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Auditory listening effort and reaction time: a comparative study between single sided deaf cochlear implant users and normal hearing controls

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Introduction: Cochlear implant (CI) provision has been shown to be the only hearing rehabilitation option that can improve speech perception in noise and sound localization in SSD listeners. Individuals with SSD are known to exert increased listening effort when compared to normal hearing individuals, and this remains true even with CI use. Recently, reaction time (RT) has emerged as a promising metric for quantifying listening effort. As such, the current study compared performance (RT and Accuracy) of SSD participants (with and without the use of their CI) to normal hearing (NH) listeners. We assessed three listening conditions: (1) monaural listening in quiet, (2) free field listening in quiet, and (3) free field listening in background noise.

Method: SSD CI data was retrospectively obtained from two past studies conducted by the group. For monaural listening and free field listening in quiet, the same 10 SSD CI participants and 10 NH controls was recruited. For free field listening in noise condition, 12 SSD CI participants and 12 NH controls were recruited. In all condition, participants were required to complete an auditory oddball task, discerning odd and even numbers. RT and target accuracy were the metrics recorded.

Results: In monaural listening conditions, SSD CI users exhibited significantly delayed RTs compared to their NHE and to NH controls when stimuli was played directly through the CI. Surprisingly, the RT for the NHE of SSD CI users was also delayed when compared to the NH controls. Free field listening in quiet conditions showed increased RTs for SSD CI users, with and without CI, compared to NH controls, indicating the persistent impact of SSD on processing. In free field listening in noise, CI use significantly improved RTs for SSD individuals but did not reach NH levels. Despite the RT differences, task accuracy remained comparable between groups.

Discussion: SSD CI users exhibited longer RTs in all test conditions, suggesting they expend more listening effort than normal hearing controls. This increased effort likely accounts for the delayed RTs, highlighting the additional processing challenges faced by SSD CI users.

KEYWORDS

cochlear implant, single sided deafness (SSD), reaction time (RT), listening effort, oddball auditory task

Introduction

Single sided deafness (SSD) is defined as a severe to profound hearing loss [>70 dB HL four-frequency pure-tone average threshold (PTA4)] in one ear and normal hearing (≤30 dB HL PTA4) in the contralateral ear (Van de Heyning et al., 2016). Individuals with SSD lack binaural hearing input, impacting their ability to discern sounds in noisy environments and to localize sound sources (Hunter et al., 2022). This is due to their inability to take advantages of the benefits of binaural hearing, which are binaural summation and squelch effects (Bernstein et al., 2016). In young children, SSD can lead to cortical reorganization where central representation of input from the normal hearing ear is increased at the expense of input from the ear with hearing loss. This phenomenon, known as aural preference syndrome, can impede rehabilitation if left unchecked for a long duration (Gordon et al., 2015) and is one of the factors motivating early intervention with auditory prostheses. Cochlear implant (CI) provision has been identified as a hearing rehabilitation option that can improve speech perception in noise and sound localization in SSD listeners (Távora-Vieira et al., 2015b; Zeitler et al., 2015; Távora-Vieira and Wedekind, 2022).

Individuals with SSD are known to exert increased listening effort when compared to normal hearing individuals, and this remains true even with CI use (Noble, 2008; Galvin and Noble, 2013). Listening effort is defined as the cognitive resources required to perform a listening task (Alhanbali et al., 2019). Individuals with hearing loss must expend greater effort to achieve the same level of comprehension, particularly in challenging listening environments (McCoy et al., 2005; Rönnberg et al., 2013). This leads to increased attentional demands and working memory usage (Peelle, 2018). It should be noted that listening effort and listening performance are not necessarily strongly correlated. Using pupil dilation to measure listening effort, Winn (2016) demonstrated that while listening to speech vocoded with degraded spectral resolution resulted in increased listening effort, speech understanding was not compromised.

The most common metrics used to assess hearing outcomes with CI use in SSD are tests of speech perception in noise and sound localization. Quality of life questionnaires are also frequently used. These metrics do not necessarily capture the impact that a CI may have on listening effort. Several methods have been devised to measure listening effort. These include pupillometry and various neurophysiological measures including electroencephalography (EEG), functional magnetic resonance imaging (fMRI), functional near infra-red (fNIR) spectroscopy, and electrodermal activity (Obleser and Kotz, 2011; Wild et al., 2012; Holube et al., 2016; Winn, 2016; Wijayasiri et al., 2017). These methods require equipment that is not commonly available in a typical audiological follow-up setting. Self-reported ratings of listening effort can be used (Perreau et al., 2017; Voola et al., 2023) but these measures can lack objectivity as perceived listening effort may vary from individual to individual. Recently, reaction time (RT) has emerged as a promising metric for quantifying listening effort. Using a speech-in-noise intelligibility task, Giuliani et al. (2021) demonstrated the validity of RT as an indicator of listening effort in individuals with normal hearing.

The current study investigated whether RT could be used to quantifying listening effort in CI users with SSD. We used an oddball target classification paradigm, and measured RT and target accuracy. We compared performance of SSD participants (with and without the use of their CI) to normal hearing (NH) listeners. We assessed three listening conditions: monaural listening in quiet, free field listening in quiet, and free field listening in background noise.

Materials and methods

This study consisted of three separate experiments. SSD CI data are used retrospectively from two previously published study articles from our group. The first study (Voola et al., 2023) compared higher order auditory processing between monaural and binaural conditions in individuals with SSD. A subset of the data from that study are used for experiments 1 and 2 in the present study. It involved ten CI users with SSD (7 female, 3 male). Their mean (SD) age was 49 (15.8) years (range 30 to 75 years). All participants had been using a MED-EL CI for at least 1 year at the time of the study. Their basic demographic characteristics are outlined in Table 1. All participants used the same SONNET2 audio processor during these experiments, which was provided by the department.

The second study (Voola et al., 2023) evaluated how CI use improves speech-in-noise intelligibility in individuals with SSD. A subset of the data from that study is used for experiment 3 in the present study. It included 12 CI users with SSD (9 female, 3 male). Their mean (SD) age was 61.4 (7.3) years (range 50 to 70 years). All participants had been using a MED-EL CI for at least 1 year at the time of the study. Their basic demographics characteristics are outlined in Table 2.

Normal hearing control data was obtained separately for the present study. All NH listeners had a hearing threshold ≤20 dB HL across all frequencies in both ears. For experiments 1 and 2, ten NH listeners (4 female, 6 male) were recruited. Their mean (SD) age was 35 (7.92) years (range 26 to 47 years). For experiment 3, 12 NH listeners (8 female, 4 male) were recruited. Their mean (SD) age was 33.3 (10.6) years (range 23 to 60 years). Three of these individuals also participated in experiments 1 and 2.

All NH participants provided signed informed consent. Ethics approval was obtained from the South Metropolitan Health Ethics Committee (reference number: 335).

Experiment 1—Monaural listening in quiet

All participants were presented with a semantic oddball task paradigm. A set of eight numbers were used (odd = one, three, five and nine; even = two, four, six and eight). The number seven was omitted as it contains two syllables. These speech files were recorded with the purpose of being used in a telephone-based speech-in-noise test called "Telescreen" (Dillon et al., 2016). Each recording was modified using Audacity (Audacity, 1999–2016) such that the stimulus had an approximate duration of 400 ms.

Participants were instructed to press a button on a response box each time they heard an odd number. Each experimental condition

TABLE 1 Demographic information of all SSD CI participants included in Experiment 1 and 2.

Participant	Age	Gender	CI Ear	Duration of deafness (years)	Etiology	CI PTA (db HL)	NHE PTA (db HL)	Electrode	CI experience (years)
1	75	M	R	0.8	ISSNHL	82	8	FLEX28	5
2	46	M	R	2	Meniere's Disease	88	12	FLEX28	2
3	38	F	R	4	ISSNHL	73	5	FLEX28	3
4	30	F	R	25	Mumps	120	8	FLEX26	1
5	68	F	R	0.7	ISSNHL	63	16	FLEX28	3
6	64	F	L	12	ISSNHL	83	9	FLEX28	2
7	34	F	R	20	ISSNHL	56	6	FLEX28	2
8	56	F	L	0.9	ISSNHL	120	7	FLEXSOFT	8
9	34	F	R	7	ISSNHL	91	18	FLEX28	3
10	55	M	L	30	ISSNHL	120	11	FLEX28	5

Age, Gender, Cochlear Implant (CI) Ear, Duration of deafness (years before implantation), Etiology (ISSNHL refers to idiopathic sudden sensorineural hearing loss), Cochlear implant (CI) ear pure tone audiometry (PTA) prior to implantation, Normal hearing ear (NHE) PTA, Electrode type, CI experience (time since implantation).

TABLE 2 Demographic information of all SSD CI participants included in Experiment 3.

Participant	Age	Gender	CI Ear	Duration of deafness (years)	Etiology	CI PTA (db HL)	NHE PTA (db HL)	Electrode	CI experience (years)
1	60	F	L	41	Mumps	NR	11	FLEX28	13
2	57	F	L	0.9	ISSNHL	NR	19	FLEX28	9
3	65	F	L	12	ISSNHL	86	8	FLEX28	3
4	69	F	L	20	Electric shock	82	17	FLEX28	3
5	70	F	R	2	Stroke	72	11	FLEX28	1
6	69	F	L	0.6	MD	73	20	FLEX28	9
7	54	F	L	0.6	ISSNHL	116	20	FLEX28	4
8	50	M	L	12	Head trauma	76	5	FLEX28	9
9	69	F	R	0.5	ISSNHL	79	20	FLEX28	2
10	56	M	L	30	ISSNHL	NR	10	FLEX28	6
11	53	M	L	8	ISSNHL	85	3	FLEX28	3
12	65	F	L	40	ISSNHL	80	12	FLEXSOFT	10

Age, Gender, Cochlear Implant (CI) Ear, Duration of deafness (years before implantation), Etiology (ISSNHL refers to idiopathic sudden sensorineural hearing loss), Cochlear implant (CI) ear pure tone audiometry (PTA) prior to implantation, Normal hearing ear (NHE) PTA, Electrode type, CI experience (time since implantation).

consisted of 180 trials. Target stimuli were presented in 20% of trials (36 presentations) and standard stimuli were presented on 80% of trials (144 presentations). The average duration of stimuli was approximately 400 ms, with an inter-stimulus duration of 1,800 ms. The experiment was programmed and delivered using Cogent 2,000 and the Psychtoolbox-3 in MATLAB (Voola et al., 2023).

Reaction time was defined as the duration between target stimulus onset and the pressing of the response button. RT was calculated at a trial level and then averaged across trials to get the grand mean. RTs $<$50 ms were excluded from further analysis. Target accuracy was calculated as the proportion of correct responses.

Two different experimental conditions were used: monaural presentation to the normal hearing ear (NHE) and monaural presentation to the deaf ear via the CI (CI). The order of these conditions was counterbalanced to account for any learning and or fatigue effect. For NH listeners, the ear of testing was matched to test the same number of left/right ears as the SSD CI participants.

For monaural presentation to the NHE, high fidelity headphones (Audio-Technica ATH-M30x) were used. Stimuli were presented at a calibrated intensity of $\sim$55 dB SPL. For monaural presentation to the CI, a direct connection cable was used and stimuli were presented at a loud but comfortable level that was subjectively determined by the patient.

Experiment 2—Free field listening in quiet

The test procedure and participants were the same as in Experiment 1. Two different experimental conditions were used: presentation in free field with the audio processor switched on (FFq-on), and presentation in free field with the processor switched off (FFq-off). It must be of note that SSD CI users completed all four conditions (NHE, CI, FFq-on, and FFq-off) in the same session and the order of condition was counterbalanced across SSD CI participants. NH listeners completed the task once in free field and similarly they also completed the monoaural listening condition in the same session with the order being counterbalanced across NH participants. Free field presentations were delivered via EDIFIER M1250 Multimedia Speakers, which were positioned directly in front of the participant. Stimuli were presented at a calibrated intensity of ∼55 dB SPL.

Experiment 3—Free field listening in noise

All participants were presented with the same semantic oddball task paradigm used in experiments 1 and 2, but in the presence of background noise.

Eight speech babble recordings (National Acoustic Laboratories) were used as the noise signal. Noise was presented at 55 dB SPL and the numbers were presented at 60 dB SPL. The signal-to-noise ratio was +5 SNR. The numbers and noise were presented from two different loudspeakers at 45°. For SSD listeners, the speech signal was always presented to the CI side. Among the NH participants the side of signal presentation was matched to test the same number of left/right ears as the SSD CI participants.

Two different experimental conditions were used: presentation in free field with the audio processor switched on (FFn-on), and presentation in free field with the processor switched off (FFn-off). Order of conditions was counterbalanced across SSD CI participants to account for any learning or fatigue effects. NH listeners completed the task once in free field.

Statistical analysis

All statistical analyses were conducted using R Studio (RStudio, 2020). The two sample t-test was conducted using the "t.test" function. Comparison between SSD CI users and NH controls was treated as independent means (i.e., FFn-On vs. NH), and comparison between SSD CI users for different conditions (i.e., FFn-On vs. FFn-Off) was treated as dependent means. Statistical significance was defined as a p-value < 0.05.

Results

Experiment 1—Monaural listening in quiet

For RT, the two sample t-test revealed a significant difference between CI and NHE [$t_{(458)} = 5.3156, p \leq 0.0001$], between CI and NH [$t_{(404)} = 11.095, p \leq 0.0001$], and between NHE and NH [$t_{(653)} = 7.4249, p \leq 0.0001$] (Figure 1A).

The two sample t-test revealed a significant difference in target accuracy between CI and NHE [$t_{(9)} = -3.6269$, $p = 0.006$] and between CI and NH [$t_{(9)} = 3.9432$, $p = 0.0034$]. No significant difference was observed between NH and NHE [$t_{(9)} = 0.5322$, $p = 0.6075$] (Figure 1B).

Experiment 2—Free field listening in quiet

The two sample t-test revealed that RT was significantly slower in the FFq-On condition when compared to the FFq-Off [$t_{(669)} = 2.1858$, $p = 0.02917$]. A significant difference was also observed between FFq-On and NH [$t_{(681)} = 6.1671, p < 0.0001$] and FFq-Off and NH [$t_{(693)} = 4.317, p > 0.0001$] (Figure 2A).

Target accuracy was high for all three conditions (∼95%) and the t-test revealed no significant difference between any of the conditions, FFq-On vs. FFq-Off [$t_{(9)} = 0.5145$, $p = 0.6193$], FFq-On vs. NH [$t_{(9)} = 0.7456$, $p = 0.4749$] or FFq-Off vs. NH [$t_{(9)} = 0.6784, p = 0.5146$] (Figure 2B).

Experiment 3—FreeField listening in noise

A Welch two sample t-test revealed that in the FFn-Off condition, SSD CI users had a significantly delayed RT when compared to the FFn-On condition [$t_{(1,067)} = 3.5184, p = 0.0045$]. SSD CI users exhibited delayed RT in both the FFn-on and FFn-off condition when compared to normal hearing controls {FFn-On vs. NH: [$t_{(1,021)} = 21.921$, $p < 0.0001$] and FFn-Off vs. NH: [$t_{(950)} = 24.508, p < 0.0001$]} (Figure 3A).

Target accuracy was similar between FFn-On vs. FFn-Off [$t_{(11)} = 2.1282, p = 0.05675$], FFn-On vs. NH [$t_{(11)} = 0.6239, p = 0.5454$] and FFn-Off vs. NH [$t_{(11)} = 1.1425, p = 0.2775$] (Figure 3B).

Discussion

In this study we sought to compare the differences in listening effort between SSD CI users and NH listeners. Under experimental conditions, participants were required to discriminate and categorize odd and even numbers. To quantify listening effort, we measured Reaction Time (RT) and Reaction Time variability. Target accuracy was assessed to measure listening performance. We compared these outcomes across three different listening conditions: (1) monaural listening in quiet, (2) free field listening in quiet, and (3) free field listening in noise. In all three conditions we identified that the NH listeners exhibited lower RTs when compared to SSD CI users. Nevertheless, the SSD CI users demonstrated good listening performance, completing the tasks with high accuracy.

Experiment 1—Monaural listening in quiet

Under monaural listening in quiet conditions, we found that RT was significantly higher when SSD listeners relied upon their CI alone compared to their NHE. The difference in RT was

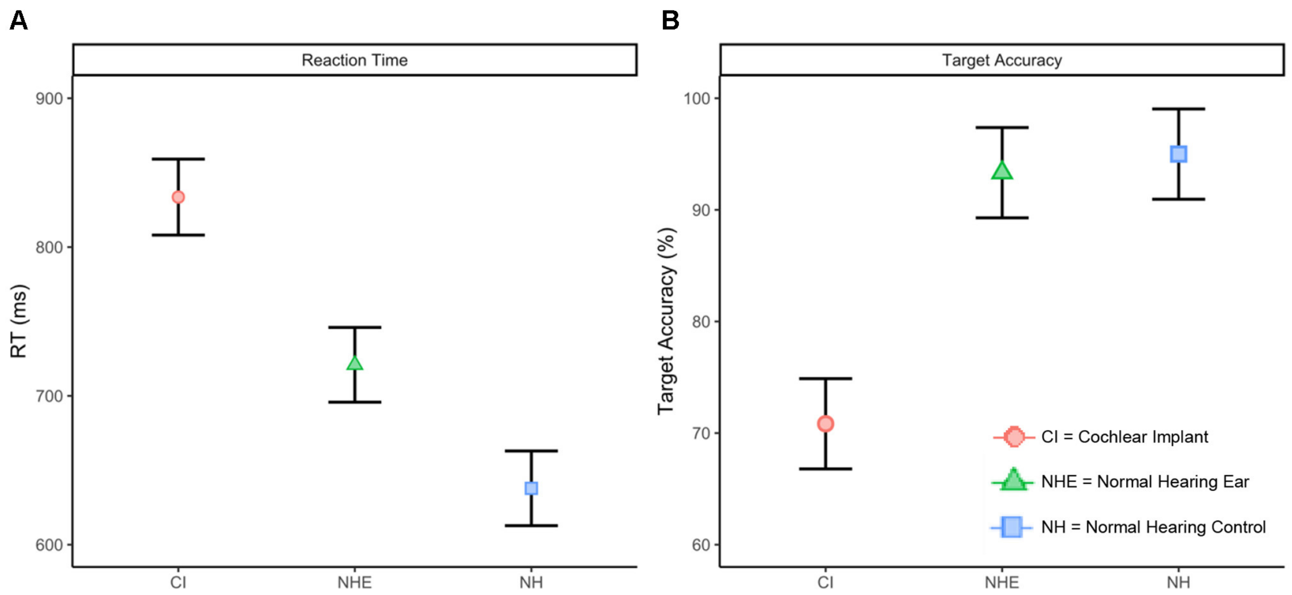

FIGURE 1
Estimated marginal means (with error bars depicting the estimated SE of the mean) for **(A)** Reaction time and **(B)** Target Accuracy in the monoaural condition.

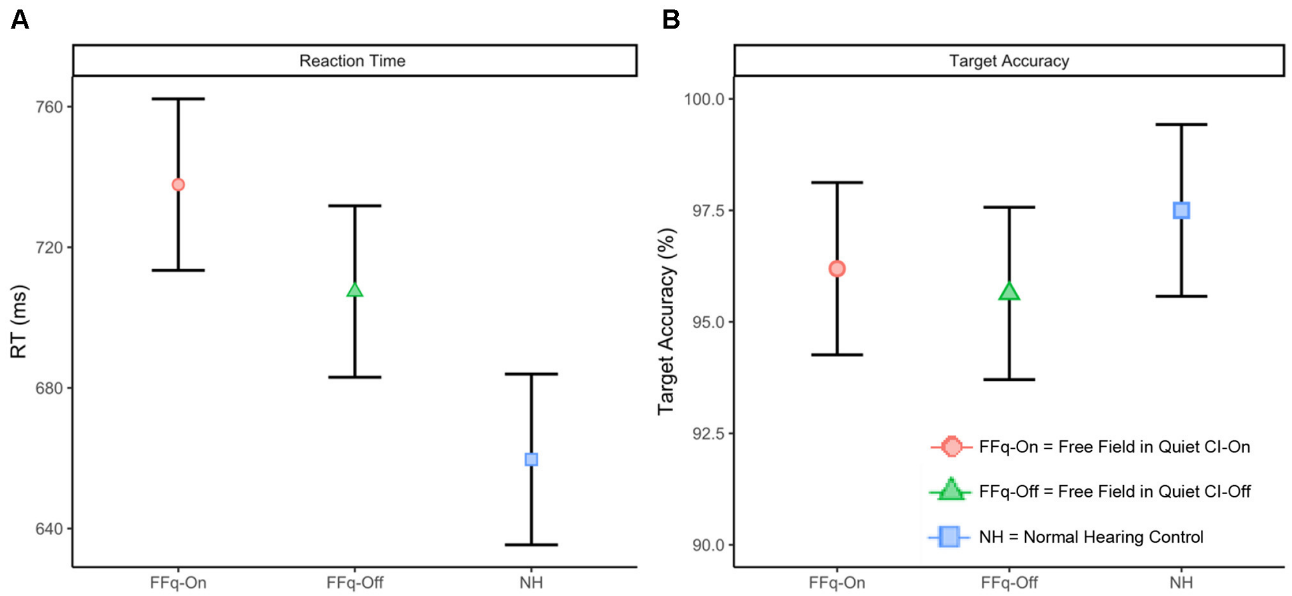

FIGURE 2
Estimated marginal means (with error bars depicting the estimated SE of the mean) for **(A)** Reaction time and **(B)** Target Accuracy in the free field in quiet condition.

around 100 ms. This finding is similar to the finding from a previous monoaural study conducted by Finke et al. (2016) who used a word-based discrimination task and observed a relative difference between the CI-on and CI-off condition of around 150 ms. Increased RT with the CI may be attributed to the reduced spectral and temporal fidelity delivered by the CI, leading to greater uncertainty and greater required listening effort to complete the task (Finke et al., 2016; Wedekind et al., 2021; Voola et al., 2023).

Along with delayed RT, we also observed significantly lower target accuracy when the CI was used (∼70% vs. ∼95% when using the NHE). Despite this significantly lower result it should be noted that when relying on the cochlear implant the SSD CI participants still performed the task with reasonably high accuracy, demonstrating benefit from their CI.

When comparing SSD listeners using their CI to NH listeners, we observed a significantly delayed RT of ∼834 ms vs. ∼638 ms for

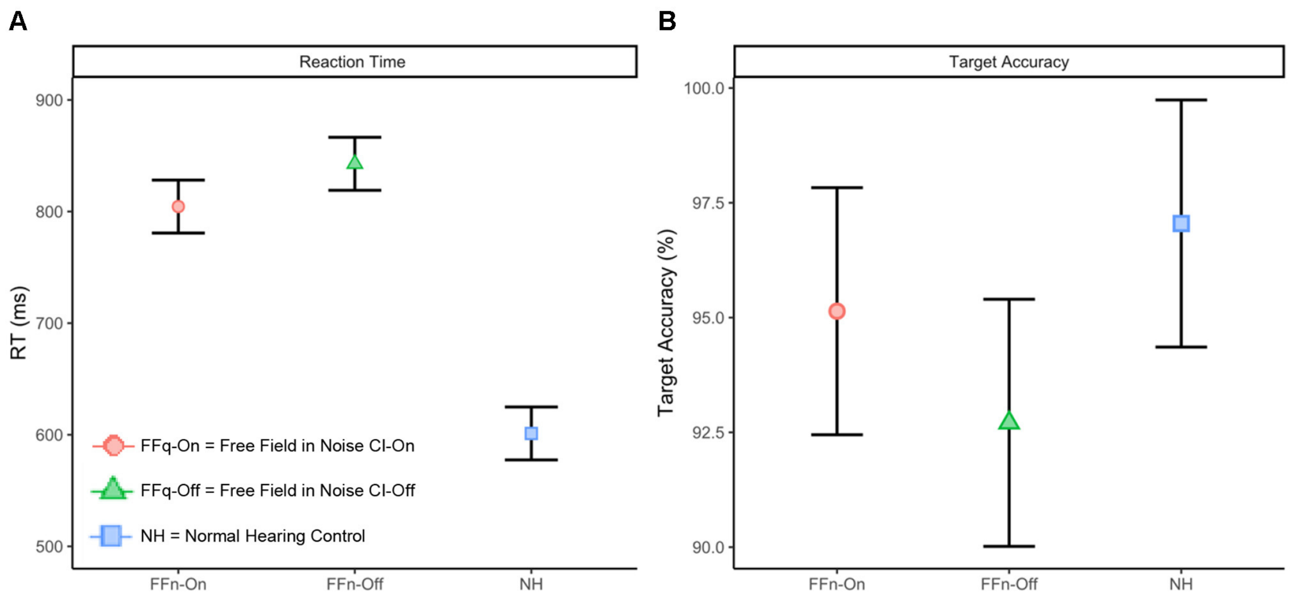

FIGURE 3
Estimated marginal means (with error bars depicting the estimated SE of the mean) for **(A)** Reaction time and **(B)** Target Accuracy in the free field in noise condition.

(monaural) NH listeners. The significant difference in RT observed between the SSD listeners using their CI and the NH listeners highlights a limitation of hearing with a CI. This difference is unlikely to be attributable to the signal processing delay of the CI, that is in the order of 1.5 ms (Zirn et al., 2015), and is more likely due to the reduced spectral and temporal fidelity of the signal provided by the CI relative to a normal hearing ear.

While the hearing threshold of the NHE is within audiometric norms, it was surprising to find that when SSD listeners used their NHE alone they had significantly greater RTs than the NH listeners. The difference in RT was approximately 80 ms. To the best of our knowledge there has been no previous study comparing RTs from the NHE of SSD listeners to those of NH listeners. We suggest that this difference could be explained by the fact that unilateral deafness results in cortical reorganization that can have a significant negative impact on working memory (Kral et al., 2012; Gordon et al., 2015; Maslin et al., 2015). It is thought that cortical reorganization can begin in even a mild to moderate hearing loss in adult-onset deafness (Kral and Sharma, 2023). In Mishra and Dey (2021) compared working memory in individuals with unilateral hearing loss (using their NHE) to NH listeners using two tests: (1) difference limens for frequency, which is the smallest change in frequency that can be detected, and (2) the digit span test, which requires participants to repeat back a sequence of numbers. Auditory stimuli was presented using supra aural earphones. They identified that the NH listeners were better able to discriminate low frequency sounds (250 Hz) and also had better working memory capacity than their SSD counterparts. No difference in discrimination ability was identified for higher frequency sounds (4,000 Hz) (Kishon-Rabin et al., 2001; Mishra and Dey, 2021). These results allude to the possibility that auditory deprivation in one ear not only causes functional hearing deficits in that ear, but also affects working memory for sounds heard by the contralateral NHE.

Experiment 2—Free field listening in quiet

In free field listening in quiet, the FFq-on condition resulted in a longer RT and larger variability in RT when compared to the FFq-off condition. These findings may indicate that in quiet environments the NHE dominates, and the provision of a second copy of the stimulus, that is delivered at a lower fidelity via the CI, may increase the level of listening effort required. Despite this, however, there was no associated negative impact on listening performance, with a similar target accuracy in both conditions. These findings highlight that in quiet environments, where binaural cues are not required, SSD CI users do not rely on their CI to discriminate and evaluate auditory stimuli. This is consistent with findings from previous studies that demonstrated similar listening performance in quiet in SSD individuals with and without a CI (Franko-Tobin et al., 2015; Távora-Vieira et al., 2015a; Forli et al., 2022).

Consistent with the findings from experiment 1, this experiment also demonstrated that SSD CI users had a significantly delayed RT (both with and without the CI) when compared to NH listeners. To the best of our knowledge only one study has investigated how the loss of binaural function in adults with acquired SSD negatively impacts auditory processing when compared to NH listeners (Shang et al., 2018). In Shang's study the auditory task involved repeating back a series of two- or four-syllable utterances that were presented in free field in quiet.

Using diffusion tensor imaging and magnetoencephalography, it was found that SSD listeners had reduced gamma band activity in frontal, parietal, and occipital regions when compared to NH listeners. This reduction in gamma band activity is thought to be an indication of reduced working memory and cognitive function (McDermott et al., 2018; Qiao et al., 2022). These findings suggest that the cognitive capacity of participants with SSD may be overloaded during auditory tasks, impeding higher order auditory processing relative to NH listeners (Shang et al., 2018). In accordance with the findings of Shang et al. (2018), the present study also found that SSD listeners with the CI switched off (i.e., utilizing their NHE in the free field setting) had significantly longer RTs compared to NH listeners.

Another potential explanation for the difference in RT observed between SSD CI users in the FFq-off condition and NH listeners may be the advantage NH listeners have of being able to utilize binaural auditory input. Although the free field experiments were not designed to assess binaural listening, it is likely that the NH listeners were able to exploit the binaural summation effect to improve their auditory perception, in contrast to the SSD listeners who were not able to benefit from this binaural summation effect (Epstein and Florentine, 2009). The fact that RTs remained significantly higher in SSD listeners even when the CI was switched on suggests that the signal delivered by the CI is not of sufficient quality (or not of sufficient perceptual match to the NHE) to yield an equivalent binaural summation effect.

Experiment 3—Free field listening in noise

In the presence of background noise, the FFn-on condition yielded significant improvement in RT in SSD listeners when compared to the FFn-off condition. This finding is in line with the findings of previous studies that have demonstrated the benefits of CI in SSD (Távora-Vieira et al., 2015a; Dorbeau et al., 2018; Legris et al., 2018; Távora-Vieira and Wedekind, 2022). Despite this, we observed that SSD listeners in the FFn-on condition had longer RTs than NH listeners. This suggests that SSD CI users remain at a disadvantage in noisy environments when compared to NH listeners. Nevertheless, target accuracy were similar across all three conditions indicating comparable listening performance.

To the best of our knowledge only one study has investigated how speech-in-noise processing in SSD individuals without a CI compares to NH listeners. In a recent study, Qiao et al. (2022) used functional MRI to examine neural activity in SSD ($n = 36$) and NH listeners ($n = 21$) whilst performing a speech-in-noise task. They identified that SSD listeners had lower neural activity in areas associated with literacy and processing (lingual gyrus and left middle frontal gyrus) when compared to NH listeners, and postulated that this reflected a reduced capacity for auditory processing in noise in SSD listeners (Qiao et al., 2022). Our observation that SSD listeners in the FFn-off condition had delayed RTs when compared to NH listeners is in keeping with this notion.

With respect to the delay between FFn-On and NH RT results, this finding could be explained by the possibility that the provision of a CI does not restore binaural hearing in SSD individuals to equivalent levels of a NH controls when testing in noise. In Finke et al. (2016), compared the listening effort of 15 MED-EL SSD CI users with NH controls in completing a semantic oddball task in the presence of background noise. They identified a significant delay in RT in SSD CI users when compared to NH controls. The authors attributed this to the limited spectral and temporal information contained in the electrical signal transmitted by the CI when compared to the signal from a normal hearing ear (Drennan and Rubinstein, 2008; Finke et al., 2016). Furthermore, the authors outlined that the limitation of this degraded electrical signal is most evident in difficult listening situations, such as speech-in-noise environments (Zeng et al., 2011). The findings from the present study support this, as we observed a RT difference of ∼100 ms between the FFq-On condition and NH when stimuli were presented in quiet, and a larger RT difference of ∼200 ms between the FFn-on condition and NH when stimuli were presented in noise. While these findings highlight the limitations of a CI, they do not change the fact that in the context of hearing in noise a CI confers significant benefit to the quality of life and functional outcomes of SSD listeners (Friedmann et al., 2016; Távora-Vieira and Wedekind, 2022).

Limitations

This study has several limitations that must be noted. First, we compared retrospective data that were obtained in previous studies on SSD CI users with prospective data from NH listeners that were obtained for the present study. While this study design is suboptimal, the experimental procedures and methods were identical, and it is therefore not anticipated that this would confer any significant effect upon the findings. A second limitation is that in the binaural listening in noise experiment (experiment 3), the SSD cohort were significantly older than the NH listeners. The mean (SD) age of the SSD group was 61.4 (7.3) years vs. 33 (10.5) years for the NH listeners. This large age difference could have contributed to the significant difference in RTs observed between the SSD users and the NH listeners in that experiment. We are therefore hesitant to conclude that the observed differences in RT between SSD users and NH listeners experiment 3 are solely attributable to the presence of SSD. Nevertheless, similar (albeit non-significant) differences in RTs were observed in the free field in quiet experiment (experiment 2), where the age difference between the two cohorts was not significant—the mean (SD) age of the SSD group was 49 (14.8) years vs. 35 (7.9) years for the NH listeners.

Conclusions

Taken all together, the present study shows that RT can be used as a measure to quantify listening effort in CI users with SSD. We identified that in noisy environments, SSD CI users exhibited a faster RT with the CI on relative to when they had the CI off, indicating a reduction in listening effort. However, in monaural conditions, we observed that the use of a CI can be detrimental to RT and task accuracy, which highlights the dominance of the NHE. These results indicate the use of RT can be used to provide an alternative method to quantify the benefit a CI is bringing to

SSD individuals. Future work should look to understand if RT can be used in other CI populations as an alternative to quantify benefit.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving humans were approved by the South Metropolitan Health Ethics Committee (reference number: 335). The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

Author contributions

MV: Writing – original draft, Writing – review & editing, Conceptualization, Formal analysis, Methodology. DT-V: Conceptualization, Methodology, Supervision, Writing – original draft, Writing – review & editing. AW: Conceptualization, Methodology, Writing – original draft, Writing – review & editing. CB: Writing – original draft, Writing – review & editing. AA: Writing – original draft, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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