoustic-only listening at visit 1. However, there were no significant differences between co-located and spatially separated configurations on PPD, likely due to the variability among this small group of participants. There was a negative correlation between SRM and SRE, indicating that improved speech intelligibility with spatial separation of target and masker is associated with a greater decrease in listening effort on those conditions.

Conclusions: The small group of patients with SSD-CI in the present study demonstrated improved speech intelligibility from spatial separation of target and masking speech, but PPD measures did not reveal the effects of spatial separation on listening effort. However, there was an association between the improvement in speech intelligibility (SRM) and the reduction in listening effort (SRE) from spatial separation of target and masking speech.

Key words: Bilateral, Cochlear implant, Listening effort, Pupillometry, Single-sided deafness, Speech understanding.

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INTRODUCTION

Listeners with normal hearing (NH) in both ears can capitalize on several binaural benefits to hear more clearly and with less perceived effort in noisy situations than listeners with hearing loss. Decades of research on this topic, commonly known as the "Cocktail-Party Problem," has identified three primary speech in noise benefits: (1) binaural redundancy, (2) monaural head shadow, and (3) binaural unmasking (Hawley et al. 1999, 2004; Bronkhorst 2000). Binaural redundancy refers to the improved detection of a target sound of interest (e.g., speech) when listeners have access to duplicate copies, one in each ear (Dieudonné & Francart 2019). For a situation in which the target and maskers originate from different spatial locations (i.e., spatially separated), the monaural "head shadow effect" can be observed, whereby the ear nearer to the target source will have a better signal to noise ratio (SNR) than the ear further from the source. In complex listening conditions such as restaurants or cafés, in which the levels of targets and maskers might fluctuate on a moment-to-moment basis, listeners can benefit from the head shadow effect, with one ear having a more favorable SNR at a given moment in time (Bronkhorst & Plomp 1992). The third phenomenon that improves our ability to hear in noisy situations when target and maskers are spatially separated is known as binaural unmasking or squelch. This benefit supports listeners' ability to perceptually separate the two sources using binaural difference cues known as interaural time and level differences. Together, these phenomena contribute to spatial release from masking (SRM) (for review, see Bronkhorst 2000, 2015), which is the improvement in detection of a target (e.g., speech) when maskers are spatially separated compared with when they are co-located. However, the magnitude of this benefit depends on many factors, including stimulus types, locations, tasks, and hearing ability of the participants (Jones and Litovsky 2011; Dieudonné & Francart 2019; Rennies et al. 2019).

One group of patients who cannot take advantage of binaural benefits are individuals with single-sided deafness (SSD).

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These individuals have clinically normal or near-NH in one ear but no functional hearing in the opposite ear. This results in increased difficulty communicating in noisy environments and localizing sounds (Firszt et al. 2017). In addition, individuals with SSD often experience decreased hearing-related quality of life (Muigg et al. 2020), and increased listening-related effort and fatigue (Alhanbali et al. 2017). Without clinical management with assistive devices, the head shadow effect is the only means through which speech in the presence of background noise can be rendered more intelligible by patients with SSD. However, it is important to note that the head shadow effect can also be deleterious if the deaf ear has a more favorable SNR compared with the hearing ear.

To benefit from the head shadow effect, an individual with SSD may need to adjust their head position such that the target speech is closer to their acoustic hearing ear and their deaf ear is closer to the noise source, maximizing the SNR. To capitalize on this monaural benefit, audiologic interventions like contralateral routing of signal (CROS) and bone conduction devices send sounds that arrive at the deaf ear to the NH ear. These devices can significantly enhance hearing-related quality of life (Kitterick et al. 2015; Fogels et al. 2020). They can also modestly improve the intelligibility of target speech in background noise (Kitterick et al. 2016; Snapp et al. 2017). However, the extent of these benefits depends on the spatial arrangement of the target and maskers (Finbow et al. 2015; Fogels et al. 2020). Ultimately, because CROS and bone conduction devices provide monaural auditory input to only the acoustic hearing ear, neither of these technologies provide listeners with access to the binaural benefits needed to optimize speech understanding in noisy environments (Lin et al. 2006; Arndt et al. 2011).

An increasing number of listeners with SSD are choosing to receive a cochlear implant (CI) in their deaf ear. CIs are implantable auditory prostheses that restore hearing in the deaf ear by stimulating the auditory nerve directly with electrical pulses. Access to bilateral auditory input offers numerous benefits compared with CROS or bone conduction devices. For example, the initial CI recipients with SSD (SSD-CI) were those with intractable, debilitating tinnitus, the disturbance from which was reduced while using the CI (Van de Heyning et al. 2008). Subsequent studies involving individuals with SSD have shown that CIs facilitate better speech intelligibility in background noise compared with listening with the acoustic ear alone (Vermeire & Van de Heyning 2009; Dirks et al. 2019), CROS, or bone conduction devices (Arndt et al. 2011). In addition, CIs facilitate better sound localization abilities compared with acoustic-only listening (Litovsky et al. 2019), improved quality of life (Dillon et al. 2017; Häußler et al. 2019), and reduced perceived listening effort (Lopez et al. 2021) compared with presurgical baselines, highlighting the numerous benefits of having access to sound in both ears. Furthermore, one prospective clinical trial comparing clinical SSD management approaches found that long-term (mean = 58 months) device retention was greatest for CI (81.1%), followed by bone conduction (64.3%) and CROS (52.5%) devices (Marx et al. 2021). Additional studies showed that these listeners can experience binaural unmasking to aid in the perceptual separation of target speech from background maskers (Bernstein et al. 2016, 2017) when the target sound is in the NH ear. However, later work from Bernstein et al. (2019) found that SSD-CI recipients can also experience poorer speech intelligibility (i.e., interference) in binaural unmasking tasks when the target speech is presented to the implanted ear.

Asymmetric Inputs Interfere With Bilateral Auditory Signal Integration

Benefits from binaural hearing are largely observed when the integrity of the auditory periphery in each ear is similar (for review, see Anderson et al. 2023). Therefore, it is unsurprising that SSD-CI patients, who listen with perhaps the greatest degree of auditory asymmetry, demonstrate limited binaural benefits compared with NH listeners. Recent work has investigated the impact of across-ear asymmetries on binaural unmasking in NH participants using bilateral vocoder simulations of CI processing that introduce different amounts of spectral resolution to each ear. Similar to SSD-CI listeners who showed interference when attending to a target in their CI ear, findings suggested that a speech masker was more likely to introduce interference (rather than unmasking) when the target speech was in the ear with poorer spectral resolution (Goupell et al. 2021). Wess et al. (2017) reported similar findings when measuring binaural unmasking in NH listeners using SSD-CI vocoder simulations. A study with bilateral CI recipients with asymmetric hearing histories from Goupell et al. (2018) showed that limited binaural benefits can be partly attributed to interaural asymmetry. Even if a listener has two CIs with identical implant types and speech processor types, as well as similar clinical programming across the two ears, today's clinical systems do not ensure that the two CIs are synchronized (Dennison et al. 2022). Other limitations (Kan et al. 2015) include differences in the integrity of each auditory nerve and location of the intracochlear electrodes. All of these factors, in addition to the fact that CIs provide poorer spectral resolution than typical acoustic hearing, result in poorer binaural sensitivity and reduced binaural benefits compared with NH listeners (Kan & Litovsky 2015; Staisloff et al. 2016; Archer-Boyd & Carlyon 2019; Kan et al. 2019). These issues are likely to be compounded even more in individuals with SSD-CI, who experience some of the greatest degrees of interaural asymmetry, with acoustic hearing in one ear and electric hearing in the other.

Listening Effort During Speech Intelligibility Tasks

Attending to a speech target in the presence of interfering maskers requires effort, even for those with two typically hearing ears (Lau et al. 2019). Individuals with SSD-CI may need to expend additional listening effort during speech-in-noise tasks, as they need to combine disparate signals across the two ears. According to the Framework for Understanding Effortful Listening, listening effort can be defined as the "deliberate allocation of mental resources to overcome obstacles in goal pursuit when carrying out a listening task" (Pichora-Fuller & Kramer 2016). Compared with those with NH, listeners with hearing loss rely on these cognitive resources to a greater extent to supplement the poor peripheral encoding of the auditory signal (Peelle 2018). This compensatory resource recruitment is associated with elevated listening effort and fatigue, which can negatively impact well-being and quality of life (Hornsby 2013; Hornsby & Kipp 2016; Holman et al. 2021). Prior work has shown that cochlear implantation in individuals with SSD facilitates decreased subjective listening effort as speech intelligibility in noise improves (Lopez et al. 2021), suggesting that

TABLE 1. Participant demographic information

Participant ID	Age at Onset of Deafness	Age at Visit 1	Hearing Loss Etiology	CI Experience (yrs; mos) at Visit 2	Speech Processor
MBA	44	47	Temporal bone fracture	1; 0	Sonnet
MBB	40	46	Meniere disease	1; 1	Sonnet
MBC	66	67	Meningioma/surgical complication	1; 1	Sonnet
MBE	25	26	SSNHL	1; 3	Sonnet
MBF	43	44	SSNHL	1; 3	Sonnet
MBG	54	55	SSNHL	1; 2	Sonnet
MBH	46	48	Viral etiology or Meniere disease	1; 0	Rondo
MBI	61	69	Meniere disease	1; 8	Rondo

CI, cochlear implant; SSNHL, sudden sensorineural hearing loss.

the benefits of having access to both ears may extend beyond behavioral improvements in speech intelligibility and sound localization.

Measuring the task-evoked pupillary response through pupillometry is a well-studied and verified means of indexing the degree of listening effort or task engagement associated with speech intelligibility (Zekveld & Kramer 2014; Winn et al. 2018). Perhaps the greatest advantage of this method is its capacity to elucidate “on-line” changes in effort as a function of a stimulus time course, an insight not possible from a poststimulus outcome measure such as percent correct sentence intelligibility or participant-reported assessments of effort (Peelle 2018; Winn et al. 2018). An increase in pupil dilation (PPD) during a listening task relative to the prestimulus baseline dilation is linked to heightened activity in the locus coeruleus, a subcortical nucleus associated with governing attention (Aston-Jones & Cohen 2005). This task-dependent activation is modulated in part by a listener’s motivation, and the complex interaction between task difficulty and listener motivation results in a nonlinear change in PPD. For example, a low-difficulty task that does not require the listener to exert much effort may result in a small increase in PPD relative to baseline, while a trial of “intermediate” difficulty might elicit a very large change in PPD relative to baseline, indicating an increase in the effort and motivation required to complete the task. However, small PPD increases relative to baseline have also been observed during tasks that are so difficult that participants struggle to complete them and “give up,” perhaps because the reward of completing the task is not sufficiently valuable to evoke motivation and engagement (Zekveld & Kramer 2014; Ohlenforst et al. 2017; Zekveld et al. 2018). As the multifaceted nature of listening effort and its nonmonotonic relationship with speech intelligibility cannot be entirely captured by subjective rating scales (Alhanbali et al. 2019), the present study operationalized measures of PPD to quantify listening effort in individuals with SSD-CI in different spatial listening configurations.

Present Study

The present study aimed to determine the impact of cochlear implantation, particularly as it relates to speech intelligibility, SRM, and listening effort, in individuals with SSD. Listeners with SSD completed speech intelligibility tasks while we recorded their pupillary responses. Listeners were tested shortly before cochlear implantation (visit 1) and 1 year following CI activation (visit 2). Previous studies have investigated the relationship between objective measures of listening effort and speech intelligibility (Zekveld et al. 2014; Xia et al. 2015), but to our knowledge, this is the first study to investigate, among listeners with SSD, whether the relationship between spatial hearing abilities and objectively measured listening effort differs before and after cochlear implantation.

MATERIALS AND METHODS

Participants and Audiologic Testing

Eight individuals were recruited as part of a clinical trial of the Med-El (Innsbruck, Austria) Flex28 implant for patients with SSD. The participants were aged 26 to 69 years and native speakers of English. Table 1 contains additional participant demographic information. All testing was completed at the Waisman Center at the University of Wisconsin-Madison, but CI surgery and activation were completed at Massachusetts Eye and Ear Infirmary. This study was approved by the University of Wisconsin-Madison IRB.

Before testing at visit 1, pure-tone air conduction audiometric thresholds were obtained for both ears using a clinical audiometer with ER-3 insert earphones (Etymotic Research, Elk Grove Village, IL). Pure-tone audiometry in the better-hearing ear was repeated at visit 2 for all listeners except *MBI*, who could not complete the audiometric testing due to fatigue. Pure-tone audiometry revealed that four of the eight participants had some degree of measurable hearing in the ear-to-be-implanted. Listener *MBB* had mild sloping to moderate sensorineural hearing loss from 125 to 250 Hz, moderately severe loss from 500 to 3000 Hz, and severe-to-profound loss from 4000 to 8000 Hz. Listener *MBE* had severe sensorineural hearing loss at 125 Hz sloping to profound loss at 500 to 8000 Hz (with no responses at the limits of the audiometer at 6000 and 8000 Hz). Listener *MBF* had an essentially flat, severe-to-profound sensorineural hearing loss from 125 to 8000 Hz. Listener *MBG* had a severe rising-to-moderate sensorineural hearing loss from 250 to 8000 Hz. In the better-hearing ear, all listeners had four-frequency pure-tone averages ≤30 dB HL, and interaural threshold differences ≥40 dB HL, consistent with one consensus definition of SSD (van de Heyning et al. 2017).

In addition to pure-tone audiometry, clinical audiologic testing in each study visit included an assessment of intelligibility for consonant-nucleus-consonant (CNC) words presented in quiet. Each CNC list consisted of 50 recordings of monosyllabic target words (each preceded by the word “ready?”) spoken by a male talker. During visits 1 and 2, one CNC word list was presented to the NH ear at 65 dB SPL via an ER-3 insert earphone. Testing of the CI ear during visit 2 was completed by presenting one CNC word list at 65 dB SPL from a loudspeaker at 0° azimuth, 1 m away from the listener. While the CI ear was tested during visit 2, the NH ear was occluded with a foam earplug beneath an earmuff.

Equipment and Stimuli

Testing was conducted in a standard IAC sound booth (Acoustic Systems, Austin, TX). Participants sat in a comfortable chair positioned in front of a table with a fixed head mount, against which they rested their forehead. The height of the table and/or chair was adjusted for each participant. A computer monitor was attached to the table via an adjustable arm and positioned so that it was approximately 65 cm away from the headrest. Consistent room illumination was maintained with two-floor lamps with three-position switches in the corners of the room behind the pupil tracking camera. Each lamp switch was set to the middle position, providing "low to moderate" illumination, but minor adjustments were made in the event of eye tracker calibration issues. The computer monitor was used to display a fixation cross for participants to look at while they listened to the stimuli. A neutral background of medium gray was used on the computer monitor to avoid excessive pupil restriction or dilation (Winn et al. 2018). The testing booth contained three loudspeakers (Model "Reveal 402," Tannoy, Coatbridge, Scotland), positioned at −90°, 0°, and +90° azimuth (i.e., far-left, center, and far-right) 110.5 cm from the listener's head, and at a height of 131 cm from the floor; at this height, the top of the computer monitor (119 cm from the floor) did not obstruct the loudspeaker in front of the participant. The pupil area was measured in pixels with an Eyelink 1000 Plus eye tracker (SR Research, Ltd., Ottawa, Ontario, Canada). The tracker's camera was affixed to the table via a desktop mount 8 cm in front of the computer monitor. Pupil area data were sampled at a rate of 1000 Hz using SR Research, Ltd.'s proprietary algorithm.

Target stimuli were selected from the Harvard Institute of Electrical and Electronics Engineers (IEEE) sentence corpus (Rothauser 1969) and were recorded by a male talker. These varied in length from 4000 to 6000 msec. Masker stimuli consisted of AzBio (Spahr et al. 2012) sentence recordings of two different male talkers. The sentences were randomly sampled and concatenated into a single file. A 180° phase difference was introduced between the concatenated masker files to minimize their coherence and prevent listeners from perceptually combining them (Saberi et al. 1991). Phase information can serve as a cue for auditory grouping; therefore, when the maskers were spatially separated, participants would, in theory, perceive them as distinct. For each trial, starting points within both of the concatenated masker files were selected randomly. Masker presentation began 250 msec before and ended 250 msec after the target sentence presentation.

Before testing, all stimuli were root mean square-equalized and saved as .WAV files. Target and masker stimuli were scaled to 65 dB(A) sound pressure level and presented through loudspeakers connected to a high-speed USB audio interface (RME Fireface; Haimhausen, Germany). To maintain a SNR of 0 dB with two maskers, the masker stimuli were individually calibrated to 65 dB(A), and then scaled down by 3 dB. Stimulus presentation and data collection were managed by a custom MATLAB script (the MathWorks, Natick, MA) using the Psychtoolbox 3 package (Kleiner et al. 2007) running on a Windows PC. This script also captured participant pupil area data from a separate laptop controlling the EyeLink system.

Procedure

Speech intelligibility and PPD were measured in three target-masker configurations with the target fixed at 0° azimuth: (1) quiet, (2) with maskers co-located at 0° azimuth [S0°N0°], and (3) with maskers spatially separated at ±90° azimuth [S0°N ± 90°]. In all configurations, the target was always presented from the loudspeaker at 0° azimuth. In the co-located configuration, both maskers were also presented from the loudspeaker at 0° azimuth at an SNR of 0 dB. In the spatially separated configuration, one masker was presented from the loudspeaker at +90° azimuth, the other was presented from the loudspeaker at −90° azimuth, and an SNR of 0 dB was maintained. These spatial configurations limit head shadow cues, allowing for a more direct evaluation of binaural summation and squelch.

Testing took place over the course of two visits: visit 1 (pre-CI) and visit 2 (post-CI). At visit 1, participants were tested in one listening mode: acoustic-only (deaf ear occluded with foam earplug beneath an earmuff). At visit 2, participants were tested in three listening modes: acoustic-only (CI speech processor removed), CI-only (NH ear occluded with foam earplug beneath an earmuff), and SSD-CI (both ears available). The target-masker configurations tested in each listening mode during the two visits are listed in Table 2.

We aimed to test 30 trials (i.e., 30 IEEE sentences) for each target-masker configuration/listening mode combination. The 30 trials were separated into two blocks of 15 sentences each, with the target-masker configuration and listening mode fixed within a block. Task-evoked pupillary responses to stimuli in easier configurations (e.g., quiet) have been found to be smaller than those for more difficult configurations (Winn et al. 2018). Thus, one additional block of 15 trials in the quiet configuration (for a total of 45 trials) was included to improve the signal (i.e., task-evoked change in pupil size) to noise (e.g., random pupil oscillations) ratio of the pupil tracks when averaged. All participants completed three blocks of 15 trials in quiet except for MBI, who could not complete the additional block due to reported fatigue. The order of blocks (and therefore target-masker configuration/listening mode combination) was randomized for each participant. For each trial, an IEEE target sentence was randomly selected (without replacement) from the corpus. Some participants were tested in the morning, while others were tested in the afternoon. Speech intelligibility was quantified as the percentage of correctly repeated IEEE key words, and listening effort was quantified as peak proportional change in PPD relative to baseline dilation.

Pupillometry

Pupil size was tracked during every trial, each of which began with 1000 msec of silence. During this time, baseline PPD was calculated as the average pupil size. The stimulus was then played, followed by 2000 msec of silence and then a response prompt (signaled by the fixation cross changing from white to green and the presentation of two "beeps" from the loudspeaker at 0° azimuth). As the participant verbally reported the contents of the target sentence, the experimenter marked which of the five key words were correct. Participants were encouraged to provide a guess if they were uncertain of what they heard. Participants were offered frequent breaks throughout the testing session to minimize fatigue. The experimenter

TABLE 2. Listening modes and target-masker configurations associated with visits 1 and 2

		Listening Modes and Test Intervals			
		Acoustic-Only		CI-Only	SSD-CI (Acoustic Ear + CI Ear)
		Visit 1	Visit 2	Visit 2	Visit 2
Target Masker Configurations	Quiet	✓	✓	✓	✓
	Target + Co-Located Maskers	✓			✓
	Target + Separated Maskers	✓			✓

CI, cochlear implant; PPD, pupil dilation; SSD, single-sided deafness.

waited 10 to 15 sec between trials to allow the pupil to return to its baseline size.

Data Analysis

Biological artifacts such as blinking or gaze drift are inevitable when recording the task-evoked pupillary response. These artifacts were removed from the final pupil track using SR Research's proprietary algorithm because the discontinuities they introduced to the response were unrelated to the task's demand. Furthermore, trials in which more than 45% of the pupil track samples contained blinks were excluded from analysis. Trials exceeding this criterion were first identified by a custom MATLAB script and later visually inspected by the authors to maximize data integrity and retention. Recent work from our lab found that using a relatively lenient blink criterion (i.e., 45%) compared with a more stringent criterion (e.g., 15%) promoted data retention without compromising the experimental results (Burg et al. 2021). Similar to the method described in Zekveld et al. (2010), traces in the remaining trials were "de-blinked" through linear interpolation of the response 80 msec before and 160 msec following a blink, and were subsequently lowpass-filtered with a moving average using the "smooth" function in MATLAB. In addition to the automated blink analysis and interpolation described earlier, the authors reviewed each track to identify and discard those containing abnormal morphology or baseline dilation values. Retained trials were organized by participant and listening condition, which included different combinations of listening mode and target-masker configuration. Baseline-adjusted pupil tracks were aligned relative to stimulus offset and averaged to produce a mean pupil trace. Tonic PPD, which is dilation not directly related to the immediate task, varies considerably. To reduce the impact of baseline variability on the magnitude of peak task-evoked PPD within each mean pupil trace, we opted for a proportional rather than a subtractive baseline correction. This method helps mitigate the effects of variation between different conditions and participants (Winn et al. 2018). The peak proportional change in PPD relative to baseline was identified within the 2 sec window following stimulus offset; this window was chosen because it has shown high amounts of task-evoked PPD associated with speech recognition (Winn 2016; Winn et al. 2018). Furthermore, it is thought to be the window of time in which the participant is planning their response (Zekveld et al. 2010). The amount of spatial release from listening effort (SRE) was calculated for each participant as the arithmetic difference in mean PPD values between the separated and co-located target-masker configurations, with a more negative value indicating more SRE.

For every retained pupillometry trial, percentage of correctly repeated words was calculated by dividing the number of correct key words by five, or the total number of key words. To examine changes in speech intelligibility across conditions, we also included two derived measures: amount of masking (% correct$_{\text{quiet}}$ − % correct$_{\text{co-located}}$) and SRM (% correct$_{\text{separated}}$ − % correct$_{\text{co-located}}$), with more positive values indicating more masking or SRM, respectively.

In this study, a mix of parametric and nonparametric tests were utilized to analyze the test results due to the diverse nature of the data distributions and the varying sample sizes across different conditions. Nonparametric tests were used when data did not meet normality assumptions or had small sample sizes, ensuring robustness. Parametric tests were used for normally distributed data, providing increased statistical power and the ability to test interactions. This combined approach ensured accurate and reliable analysis tailored to the characteristics of the data.

Hypotheses

Given that SSD-CI listeners self-report reductions in effort with the addition of a CI in certain noise configurations, we aimed to examine the relationship between speech intelligibility and listening effort in quiet and with maskers using pupillometry, an objective measure of listening effort. We hypothesized that:

1. When listening to speech in the presence of maskers (i.e., co-located and spatially separated target-masker configurations), participants would demonstrate

(A) improved speech intelligibility and (B) smaller peak proportional change in PPD after cochlear implantation (SSD-CI listening) compared with before (acoustic-only) due to restored access to sound in both ears, which can facilitate binaural redundancy.

2. When comparing the spatially separated and co-located target-masker configurations, in the acoustic-only (visit 1) and SSD-CI (visit 2) listening modes, participants would exhibit (A) better speech intelligibility (SRM) and (B) lower peak proportional change in PPD in the spatially separated condition (SRE), due to an improvement in the availability of spatial cues that facilitate binaural unmasking, and/or effective SNR at each ear from the head shadow effect.
3. The magnitude of (A) SRM and (B) SRE would be greater in the SSD-CI listening mode compared with the acoustic-only mode due to the availability of binaural cues that can aid in the perceptual separation of target and maskers.
4. Improvement in speech intelligibility from co-located to spatially separated configurations (SRM) would be associated with reduction in PPD from co-located to spatially separated configurations (SRE) in the SSD-CI listening mode due to improved access to spatial hearing cues that can facilitate the perceptual separation of target and maskers.

This work is clinically relevant due to the increasing number of patients with SSD who are receiving CIs. To improve patient outcomes, it is imperative to understand how SSD-CI listeners combine information across ears and function in realistic noisy environments.

RESULTS

Audiologic Test Results

Table 3 shows pure-tone air conduction audiometric thresholds for the acoustic ear obtained at each study visit (except for *MBI* who only completed audiometric testing at visit (1). The mean difference in thresholds between visits was less than 5 dB HL at each frequency, indicating no clinically significant change. Speech recognition scores for CNC words in quiet were recorded across different listening modes and visits. In the CI-only mode during visit 2, scores ranged from 0 to 64% (M = 37.7%, SD = 20.32%). It is important to note the possibility that the acoustic ear (which was occluded with a plug and earmuff but not presented with masking noise) may have contributed to the speech intelligibility scores in the CI-only mode during visit 2. For the acoustic-only mode, scores from visit 1 ranged from 96 to 100% (M = 98.5%, SD = 1.41%), while scores from visit 2 ranged from 90 to 100% (M = 97.33%, SD = 3.93%). Because two participants (*MBE* and *MBI*) did not complete CNC testing in quiet in the acoustic-only listening mode during visit 2, we could only determine group differences for a subset of the participants. We used a Wilcoxon Signed-Rank test to assess the small difference in CNC scores in the acoustic-only listening mode between visits 1 and 2. This exploratory post hoc analysis did not reveal a statistically significant difference (M = 1.17%, z = 0.65, p = 0.66).

Speech Intelligibility in Quiet

Figure 1 shows scores for IEEE sentences presented in quiet by listening mode. We first tested whether use of a CI in the initial year following surgery affects the acoustic hearing ear by comparing scores for IEEE sentences presented in quiet in the acoustic-only listening mode between visit 1 and visit 2. A Shapiro–Wilk normality test revealed that differences in scores were not normally distributed ($p < 0.05$). As such, a Wilcoxon-signed rank test was conducted on these scores. The result of this test suggested that scores for IEEE sentences presented in quiet with the acoustic-only listening mode did not differ between visit 1 and visit 2 (M = 0.44%, SD = 0.79%, $z = -1.68$, p = 0.10).

A post hoc assessment of listening mode (three levels: “acoustic-only (visit 1),” “SSD-CI (visit 2),” “CI-only (visit 2)”) on intelligibility for IEEE sentences presented in quiet was conducted. Mauchly test of sphericity revealed heterogeneous variance of the differences between listening modes ($p < 0.001$). A Shapiro–Wilk normality test indicated that the residuals of a

TABLE 3. Pure-tone thresholds (dB HL) for the acoustic ear

		Frequency (Hz)								
Participant ID	Visit	125	250	500	1000	2000	3000	4000	6000	8000
MBA	1	20	25	20	25	25	10	10	15	5
	2	10	15	20	15	20	5	15	20	5
MBB	1	5	5	5	0	10	10	10	20	20
	2	5	5	0	0	5	10	10	15	20
MBC	1	10	10	5	10	15	30	15	40	45
	2	5	5	5	5	10	25	15	40	50
MBE	1	5	5	5	10	5	10	10	10	0
	2	5	10	0	10	5	10	5	5	0
MBF	1	20	25	20	15	35	30	30	35	35
	2	20	25	20	20	35	30	25	30	15
MBG	1	15	20	20	15	10	5	15	20	25
	2	15	15	15	15	10	10	20	20	30
MBH	1	5	5	10	10	10	10	5	10	0
	2	–5	0	0	5	0	5	5	5	5
MBI	1	10	10	15	15	15	20	25	30	50
	2	–	–	–	–	–	–	–	–	–
Mean difference		3.57	2.86	3.57	2.14	3.57	1.43	0	2.14	0.71

repeated measures analysis of variance were not normally distributed ($p < 0.05$). Therefore, we tested the main effect of listening mode on speech intelligibility with a Friedman analysis of variance (ANOVA), conducted Wilcoxon-signed rank tests to assess the differences between each pair of listening modes, and used Bonferroni-adjusted significance values to reduce the likelihood of type I error when conducting multiple comparisons.

The omnibus test indicated a significant difference across listening modes [$x^2(2) = 14.25$, $p < 0.001$] for speech presented in quiet. There was a very small, but significant difference between the scores from the acoustic-only (visit 1) listening mode and the SSD-CI (visit 2) listening mode (M = 0.95%, SD = 0.89%, $z = -2.38$, $p_{\text{Bonferroni}} = 0.05$). When comparing the CI-only mode with the other listening modes, performance was significantly better for the acoustic-only (visit 1) listening mode (M = 16.23%, SD = 11.66%, $z = 2.52$, $p_{\text{Bonferroni}} = 0.02$) and the SSD-CI (visit 2) listening mode (M = 17.18%, SD = 12.49%, $z = 2.52$, $p_{\text{Bonferroni}} = 0.02$). Unsurprisingly, these findings suggest that access to acoustic hearing in one ear drives performance in quiet. It is important to note that combining the acoustic hearing ear with a CI in the opposite ear does not negatively affect performance in quiet. As discussed later in more detail, some caution is warranted when considering significant findings that are somewhat small in value, as their clinical significance might not be very high.

Speech Intelligibility With Interfering Maskers

Next, we evaluated the amount of masking across listening modes by calculating the difference in speech intelligibility between quiet and co-located target-masker configurations. We compared percent correct scores for the acoustic-only listening mode at visit 1 to the SSD-CI listening mode at visit 2 to examine the effect of adding a CI to the deaf ear. Figure 2 shows the average amount of masking was higher in the acoustic-only (visit 1) listening mode compared with the SSD-CI (visit 2) listening mode. For all listeners but one (*MBI*), masking was similar or lower for the SSD-CI (visit 2) listening mode (M = 37.29%, SD = 18.17%) compared with acoustic-only (visit 1) listening mode (M = 45.74%, SD = 8.66%). We conducted a post hoc assessment of the effect of listening mode on the amount of masking using a paired-samples t test. To confirm that the differences in amount of masking were normally distributed, we used the Shapiro–Wilk test. The amount of masking was not significantly different between acoustic-only (visit 1) and SSD-CI (visit 2) listening modes [M = 8.45%, SD = 14.96%, $t(1,7) = 1.6$, $p = 0.15$].

Figure 3 shows speech intelligibility scores for the two masker configurations, during the two visits. To examine the within-subjects effect of target-masker configuration and listening mode on speech intelligibility, we conducted a two-way repeated measures factorial ANOVA with listening mode (two levels: acoustic-only [visit 1], SSD-CI [visit 2]), and target-masker configuration (two levels: co-located, separated) as the independent variables. Shapiro–Wilk tests were used to check the normality of residuals of both factors and their interaction ($p > 0.05$ for all).

Hypothesis 1A was that participants would demonstrate improved speech intelligibility in the presence of maskers after receiving a CI in the deaf ear. Speech intelligibility scores across both configurations were 10.3% higher in the SSD-CI (visit 2) listening mode compared with the acoustic-only (visit 1) listening mode (Fig. 3), however the main effect of listening mode did not reach significance [M = 10.3%, $F(1,7) = 4.91$, $p = 0.06$, $\eta^2_{\text{generalized}} = 0.10$]. Hypothesis 2A was that participants would perform better when target and maskers were spatially separated compared with when they were co-located (regardless of listening mode). In line with this hypothesis, speech intelligibility scores were significantly higher in the separated target-masker configuration [M = 7.8%, $F(1,7) = 6.94$, $p = 0.03$, $\eta^2_{\text{generalized}} = 0.06$), indicating that participants demonstrated SRM. Hypothesis 3A was that participants would benefit more from spatial separation of target and maskers (i.e., obtain more SRM) in the SSD-CI listening mode compared with acoustic-only listening mode. On average, participants demonstrated SRM values of 6.97% in the acoustic-only (visit 1) listening mode (range: −23.49 to 14.67%, M = −6.97%, SD = 13.33%),

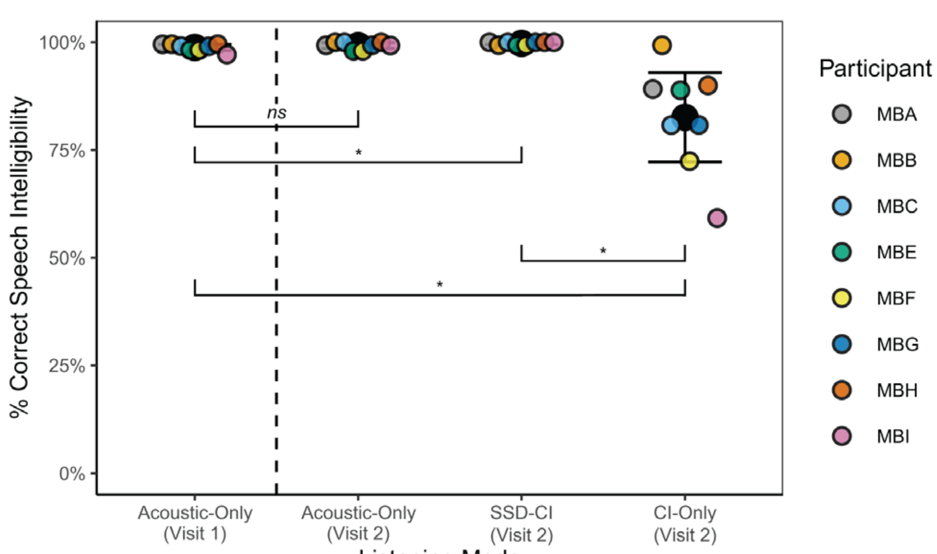

Fig. 1. Percent correct scores for the speech understanding task are shown for each participant and for each listening mode in quiet. Error bars indicate 95% CIs. The dotted line distinguishes scores obtained during visit 1 from visit 2. * indicates $p < 0.05$; ns, $p \geq 0.05$.

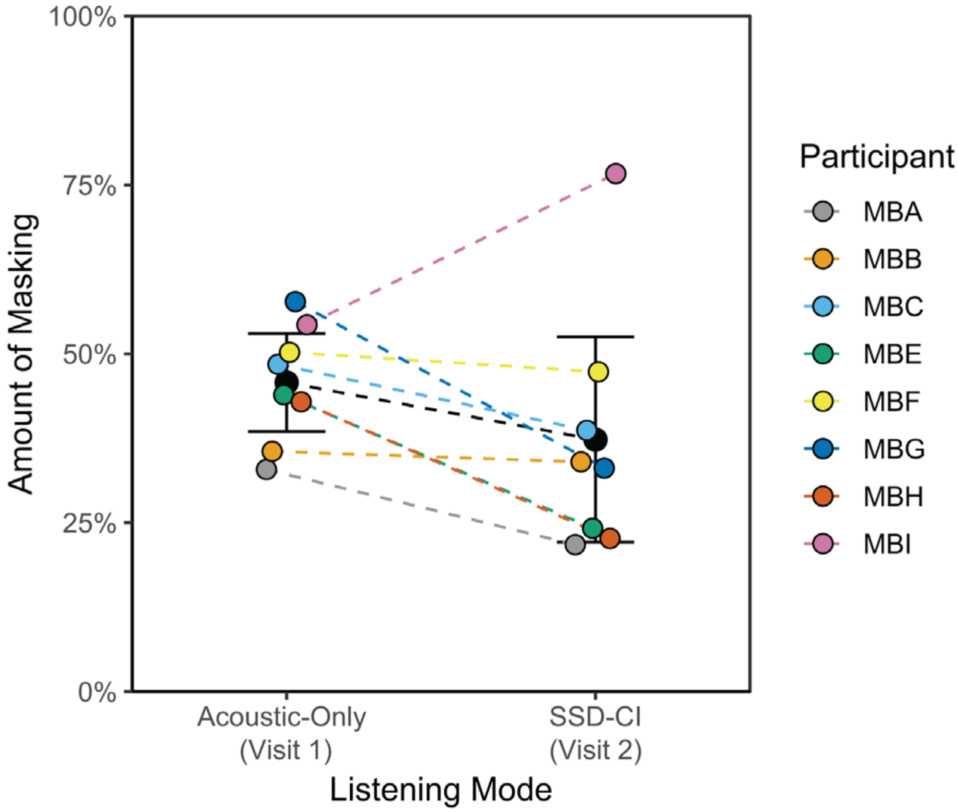

Fig. 2. For each participant, mean masking (% correct quiet – % correct co-located) is shown for acoustic-only (visit 1) and SSD-CI (visit 2). Error bars indicate 95% confidence intervals. CI indicates cochlear implant; SSD, single-sided deafness.

and 8.72% in the SSD-CI (visit 2) listening mode (range: −16.97 to 0.09%, $M = -8.72\%$, SD = 6.67%). The interaction between target-masker configuration and listening mode was not significant [$M = 1.75\%$, $F(1,7) = 0.15$, $p = 0.71$], indicating that, although in the predicted direction, SRM was not statistically different between the two listening modes.

Effect of Listening Mode on PPD in Quiet

Figure 4A shows the grand mean pupil traces for sentences presented in quiet for each listening mode. The 2-sec interval between the vertical dashed lines comprises the analysis window from which PPD was obtained. Figure 4B shows mean task-evoked PPD for sentences presented in quiet by listening mode. Our analyses tested whether use of a CI in the initial year following surgery affected the listening effort associated with acoustic-only listening in quiet by comparing PPD between visit 1 and visit 2. After confirming that differences in amounts of PPD were normally distributed with a Shapiro-Wilk normality test ($p > 0.05$), we conducted a paired-samples t test on the differences in amounts of PPD. The result of the t test suggested that task-evoked PPD for sentences presented in quiet with the acoustic-only listening mode did not differ significantly between visit 1 ($M = 0.11$, SD = 0.05) and visit 2 ($M = 0.11$, SD = 0.06) [$t(7) = -0.12$, $p = 0.91$].

We next completed a post hoc assessment of the effect of listening mode on the listening effort associated with sentences in quiet. We completed a repeated measures factorial ANOVA with listening mode as the independent variable (three levels: “acoustic-only (visit 1),” “SSD-CI (visit 2),” “CI-only (visit 2)”) on task-evoked PPD. A Shapiro–Wilk normality test suggested that residuals were normally distributed ($p > 0.05$), and Mauchly test of sphericity suggested homogeneity of variance ($p > 0.05$). The ANOVA revealed a significant effect of listening mode on PPD [$F(2,14) = 5.28$, $p = 0.02$, $\eta^2_{generalized} = 0.27$]. After confirming that the differences in PPD between listening modes were normally distributed with Shapiro–Wilk normality tests ($p > 0.05$ for all), we assessed the differences with paired t tests and used Bonferroni-adjusted significance values to reduce the likelihood of type I error when conducting multiple comparisons. PPD was significantly higher in the CI-only (visit 2) listening mode ($M = 0.22$, SD = 0.09) than the acoustic-only (visit 1) listening mode ($M = 0.11$, SD = 0.05) [$t(7) = 3.58$, $p_{Bonferroni} = 0.03$]. There was a non-significant difference in amount of PPD in the CI-only (visit 2) listening mode compared with the SSD-CI (visit 2) listening mode ($M = 0.12$, SD = 0.09) [$t(7) = 2.15$, $p_{Bonferroni} = 0.21$], and there was a non-significant difference in amount of PPD in the SSD-CI (visit 2) listening mode and the acoustic-only (visit 1) listening mode [$t(7) = -0.52$, $p_{Bonferroni} = 1$]. This suggests that listening in CI-only mode requires significantly more listening effort compared with acoustic-only mode, while the effort required for SSD-CI mode does not significantly differ from either CI-only or acoustic-only modes.

Effect of Listening Mode and Masker Configuration on PPD

To examine the effect on PPD of masker configuration and listening mode, we conducted a two-way repeated measures factorial ANOVA with listening mode (two levels: acoustic-only [visit 1], SSD-CI [visit 2]), and target-masker configuration (two levels: co-located, separated) as the independent variables.

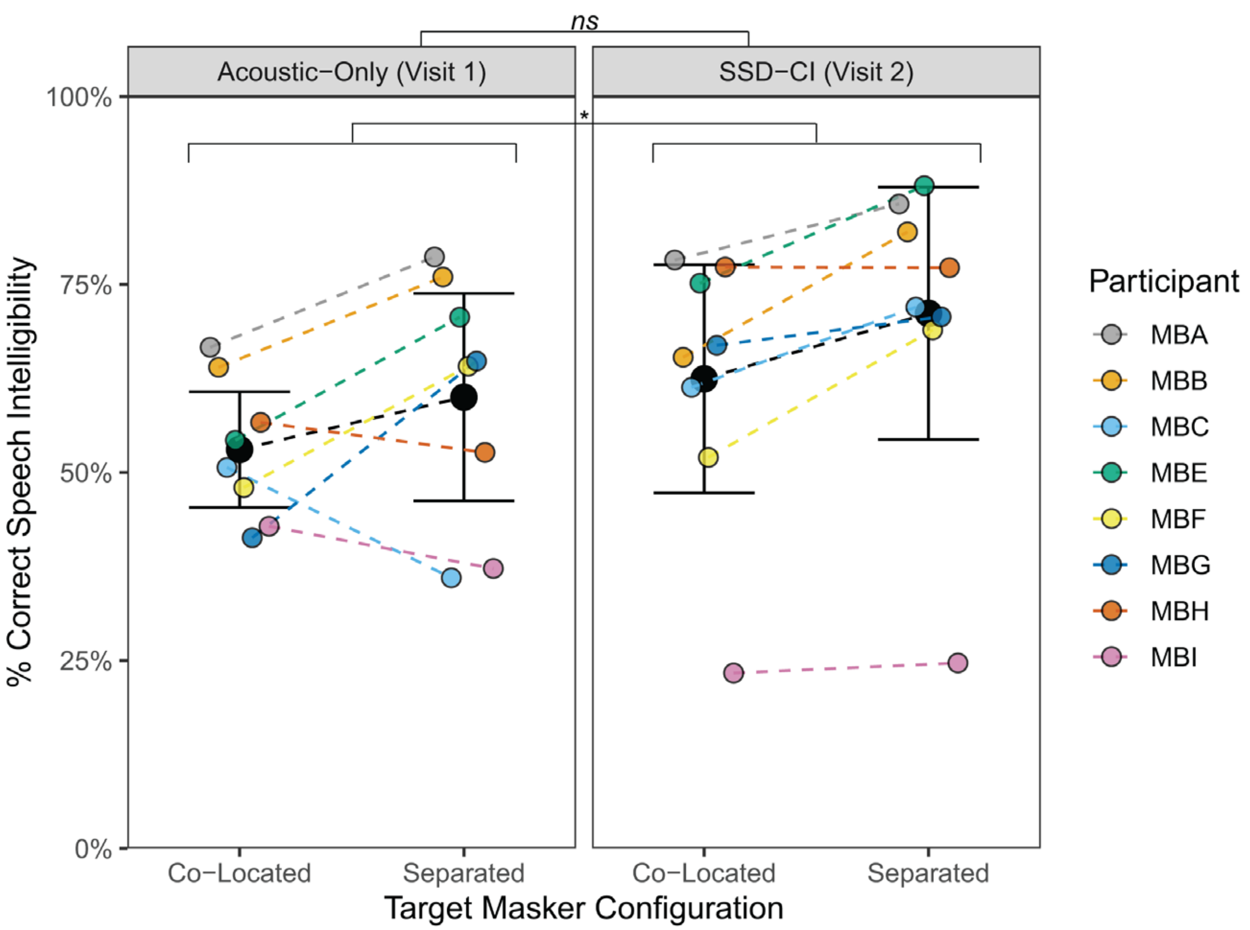

Fig. 3. Percent correct for speech target is shown for each participant, comparing co-located and separated target-masker configurations, in the acoustic-only (visit 1) and SSD-CI (visit 2) listening modes. Error bars indicate 95% confidence intervals. CI indicates cochlear implant; SSD, single-sided deafness; *, $p < 0.05$; *ns*, $p \geq 0.05$.

Shapiro–Wilk Tests confirmed that residuals for both factors and their interaction were normally distributed ($p > 0.05$ for all). Figure 5 shows individual and grand-mean pupil traces for each masker configuration grouped by listening mode. Individual and group PPD values are plotted in Figure 6.

Hypothesis 1B was that participants would demonstrate smaller proportional change in PPD following implantation on visit 2 (SSD-CI listening mode) compared with before implantation on visit 1 (acoustic-only listening mode) due to restored access to sound in both ears. The right panel of Figure 6 shows that on average, PPD across the co-located and separated target-masker configurations was higher in the SSD-CI (visit 2) compared with the acoustic-only (visit 1) listening mode. However, the main effect of listening mode on PPD was not significant [$M = 0.05$, $F(1,7) = 2.64$, $p = 0.15$, $\eta^2_{\text{generalized}} = 0.07$]. Hypothesis 2B was that when comparing the spatially separated and co-located target-masker configurations, participants would exhibit lower peak proportional change in PPD in the spatially separated target-masker configuration, that is, SRE, due to binaural unmasking and/or an improvement in the effective SNR at each ear from the head shadow effect. Note that SRM is reflected in positive differences in speech scores between separated versus co-located target-masker configurations, whereas SRE would be observed as negative differences in PPD between separated versus co-located target-masker configurations. Both panels of Figure 6 show that average PPD was smaller for the separated configuration compared with the co-located configuration, but there was significant variability among participants. The main effect of target-masker configuration on PPD was not significant [$M = 0.02$, $F(1,7) = 0.43$, $p = 0.54$, $\eta^2_{\text{generalized}} = 0.01$]. Hypothesis 3B was that SRE would be greater in the SSD-CI (visit 2) listening mode compared with the acoustic-only (visit 1) mode due to the availability of binaural cues that can aid in the perceptual separation of target and maskers. The test of the interaction between listening mode and target-masker configuration was also not significant [$M = 0.03$, $F(1,7) = 0.30$, $p = 0.6$, $\eta^2_{\text{generalized}} = 0.01$]. Because the ANOVA did not reveal any significant main effects, we did not proceed with our planned pairwise comparisons. This suggests that while there were observable trends in PPD changes across different listening modes and target-masker configurations, the variability among participants and the lack of significant main effects indicate that the expected benefits of binaural redundancy and spatial separation on listening effort were not consistently realized in this sample.

Relationship Between Spatial Benefits to Speech Intelligibility and Listening Effort

Hypothesis 4 was that improvements in speech intelligibility from co-located to spatially separated target-masker configurations, that is, SRM, would be associated with reductions in PPD

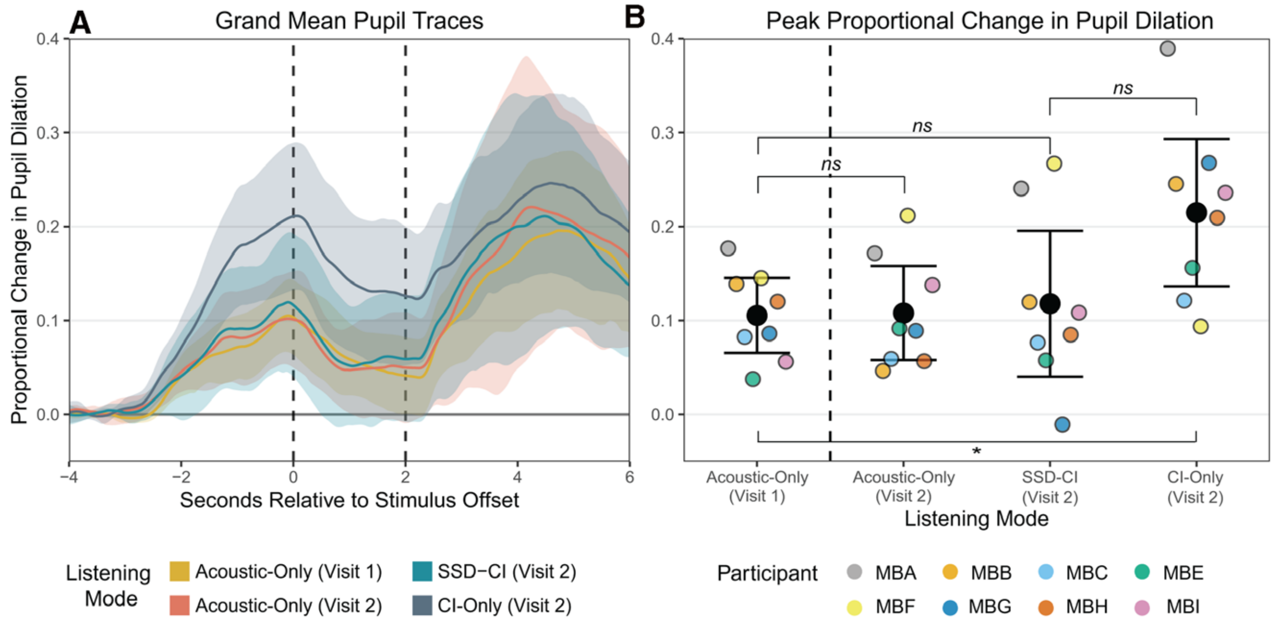

Fig. 4. Proportional change in PPD relative to baseline in the quiet target-masker configuration. A, Group-level grand mean pupil tracks (solid lines) surrounded by 95% CIs (shaded ribbons) for each listening mode, for a total of 10 sec. Baseline dilation was obtained for 4 sec before stimulus onset, and the following 6 sec reflect PPD following stimulus onset. The dotted vertical bars indicate the "waiting" period between sentence presentation and the response prompt, and is the interval from which the peak PPD is obtained. B, Individual participants' (filled circles) and group (black circles and 95% confidence error bars) peak PPD for each listening mode. The dotted line distinguishes scores obtained during visit 1 from visit 2. CI indicates cochlear implant; *, $p < 0.05$; ns, $p \geq 0.05$; PPD, pupil dilation; SSD, single-sided deafness.

from co-located to spatially separated target-masker configurations, that is, SRE, in the SSD-CI (visit 2) listening mode. In other words, we tested whether improvements in spatial hearing abilities provided benefit beyond better behavioral performance. Results from a Pearson correlation analysis presented in Figure 7 indicated that SRE was negatively correlated with SRM. Specifically, larger improvements in speech intelligibility due to spatial separation of the target and maskers were associated with greater reductions in listening effort [$t(6) = -2.62$, $r = -0.73$, $p = 0.04$]. This suggests that SSD-CI listeners experience benefits to both speech intelligibility and listening effort when speech targets and maskers are in different spatial locations. Due to concerns that listener *MBF* exerted high influence on the significance of the correlation, we removed them from the dataset and tested the correlation again. With *MBF* removed, the strength of the correlation was similar but no longer significant [$t(5) = -2.38$, $r = -0.73$, $p = 0.06$].

DISCUSSION

This study aimed to evaluate the effects of cochlear implantation on both speech intelligibility and PPD, the latter used as an indicator of listening effort, in individuals with SSD who received a CI in the deaf ear (SSD-CI). The research primarily focused on how these outcomes differed when participants were exposed to speech maskers positioned in various spatial configurations, across different listening modes, NH acoustic ear alone and SSD-CI. Our aim was to determine the extent to which a CI could alleviate some of the challenges faced by SSD patients, namely, difficulty understanding speech-in-noise and the need to exert elevated levels of effort to hear and communicate. These questions are critical to address because previous research involving SSD-CI recipients mainly highlighted outcomes such as the reduction of tinnitus disturbance (Van de Heyning et al. 2008), decrease in perceived listening effort (Lopez et al. 2021), enhancements in sound localization (Litovsky et al. 2019), and improvements in speech intelligibility (Vermeire & Van de Heyning 2009; Arndt et al. 2011; Bernstein et al. 2016; Dirks et al. 2019). These studies collectively support the notion that cochlear implantation in patients with SSD leads to significantly enhanced outcomes, including quality of life improvements (Dillon et al. 2017; Häußler et al. 2019).

Two major findings from the present study are that (1) patients demonstrated statistically significant SRM (hypothesis 2A), and (2) there was an association between SRM and SRE (hypothesis 4), such that increases in SRM benefits were associated with decreased listening effort. The results from this study suggest that for listeners with SSD, adding a CI does not interfere with SRM and is associated with a trend toward better target speech intelligibility regardless of speech masker spatial configuration compared with acoustic-only listening. These benefits are in accordance with a number of positive outcomes for SSD-CI recipients already demonstrated in the literature, as described earlier.

Speech Intelligibility With Maskers Pre- and Post-Cochlear Implantation

Initially, we compared audiograms of the acoustic ear before and after a year of CI experience. The mean pure-tone thresholds did not vary by more than 5 dB HL at any frequency; indeed, most thresholds were lower (i.e., improved) when measured during the second visit. However, this should not be interpreted as an improvement in thresholds but rather

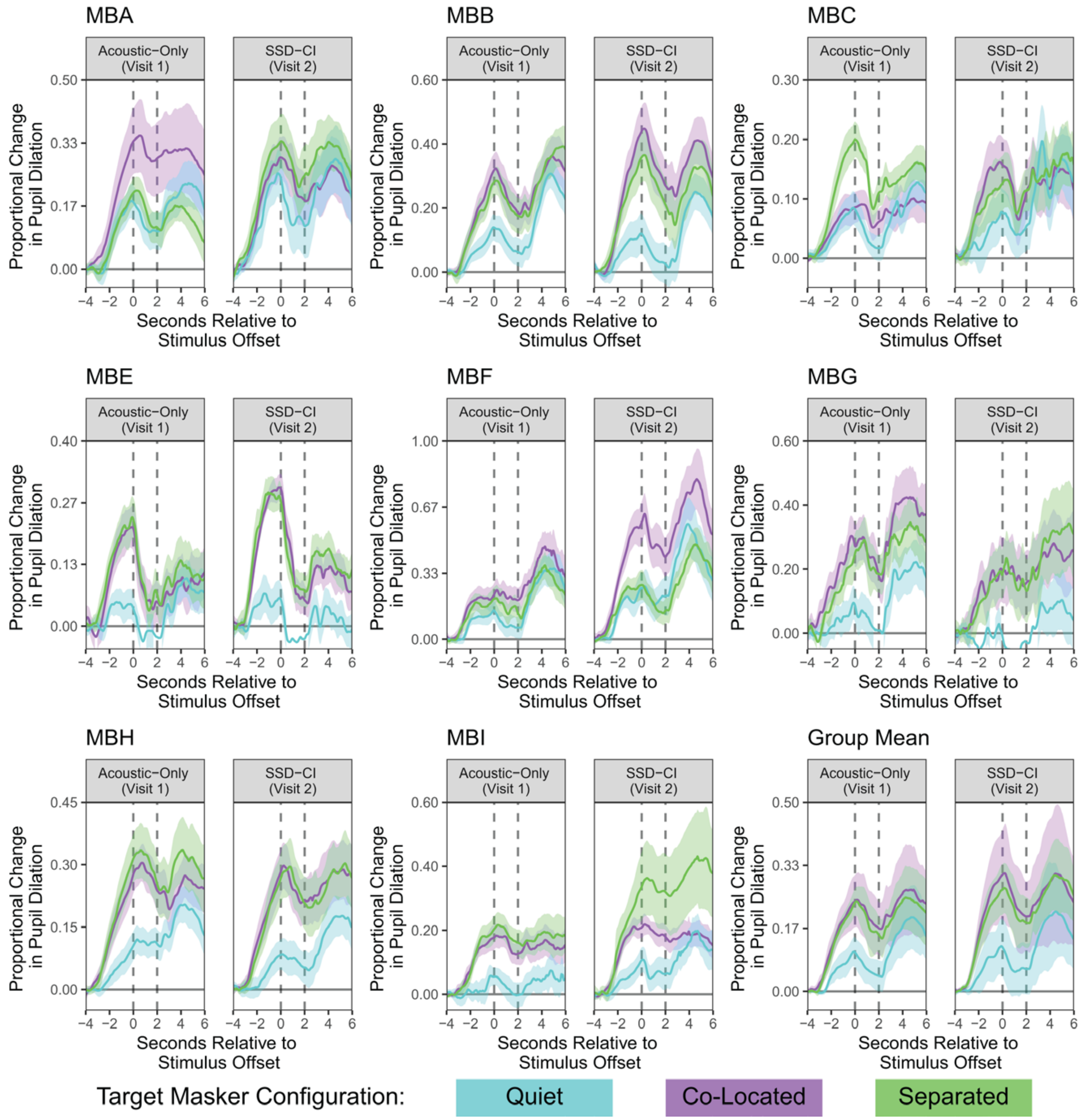

Fig. 5. For each participant (one per plot), the grand mean traces of proportional change in PPD relative to baseline as a function of time relative to stimulus offset for each target-masker configuration, faceted by listening mode. Participant codes are displayed earlier each plot. 95% confidence intervals (shaded color ribbons) surround the grand mean (solid lines). Group PPD traces (mean + 95% confidence intervals) are shown in the bottom-right corner. Note the unique *y*-axis values, which were scaled independently for each subplot to improve legibility. CI indicates cochlear implant; PPD, pupil dilation; SSD, single-sided deafness.

as an indication of their stability. This differs from findings in a study by Arndt et al. (2020), who reported that SSD-CI patients showed poorer four-frequency pure-tone averages in the acoustic ear at a 1 year follow up compared with an age-matched cohort of SSD patients who did not pursue CI. In addition, we observed that speech intelligibility in quiet, measured using IEEE sentences and CNC words in the acoustic-only listening mode, did not show significant differences between the first and second visits. Although we observed a significant difference in scores for IEEE sentences in quiet between the acoustic-only (visit 1) and SSD-CI (visit 2) listening modes, it is important to note that the difference was very small (M = 0.95%, SD = 0.89%), and not clinically meaningful. In the present study, when participants listened to a speech target with co-located maskers, most showed similar or reduced levels of masking in the SSD-CI listening mode during the second visit compared with the acoustic-only mode during the first visit (although the differences in masking levels between these listening modes were not statistically significant). This result is consistent with a previous study in which listeners did not

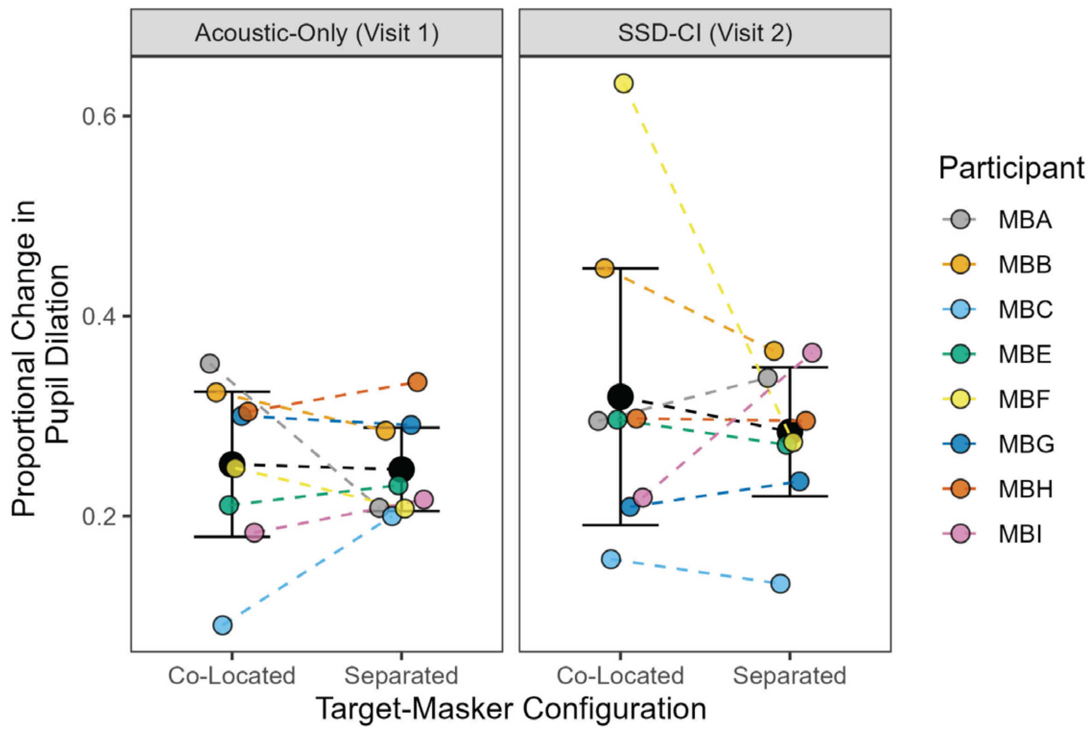

Fig. 6. Proportional change in PPD relative to baseline is shown for each participant, comparing co-located and separated target-masker configurations, in the acoustic-only (visit 1) and SSD-CI (visit 2) listening modes. Error bars indicate 95% confidence intervals. CI indicates cochlear implant; PPD, pupil dilation; SSD, single-sided deafness.

experience a difference in speech target understanding in the presence of a co-located masker with the addition of their CI (Bernstein et al. 2017). However, our findings are not entirely comparable. The observed difference in our study could be due to the availability of a second auditory pathway, which allows additional opportunities for the monaural "glimpsing" of the signal from the ear with a favorable SNR at specific moments. However, compared with the robust glimpsing abilities of listeners with typical hearing (Brungart & Iyer 2012; Glyde et al. 2013), some studies have shown that SSD-CI listeners have limited access to this benefit (Döge et al. 2017; Prejban et al. 2018). Alternatively, those listeners who experienced lower amounts of masking in the SSD-CI listening mode during the second visit, as opposed to the acoustic-only mode during the first visit, might have benefited from binaural summation (Bronkhorst & Plomp 1988), the purported mechanism by which the SSD-CI listeners showed target intelligibility benefit in the report by Prejban et al. (2018). Another possibility is that the difference in speech intelligibility with co-located maskers between listening modes was due in part to familiarity with the task. It is worth noting that the only listener (MBI) with a greater amount of co-located masking in the SSD-CI (visit 2) compared with the acoustic-only (visit 1) listening mode also had the poorest speech intelligibility in the CI-only (visit 2) listening mode for both IEEE sentences and CNC words presented in quiet. Listener MBI was the oldest participant in the study and had the longest duration of unilateral auditory deprivation before implantation. In addition, this participant had difficulty completing all visit 2 test measures due to reported fatigue, which could have influenced the amount of masking demonstrated. Among our small cohort of eight listeners with SSD-CI, it is possible that the degree to which the ears differed did not exceed some limit for these listeners save for *MBI*, whose implant proved detrimental rather than advantageous in the co-located target-masker configuration. Additional studies with a larger data set are needed to further explore this issue.

Spatial Release From Masking and Listening Effort

Spatial separation of speech maskers from the speech target led to SRM, yet the magnitude of SRM did not differ between the SSD-CI mode during visit 2 and the acoustic-only mode during visit 1. Due to the lack of a statistically significant interaction and marginal significance of the effect of listening mode, it is difficult to know whether the addition of electrical stimulation from the CI facilitated SRM. However, it is encouraging that the CI did not interfere with the ability of listeners to benefit from spatial separation of maskers from the target. Although Bernstein et al. (2017) observed greater SRM in the SSD-CI mode than in the acoustic-only mode, a direct comparison with our study is not feasible. Bernstein et al. adaptively tracked the SNR at which key words were repeated correctly, while our study measured the percentage of target words repeated at a 0 dB SNR. Second, their acoustic-only and SSD-CI testing were both completed after implantation. Our decision to test at different time points in the present study was driven by a desire to understand the effects of receiving and using a CI for 1 year on speech intelligibility and listening effort. We aimed to assess long-term outcomes to capture potential improvements or changes after extended CI use. However, by not comparing outcomes within the same visit, we acknowledge a methodological limitation: it becomes challenging to disentangle the effects of

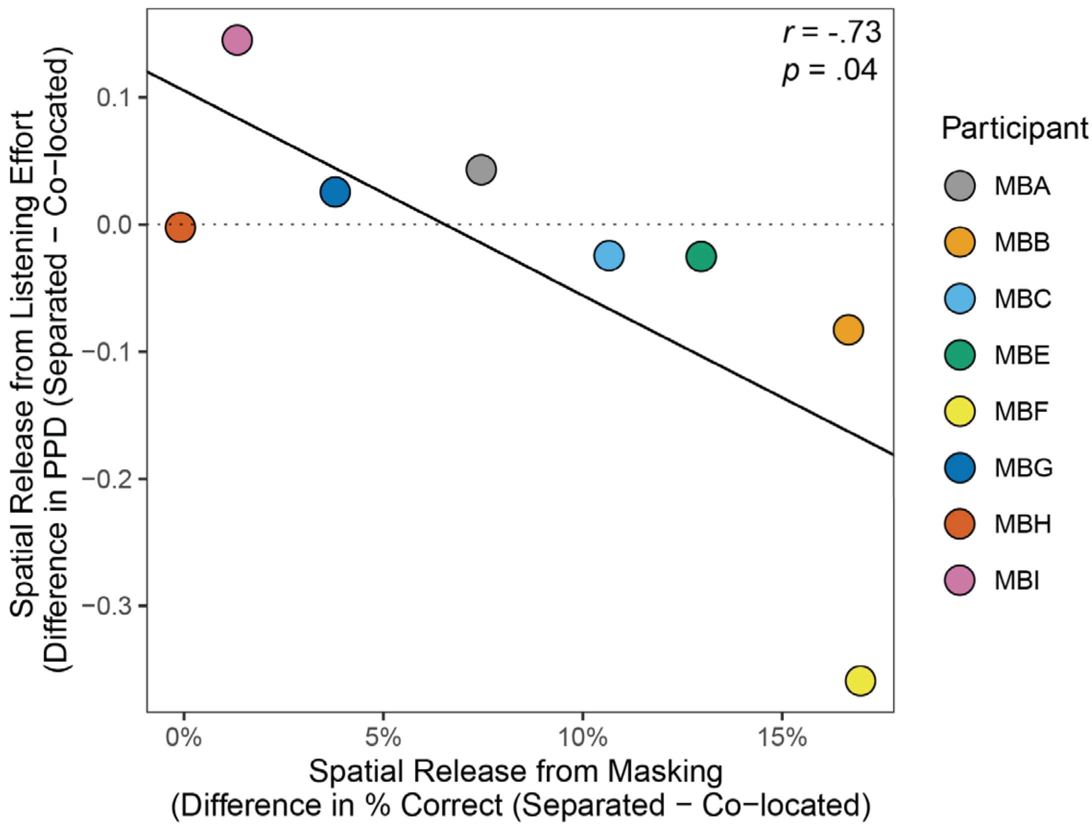

Fig. 7. SRE is plotted as a function of SRM for each listener in the SSD-CI (visit 2) listening mode. The horizontal line at 0 on the *y*-axis indicates equal amounts of proportional change in PPD relative to baseline for the separated and co-located target-masker configurations. CI indicates cochlear implant; PPD, pupil dilation; SRE, spatial release from listening effort; SRM, spatial release from masking; SSD, single-sided deafness.

task familiarity and clinical intervention. Participants may have become more adept at the tasks through repetition 1 year later, irrespective of any benefit from the CI itself.

We did not observe a significant amount of SRE in the acoustic-only (visit 1) or SSD-CI (visit 2) listening modes. Very few data exist in which similar measures have been made. In a group of listeners with typical hearing, Zekveld et al. (2014) found that, although spatial separation of maskers from a target facilitated greater intelligibility for target speech, it did not influence PPD. It is worth noting, however, that rather than investigating the task-evoked pupillary response at the SNR yielding 50% intelligibility, we tested all listeners at the same SNR. Another key difference between previous studies and the current research is the greater age variability within our cohort. This diversity in age was a result of the relatively small population of individuals undergoing CI surgery for SSD in 2016, when our study commenced. This limited pool necessitated a broader age range among participants to gather sufficient data for analysis.

Pupillary Responses Across Listening Modes and Target-Masker Configurations

When presented with IEEE sentences in quiet, listeners showed significantly greater PPD in the CI-only (visit 2) compared with the acoustic-only (visit 1) listening mode. This suggests that listening to speech in quiet with the CI alone after a year of CI experience requires more listening effort compared with listening with the acoustic ear alone before implantation. However, listening to speech in quiet required similar amounts of effort for SSD-CI listening (visit 2) and acoustic-only listening (visit 1), suggesting that in quiet, access to the acoustic ear mitigates the effort required of electric hearing. For a CI recipient with SSD, a CI-only listening mode is only possible by occluding the acoustic hearing ear (e.g., with an earplug). While this practice is recommended by some audiologists and CI manufacturers for (re)habilitation to the CI (Med-El 2021; Lavoy 2023), it is more likely that a CI recipient with SSD would listen through an acoustic-only or SSD-CI "listening mode" in daily life.

While some listeners exhibited greater magnitudes of SRE between the acoustic-only (visit 1) and SSD-CI listening mode, no significant group-level differences were observed. Across the co-located and separated target-masker configurations, SSD-CI listeners demonstrated increased PPD when using the SSD-CI mode during visit 2 compared with the acoustic-only mode during visit 1. This suggests that integrating acoustic and electric inputs incurs a higher "cost" in terms of listening effort. The design of this study precludes direct comparisons to other studies investigating the difference in listening effort before and after cochlear implantation for patients with SSD. Previous research by Lopez et al. (2021) documented a reduction in self-reported listening effort following cochlear implantation compared with when patients listened with only the acoustic ear or utilized other SSD management strategies, such as CROS devices or bone-anchored hearing devices. However, it is important to note that the outcome measure used in their study was the SSQ, which relies on subjective self-report. In contrast, our study employed an objective, real-time measure of listening effort. This distinction is crucial, as objective measures can provide more direct and quantifiable evidence of changes in listening effort, potentially offering a clearer picture of the benefits of CIs over other interventions.

Our observation that several participants exhibited similar, if not greater, amounts of PPD in the SSD-CI (visit 2) listening mode may initially appear inconsistent with the finding of reduced self-reported listening effort following cochlear implantation for SSD (Lopez et al. 2021). This discrepancy suggests either that different effects were observed in the two studies, or that objective measures of listening effort, such as PPD, may not always align with subjective experiences of effort. It raises questions about the complexity of how listening effort is experienced and reported by individuals with SSD, and supports the evidence that subjective and objective assessments are not correlated, and thus capture different facets of listening effort (Alhanbali et al. 2019). Further, Giuliani et al. (2021) compared the sensitivity of objective and subjective approaches to quantifying listening effort and found pupillometry to be consistently the most sensitive. Subjective reports of reduced listening effort with SSD-CI may reflect internal perceptual judgments, while PPD, which is influenced by involuntary neural mechanisms underlying task-evoked pupillary responses, should be compared with caution.

One explanation for why some listeners experienced greater PPD in the SSD-CI (visit 2) compared with the acoustic-only (visit 1) listening mode could be that increased listening effort is required to integrate sound when the two ears are characterized by different degrees of spectral and temporal resolution. The listeners in the present study acquired SSD following decades of hearing with a binaural auditory system that calculated differences in the inputs to two similar ears. In the SSD-CI listening mode, sounds in the implanted ear can be spectrotemporally distinct approximations of the familiar sounds heard by the acoustic ear. A study by Wess et al. (2020) suggested that SSD-CI listeners may experience only "partial fusion" of diotic stimuli presented to ears with asymmetric spectral resolution. Furthermore, reduced binaural fusion has shown to be associated with increased listening effort among children with bilateral CIs, a population that commonly present with asymmetric hearing (Steel et al. 2015). Therefore, in the present study, the increased PPD values observed in the SSD-CI (visit 2) compared with the acoustic-only (visit 1) listening mode may be attributed to the inherent difficulty in integrating acoustic and electric signals.

Another possible explanation for why most listeners exhibited increased PPD in the SSD-CI (visit 2) mode, as opposed to the acoustic-only (visit 1) listening mode, could be that the addition of a CI introduced an asymmetry in spectral resolution between the ears. According to a previous vocoder study by DeRoy Milvae et al. (2021), interfering vocoded speech with more spectral channels than the speech target is associated with increased listening effort. This suggests that the disparity in auditory input quality between the implanted and non-implanted ears could heighten cognitive load, leading to greater effort in processing speech, as reflected in the increased PPD observed. This is consistent with findings from Burg et al. (2022), who reported that listeners with bilateral CIs and asymmetric across-ear speech intelligibility showed increased PPD when listening to speech in quiet with both ears compared with only the better ear. Although these results came from participant groups with distinct auditory profiles, they support the notion proposed by Bernstein and colleagues that "ignoring a clearer interferer is difficult" (Bernstein et al. 2019).

A trend toward higher speech intelligibility scores in both target-masker configurations with the SSD-CI (visit 2) compared with the acoustic-only (visit 1) listening mode suggests that participants benefited from improved access to the speech target provided by the CI. However, the CI also enhanced the audibility of the interfering speech masker located contralateral to the acoustic ear. This dual effect indicates that while the CI helped in discerning speech, it concurrently increased the challenge posed by background speech noise, illustrating a complex interplay between enhanced speech perception and increased auditory competition. Thus, even though SSD-CI listening promoted better speech target intelligibility relative to acoustic-only listening for most listeners, it also resulted in higher PPD values given the maskers to-be-ignored were more intelligible as well.

Summary

The current study highlights findings in patients who listen with one acoustic and one implanted ear (SSD-CI) compared with listening with one acoustic ear, focusing on outcomes for speech intelligibility and listening effort. Consistent with previous literature, speech intelligibility scores were higher for speech targets presented with spatially separated compared with co-located maskers. Overall, speech intelligibility in the presence of maskers improved for most listeners in the SSD-CI (visit 2) listening mode compared with the acoustic-only (visit 1) listening mode, but the effect ($p = 0.06$) did not reach the significance threshold and did not differ by target-masker configuration. In terms of listening effort measured with PPD, across both target-masker configurations and listening modes, there were no significant differences relative to baseline at the group level. However, most listeners showed greater amounts of PPD in the SSD-CI compared with the acoustic-only listening mode. This might be attributable to the asymmetry introduced by the CI, greater task engagement, greater effort expenditure, or a combination of these factors.

LIMITATIONS

We lost one participant due to attrition, and the arrival of the COVID-19 pandemic precluded our plans to collect additional postoperative data for two listeners in our clinical trial cohort. Were we to test them at this point, they would have the advantage of at least an additional year of experience with electrical stimulation, which may improve speech understanding with the implant alone and in the SSD-CI listening mode. In addition, the modest sample size reported here does limited generalizability, and the heterogeneity (in age, etiology, and duration of deafness) of participant characteristics might have obscured some hypothesized effects.

CONCLUSION

Most SSD-CI recipients experienced improved speech understanding in noise when using both ears, in the SSD-CI listening mode, which correlated with increased PPD for many participants, indicating heightened listening effort or task engagement. Clinically, it is notable that seven out of 8 participants showed enhanced speech understanding in challenging environments with the SSD-CI mode compared with using only the acoustic ear before implantation. These promising results warrant further investigation in future studies with larger and more homogeneous samples in terms of clinical and demographic characteristics.

ACKNOWLEDGMENTS

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L.S. completed statistical analyses and contributed major portions of the writing; T.T., E.B., and L.S. completed raw pupil trace preprocessing; all coauthors contributed to the writing, with varying amounts of edits and suggestions on drafts of the manuscript; R.Y.L. and D.L. initiated the study design and conceptual framework for the investigation; T.T., E.B., S.P.G., D.L., and R.Y.L. contributed to experimental design and implementation; T.T., E.B., and S.P.G. collected the data. D.L. Performed cochlear implant surgery for all participants.

This study was approved by the University of Wisconsin-Madison Institutional Review board (UW-Madison IRB protocol number 2015-1438; R.Y.L., P.I.).

The authors have no conflicts of interest to disclose.

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