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Greater working memory in cochlear implant users is related to higher subjective quality of life

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Introduction: A common concern for individuals with moderate-to-profound hearing loss who have received a cochlear implants (CIs) is difficulty following conversations in noisy environments. A possible reason is the increased use of cognitive resources (attention and working memory) to disambiguate the speech stimuli potentially causing detriments in functional aspects of life. However, this relationship is not well-documented. The overall arching goal of this study was to quantify the relationships between Patient-Reported Outcome Measures (PROMs) and cognitive ability through working memory and speech perception measures.

Methods: In the current study, 31 adult CI users and typical hearing (TH) age-matched controls were recruited. CI users completed PROMs including Speech, Spatial and Quality of hearing survey (SSQ) and versions of a quality of life (QOL) for CI users (CIQOL) and Nijmegen Cochlear Implant Questionnaire (NCIQ). Measures of cognition were assessed using internet-based tools. Outcomes were compared between groups and PROMs and were related to the cognitive tasks.

Results: Reduced auditory working memory and speech perception in noise were observed in CI users compared to TH controls. Correlation analyses revealed significant domain-specific PROM relationships with cognitive tasks in CI users, but not in TH controls. The SSQ had more significant relationships compared to the other PROMS.

Conclusion: These results suggest that internet-based metrics of cognitive ability are associated with the functional hearing aspects of life in CI users and that SSQ is more sensitive to investigate the cognitive related effects of QOL compared to other commonly used PROMs.

KEYWORDS

cochlear implants, online testing, working memory, speech perception, quality of life

1 Introduction

Speech perception in noise in cochlear implant (CI) users is known to be highly variable. Patient factors such as etiology and duration of deafness, age, device-related factors and surgical factors only account for <22% of the observed variance (Blamey et al., 1996, 2013; Lazard et al., 2012; Holden et al., 2013; Lazard and Giraud, 2017). Some studies have suggested that differences in individual cognitive processing abilities are related to the variability of speech perception outcomes (Lenarz et al., 2012; Mahmoud and Ruckenstein, 2014; Hast et al., 2015; Skidmore et al., 2020). Brain imaging studies have suggested greater deployment of cognitive resources through attention and working memory especially when participants listen to degraded vs. clear speech (reviewed in Peelle, 2018) and therefore, larger allocation of cognitive resources may be deployed toward disambiguating spectrally degraded auditory signals from listening through a CI (Rönnberg et al., 2010, 2016; Mattys et al., 2012; Ohlenforst et al., 2017). However, the effects of increased use of cognitive reserves are thought to result in an exhaustion of cognitive reserves needed for other functions (Pichora-Fuller et al., 1995; Chang et al., 2004; Lee et al., 2004; Lin et al., 2008, 2012; Tun et al., 2009; Wu et al., 2009; Gates et al., 2011; Rönnberg et al., 2013; Wingfield, 2016). This depletion of cognitive reserves may lead to prolonged listening effort contributing to social isolation, depression and cognitive decline over time (Strawbridge et al., 2000; Akeroyd, 2008; Gallacher et al., 2012; Lin et al., 2013, 2014; Gurgel et al., 2014; Fulton et al., 2015; Fritze et al., 2016; Wingfield, 2016; Golub, 2017; Loughrey et al., 2018).

The results from comparing cognitive ability between CI users and TH controls are inconsistent and limited across the literature depending on the modality used; outcomes from visual tasks were more consistent however, auditory tasks yielded differing results even when using the same task. Most studies have compared visual working memory with very few comparing auditory working memory between groups; we and others have shown that visual working memory performance in CI users is comparable to TH (Moberly et al., 2017c; Kramer et al., 2018; Prince et al., 2021; Völter et al., 2021; Pérez et al., 2023). Four studies used digit span tasks to compare auditory working memory in which participants hear and recall a sequence of digits; the length of sequences increase as participants recall them correctly. Performances for CI users were reduced in Tao et al. (2014) and Hamdy et al. (2023) but similar between groups in Moberly et al. (2017a) and Cleary et al. (2018). The latter is possibly a result of each sequence length being presented twice allowing participants a chance to perform better on each sequence and therefore, resulting in no significant differences. Caution is warranted given the paucity of literature comparing auditory working memory between CI and TH.

The effects of a reduced cognitive performance on the quality of life (QOL) of CI users is unclear as well due to the limited number of studies and inconsistent results. Commonly used Patient-Reported Outcome Measures (PROMs) for QOL in the clinical setting are the Nijmegen Cochlear Implant Questionnaire (NCIQ; Hinderink et al., 2000), Speech, Spatial and Qualities of Hearing Scale (SSQ; Gatehouse and Noble, 2004) and the recently developed survey Cochlear Implant Quality of Life (CIQOL; McRackan et al., 2017). Many studies have reported speech perception in noise to be positively correlated with certain domains of the NCIQ (advanced speech perception, self-esteem, and speech production), all domains of the SSQ (Wallhäusser-Franke et al., 2018; Häußler et al., 2019; Moberly et al., 2019; Dingemanse and Goedegebure, 2020; Dietz et al., 2022; Myhrum et al., 2023) and one with global outcomes of CIQOL (McRackan T. et al., 2019). However, only six studies were found relating cognitive performance with NCIQ and only two with SSQ but in hearing aid users; none were found for CIQOL.

For NCIQ, positive relationships were reported between general cognition and self-esteem (Calvino et al., 2022), speech production (Ohta et al., 2022), attention and social interactions (Moberly et al., 2019). Skidmore et al. (2020) reported that each domain of the NCIQ required a combination of cognitive, sensory, and demographic predictors where cognitive factors primarily predicted the physical (basic sound perception, advanced sound perception, and speech production) and social domains (activity limitations and social interactions). The two other studies, however, reported no significant relationships (Völter et al., 2018, 2020). Correlations with SSQ and cognitive ability in hearing aid users (not CI users) revealed that lower SSQ outcomes correlated with lower inhibitory control (Perron et al., 2022) and slower processing speed (Ng et al., 2013).

Given the limited and inconsistent literature when comparing cognitive ability between CI users and TH controls and when relating cognition with the different PROMs (SSQ, CIQOL, NCIQ), we sought to quantify cognitive ability through working memory and speech perception tasks and compare performances between CI users and TH controls. We also compared the relationships between these cognitive tasks and the three commonly used PROMs. Through comparing correlations across PROMs, we can investigate what aspects of QOL are more influenced by performance on these cognitive tasks. We hypothesized that CI users, compared to TH controls, would exhibit lower performance on auditory working memory and speech perception tasks. We also hypothesized that PROM outcomes would be more affected by performance on the cognitive tasks in CI users than TH controls.

2 Materials and methods

2.1 Participants

The demographic information of all participants is shown in Table 1. Thirty-one CI users were recruited from the patient population in the Department of Otolaryngology at Sunnybrook Health Sciences Center. Multiple device manufacturers were included to ensure that results were not biased toward single manufacturers. Ages ranged between 20 and 82 years ($M = 53.5$, SD $= 19.1$) and included 17 males and 14 females with no underlying neurological conditions. CI users consisted of 10 bilateral users (CI on left and right side), 12 unilateral users (CI on left or right side), and nine bimodal users (unilateral CI and hearing aid). Hearing-related demographics include duration of implantation, age of implantation, onset of deafness, and duration of deafness, which was obtained by subtracting the date of implantation from their onset of deafness based on subjective reports. These variables were used for correlational analyses along with outcomes from online tests and surveys that were completed. No significant correlations were observed between severity of hearing loss before obtaining a CI and PROMs or speech perception. CI users consisted of pre- and post-lingually deafened participants with 11 being implanted as children and the rest having adult-onset hearing loss. Age was used as a covariate to determine relationships with QOL and clinical speech perception. Thirty-one age-matched controls were also recruited with ages ranging from 20 to 85 ($M = 53$, SD $= 17.2$) and included 14 males and 17 females with no underlying neurological conditions, (e.g., stroke, dementia, or Parkinson's disease) based on self-reported history. They were recruited through local databases and online social media groups in the Toronto, Canada area. The ages of the CI users and TH controls were closely matched yielding no significant differences between groups.

All participants provided written and informed consent for the study procedures, which were conducted in accordance with the Research Ethics Board (REB) at Sunnybrook Health Sciences Center. The approved protocol was in agreement with the Declaration of Helsinki. Participants performed all online tests and surveys using their own devices outside of the hospital and were monetarily compensated for their participation.

2.2 Online tests and PROMs

All online tests and surveys were created using JavaScript and uploaded onto an online server. Participants were tasked with three working memory sentence span tasks (Daneman and Carpenter, 1980; Conway et al., 2005). Each working memory test followed a similar paradigm but in different conditions: reading span (visual), listening span in quiet and listening span in noise (+10 dB SNR). In addition to the working memory span tests, participants completed two matrix sentence tests to measure speech perception in low (+20 dB SNR) and high (+5 dB SNR) background noise (Hagerman, 1982). Before starting the auditory tests, participants were given the opportunity to adjust their device volumes to a comfortable level. Four participants who reported that they could not hear the stimuli even after adjustment and were not included in the study. Three commonly used PROMS in a clinical setting were completed measuring different aspects of QOL as described below. Since the tasks are available online, participants performed the tasks on their personal mobile devices or computers.

2.3 Working memory tasks

Working memory was tested using reading and listening sentence span tests which have been used in many studies and are considered to be reliable and valid measures of working memory capacity (Conway et al., 2005). In all three sentence span tests, participants were presented with a sentence and asked to make a judgement if the sentence was semantically plausible. The sentence for reading span was displayed on the computer screen until a decision was made. For the listening span tests, sentences were played through the device speakers. Participants were asked to make a sentence plausibility judgement by selecting "Yes" or "No." In either reading or listening, a plausible sentence could be *"He ran out of money so he had to stop playing poker"* whereas *"The acid is so big that it doesn't fit in the parking lot"* would be considered implausible.

The listening span test was performed in two conditions, quiet and multi-talker babble in the background at a SNR of +10 dB. After pressing "Yes" or "No" for plausibility, a single "to-be-remembered" word (e.g., *book*) was visually presented for 950 ms and removed from the screen. Pilot testing indicated that 950 ms was of sufficient duration to successfully read the single word. For the listening span tasks, the "to-be-remembered" words were auditorily presented. Participants were asked to memorize these words, in order, and then recall them at the end of the trial. In total, five loads of sentence-word pairings were used varying from two to six pairings. Participants were instructed to type out all recall words when prompted. Each load size was presented three times yielding a total of 15 trials. Participants were presented two practice trials and told to use the trials as a means of adjusting the volume of their device to an optimal level. Performance on each task was measured by the total number of words correctly recalled across all trials (Figures 1A, B).

2.4 Matrix sentence tests

Participants completed two versions of the matrix sentence test (Hagerman, 1982), one at a low background noise (SNR of +20 dB) and the other at a high background noise (SNR of +5 dB) using speech-shaped noise as a masker. Ten sentences for each condition were completed with practice trials before starting the test. Participants were told to use the practice tests as a means of adjusting the volume of their device to a comfortable level; an unlimited number of trials was available to them until they achieved a comfortable level. Each sentence consisted of five randomly presented, single-syllable words following a format of: person's name, verb, a number from two to nine (excluding seven), an adjective, and an object (e.g., *Ben bought 5 blue pens*). Performance on both tasks was determined by the number of words correctly identified across all sentences presented in that condition (Figure 1C).

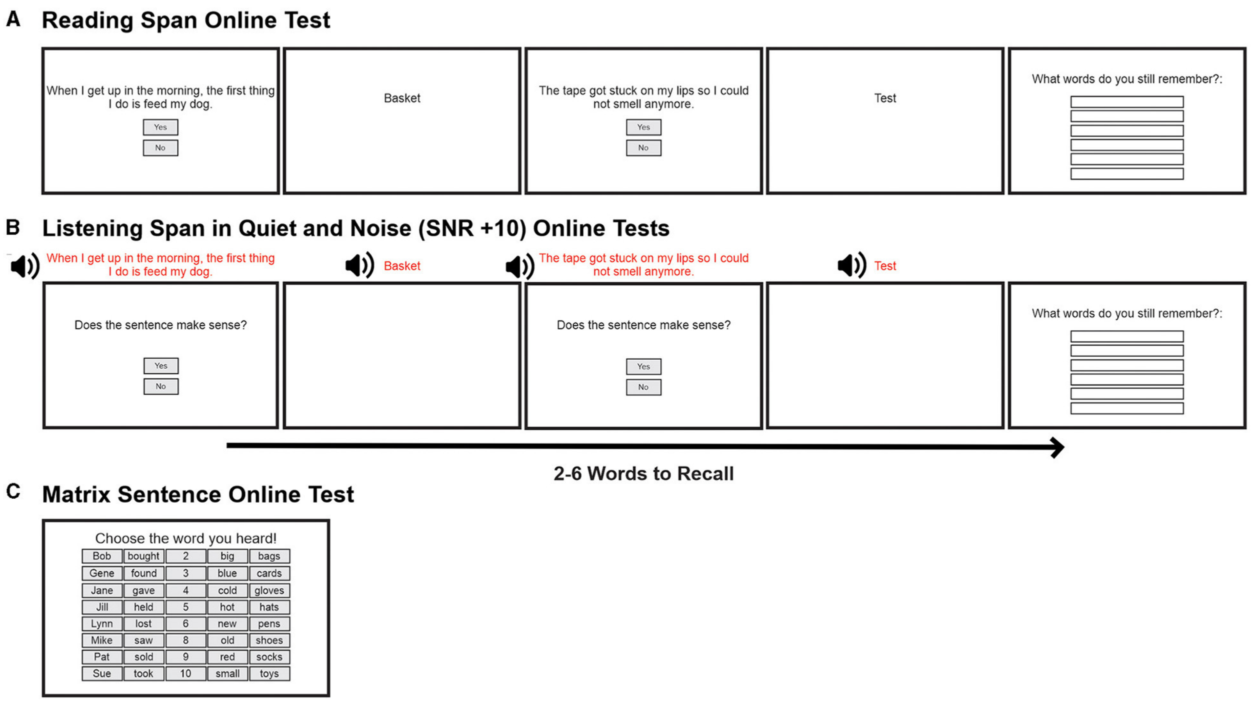
2.5 Nijmegen cochlear implant questionnaire

The Nijmegen Cochlear Implant Questionnaire (NCIQ) was designed for CI users and has proved to be reliable, valid and sensitive to clinical changes (Hinderink et al., 2000). This questionnaire is composed of 60 questions assessing physical, psychological, and social functioning in various environments. Under the physical domain were subdomains: basic sound perception, advanced sound perception, and speech production, under the psychological domain was one subdomain: self-esteem and under the social domain were subdomains: activity limitations and social interactions. The items are scored using the same five answers for 55 questions (never, sometimes, often, mostly and always) and for the other five, the responses were different (no, poorly, moderate, adequate and good); "not applicable" was included as a possible option. Each answer corresponded to a number from one to five or in some cases, the reverse; the scores of each subdomain were averaged (dividing by the number of completed items excluding "not applicable"). The higher the score (from 0 to 100), the better their self-reported functional ability is in the different domains measured. The NCIQ was administered to the CI users and not to the TH controls.

TABLE 1 Demographics and clinical test scores of participants.

Participants	Gender	Mode of implantation	Age (years)	Age of implantation (years)	Onset of deafness (years)	Duration of implantation (years)	Duration of deafness (years)	CI manufacturer and model
1	M	Bilateral	20	2	0	18	2	Cochlear: Nucleus
2	M	Bilateral	23	8.17	0	15	8.17	Cochlear: Nucleus
3	F	Unilateral	24	2	0	22	2	Cochlear: Nucleus
4	F	Bilateral	24	1.91	0	22	1.91	Cochlear: Nucleus
5	M	Unilateral	24	0	0	24	0	Cochlear: Kanso
6	F	Unilateral	27	5	0	22	5	Advanced Bionics: Harmony
7	F	Bilateral	31	23	13	8	10	MED-EL: Rondo
8	M	Bilateral	35	29	29	6	0.08	Cochlear: Nucleus
9	M	Bilateral	40	30	27	10	3	MED-EL: Sonnet
10	F	Bimodal	47	42	17	5	25	MED-EL: Sonnet
11	M	Unilateral	48	42	23	6	19	MED-EL: Sonnet
12	M	Bimodal	54	47	25	7	22	Advanced Bionics: Naída
13	F	Unilateral	54	51	28	3	23	MED-EL: Sonnet
14	M	Bilateral	55	47	14	8	33	Advanced Bionics: Naída
15	M	Unilateral	56	46	31	10	15	MED-EL: Sonnet
16	F	Unilateral	59	50	21	9	29	Advanced Bionics: Neptune
17	M	Bimodal	59	55	25	4	30	MED-EL: Sonnet
18	F	Unilateral	60	37	0	23	37	Cochlear: Nucleus
19	M	Bilateral	62	55	21	7	34	MED-EL: Sonnet
20	M	Bimodal	63	60	54	3	6	Cochlear: Nucleus
21	F	Bimodal	64	60	49	4	11	MED-EL: Sonnet
22	F	Unilateral	66	59	58	7	1	Cochlear: Kanso
23	F	Unilateral	68	59	24	9	35	Advanced Bionics: Neptune
24	M	Bilateral	69	66	15	3	51	MED-EL: Sonnet
25	M	Unilateral	70	65	35	5	30	MED-EL: Sonnet
26	F	Bimodal	71	66	51	5	15	MED-EL: Rondo
27	M	Bilateral	74	66	52	8	14	MED-EL: Sonnet
28	M	Bimodal	75	71	59	4	12	MED-EL: Sonnet
29	M	Bimodal	75	75	18	1	57	MED-EL: Sonnet
30	F	Unilateral	80	74	52	6	22	MED-EL: Sonnet
31	F	Bimodal	82	80	59	2	21	Cochlear: Kanso

CI participants are numbered 1–31 from youngest to oldest and their corresponding mode of implantation (bilateral, unilateral, or bimodal if a HA, is used), age of implantation, onset of deafness, duration of CI use in years, duration of deafness before implantation and their CI manufacturer and model are recorded, respectively, in the columns from left to right.



Bob	bought	2	big	bags
Gene	found	3	blue	cards
Jane	gave	4	cold	gloves
Jill	held	5	hot	hats
Lynn	lost	6	new	pens
Mike	saw	8	old	shoes
Pat	sold	9	red	socks
Sue	took	10	small	toys

FIGURE 1
Schematic diagram of online tests. **(A)** Reading span working memory test. A sentence is visually presented with a "Yes" and "No" button. Participant must identify if the sentence makes sense. Then a word is presented that must be remembered. This occurs in 2–6 sets. **(B)** Listening span working memory tests. A similar paradigm to the reading span test however, the sentences and words are presented auditorily as indicated by the red text. It consists of two conditions with a quiet background and with a noisy background (SNR +10). **(C)** Matrix sentence test. A simple five-word sentence is presented auditorily, and participants must listen and respond with the sentence that was heard. It consists of two conditions with a noisy background (SNR +5) and with a quieter background (SNR +20).

2.6 Cochlear implant quality of life survey

The Cochlear Implant Quality of Life (CIQOL) profile instrument was also designed specifically for CI users (McRackan et al., 2017, 2018; McRackan T. et al., 2019; McRackan T. R. et al., 2019). Compared to other QOL surveys, CIQOL demonstrates strong construct and convergent validity and strong to very strong reliability (McRackan et al., 2021). The survey is composed of 35 questions to assess the impact of their hearing ability across six different domains: communication (receptive and expressive communication ability in different situations), emotion (impact of hearing ability on emotional wellbeing), entertainment (enjoyment and clarity of TV, radio, and music), environmental (ability to distinguish and localize environmental sound), listening effort (degree of effort and resulting fatigue associated with listening), and social (ability to interact in groups and to attend and enjoy social functions).

The items are scored using the same five answers (never, rarely, sometimes, often, and always) with each answer corresponding to a number from one to five or in some cases, the reverse. The scores are then summed (after correcting for some questions of reverse numeric order) for each domain and then converted to the interval-scale score as derived from item-response theory (McRackan T. et al., 2019; McRackan T. R. et al., 2019). The higher the score (from 0 to 100), the better their self-reported functional ability is in the different domains measured. The CIQOL was administered to the CI users and not to the TH controls.

2.7 Speech, spatial and quality of hearing survey

The speech, spatial and quality of hearing (SSQ) self-report survey is a validated (Gatehouse and Noble, 2004), highly reliable assessment instrument for CI users (Tyler et al., 2009), hearing aid users and those with hearing loss (Pennini and de Almeida, 2021). The purpose of this questionnaire is to assess three domains of hearing: speech hearing (ability to hear speech in various competing contexts and difficulties), spatial hearing (ability to judge distance, direction and movement of sounds) and other qualities of hearing (ability to segregate and recognize sounds, the clarity of speech, and listening effort). The number of questions vary for each domain with 14 dedicated to speech hearing, 17 for spatial hearing and 18 for other quality of hearing aspects. Questions for each domain are answered by a rating between zero and 10 where higher ratings represent "better" quality of hearing. The ratings were then averaged for each domain. The SSQ was administered to both CI users and TH controls.

2.8 Statistics

To compare the outcomes between CI and TH, for the sentence span tests, matrix sentence tests and SSQ survey outcomes, mixed ANOVA tests were performed using R (*afex* package; R Core

Team, 2020). For the sentence span test, a 2 × 3 mixed ANOVA was performed comparing between-subjects factor of group (CI vs. TH) and within-subjects factors of condition (reading vs. listening in quiet vs. listening in noise). For the SSQ survey, a 2 × 3 mixed ANOVA was performed comparing between-subjects factor of group (CI vs. TH) and within-subjects factors of condition (speech vs. spatial vs. quality of hearing). For the matrix sentence tests, 2 × 2 mixed ANOVA was performed comparing between-subjects factor of group (CI vs. TH) and within-subjects factors of condition (+20 dB SNR vs. +5 dB SNR). *Post-hoc* comparisons were completed using the *emmeans* package and were corrected for false discovery rate (Benjamini and Hochberg, 1995). Results are reported alongside η^2 to express effect size.

Spearman correlational analyses were performed to investigate if sentence span scores and matrix sentence scores were related to NICQ, CIQOL, and SSQ survey outcomes. Spearman correlation was chosen because it is less sensitive to outliers compared to Pearson (Rousselet and Pernet, 2012). At first, the sentence span and matrix sentence scores were correlated to each PROM subdomain and then we used a composite measure for each PROM (averaging across all subdomains) to compare correlations between PROMs. As exploratory measures, the relationships between hearing related demographic outcomes and PROMs were incorporated. Correlation analyses were performed using the *psych* package (Revelle, 2023). *p*-values for the correlational analyses were corrected for multiple comparisons through the false discovery rate (FDR) method (Benjamini and Hochberg, 1995). A correlational matrix was created for each PROM (see Figure 3); each were related to working memory, speech perception and demographic metrics. The results of the correlations matrix were summarized graphically such that correlations that survived multiple comparison corrections are shown as circles. The size of the circle is scaled to the value of the Spearman correlation coefficient.

All *t*-tests and Spearman correlations were two-tailed, and the alpha criterion for Type I error was set at 0.05.

3 Results

3.1 Behavioral results

Figure 2 compares CI and TH performance on word recall in the sentence span tests, performance on matrix sentence tests, and SSQ survey outcomes (note that CIQOL and NICQ were not administered to the TH group since they were designed for CI users). All significant effects shown in Figure 2 remained significant after multiple comparison correction.

For word recall (Figure 2A), the ANOVA revealed a significant interaction between group and condition [$F_{(1,29)} = 43.71$, $\eta^2 = 0.42$, 90% confidence interval: (0.33, 1)]. Follow-up tests showed that the TH group performance was higher (p's all < 0.0001) on the listening in quiet ($M = 58.9\%$, SD = 24.6) and in noise conditions ($M = 55.2\%$, SD = 21.4) compared to the CI group (in quiet: $M = 31.3\%$, SD = 19.1; in noise: $M = 19.6\%$, SD = 18.9). Within the CI group, performance on reading span ($M = 57.3\%$, SD = 24.3) was higher than both listening spans and listening in quiet was higher than in noise (p's all < 0.0001); again, no within-subject differences were found for the TH group.

For the matrix sentence tests, performance (percent words correct) was subjected to a 2 × 2 ANOVA and a significant interaction between group and condition was observed [$F_{(1,29)} = 8.35$, $\eta^2 = 0.12$, 90% confidence interval: (0.04, 1]). *Post-hoc* tests showed that performance between groups was significantly different in the +20 dB SNR condition ($p = 0.0003$) where the TH group scored higher ($M = 96.9\%$, SD = 5.7) than the CI group ($M = 89\%$, SD = 9.9). Between group comparison of the +5 dB SNR condition was also significantly different ($p < 0.0001$) with higher scores in the TH group ($M = 94.3\%$, SD = 7.7) than the CI group ($M = 79.4\%$, SD = 14.8). Additionally, within group comparison results showed no difference between conditions in the TH group, however, CI users performed higher in the +20 dB SNR condition compared to +5 dB SNR condition ($p < 0.0001$). Results are summarized in Figure 2B.

For the SSQ survey outcomes (Figure 2C), results were subjected to a 2 × 3 ANOVA and a significant main effect for group was observed [$F_{(1,29)} = 18.64$, $\eta^2 = 0.24$, 90% confidence interval: (0.12, 1)]. *Post-hoc* tests showed that speech, spatial and quality of hearing were significantly different between groups (speech: $p = 0.0004$; spatial: $p < 0.0001$; quality of hearing: $p = 0.0045$). The TH group reported better ratings of speech hearing ($M = 7.47$; SD = 1.4), spatial hearing ($M = 7.46$; SD = 1.9) and quality of hearing ($M = 8.32$; SD = 1.4) compared to the CI group (speech: $M = 5.66$; SD = 2.3; spatial: $M = 4.66$; SD = 2.6; quality of hearing: $M = 6.88$; SD = 2.3).

3.2 Correlations

The objective of this analysis was to assess if the online tests (reading/listening span, matrix sentence) and hearing related demographics were related to QOL PROMs. Figure 3 shows the correlational matrix for each PROM where significant correlations that survived multiple comparisons are indicated. In CI users, we found that SSQ and CIQOL outcomes yielded positive correlations with working memory performance and speech perception and SSQ had higher and more significant correlations that survived after multiple comparison corrections than CIQOL (Figure 3). No significant correlations were observed with NCIQ for CI users and no significant correlations were observed in TH controls when relating SSQ with the cognitive tasks.

Scores on the SSQ speech hearing subdomain were positively correlated with performance on reading and listening span in quiet and noise ($\rho = 0.47$, $p = 0.007$; $\rho = 0.44$, $p = 0.01$; $\rho = 0.56$, $p = 0.001$ respectively), matrix sentence test in +5 and +20 dB SNR ($\rho = 0.58$, $p = 0.0006$; $\rho = 0.63$, $p = 0.0001$ respectively). Similarly, SSQ spatial hearing subdomain was significantly correlated with performance reading and listening span in quiet and noise ($\rho = 0.57$, $p = 0.0008$; $\rho = 0.55$, $p = 0.001$; $\rho = 0.61$, $p = 0.0003$ respectively), matrix sentence test in +5 and +20 dB SNR ($\rho = 0.66$, $p = 0.0002$; $\rho = 0.62$, $p < 0.0001$ respectively). Lastly, SSQ quality of hearing subdomain was positively correlated with performance in reading span ($\rho = 0.43$, $p = 0.02$) and matrix sentence test in +20 dB SNR ($\rho = 0.44$, $p = 0.01$). Additionally, SSQ

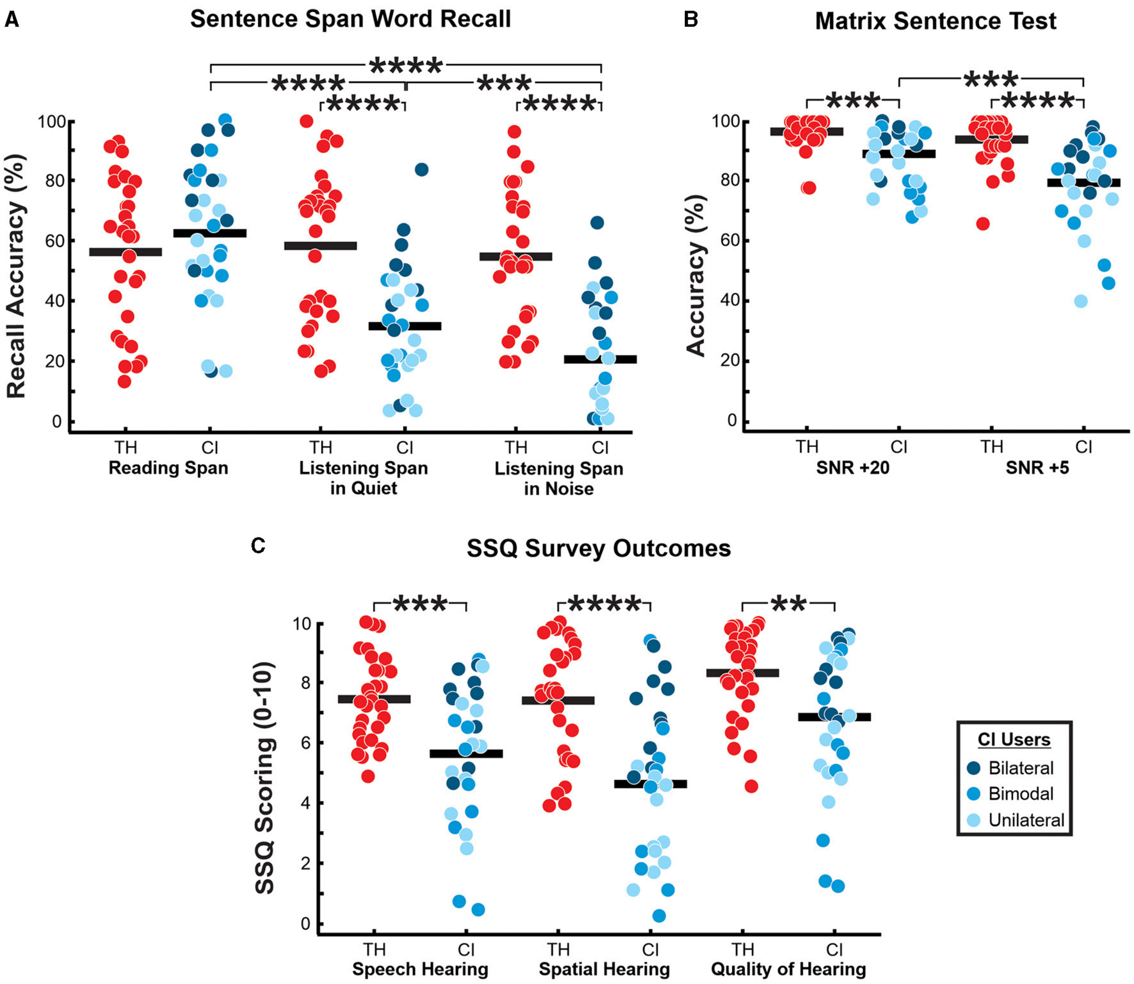
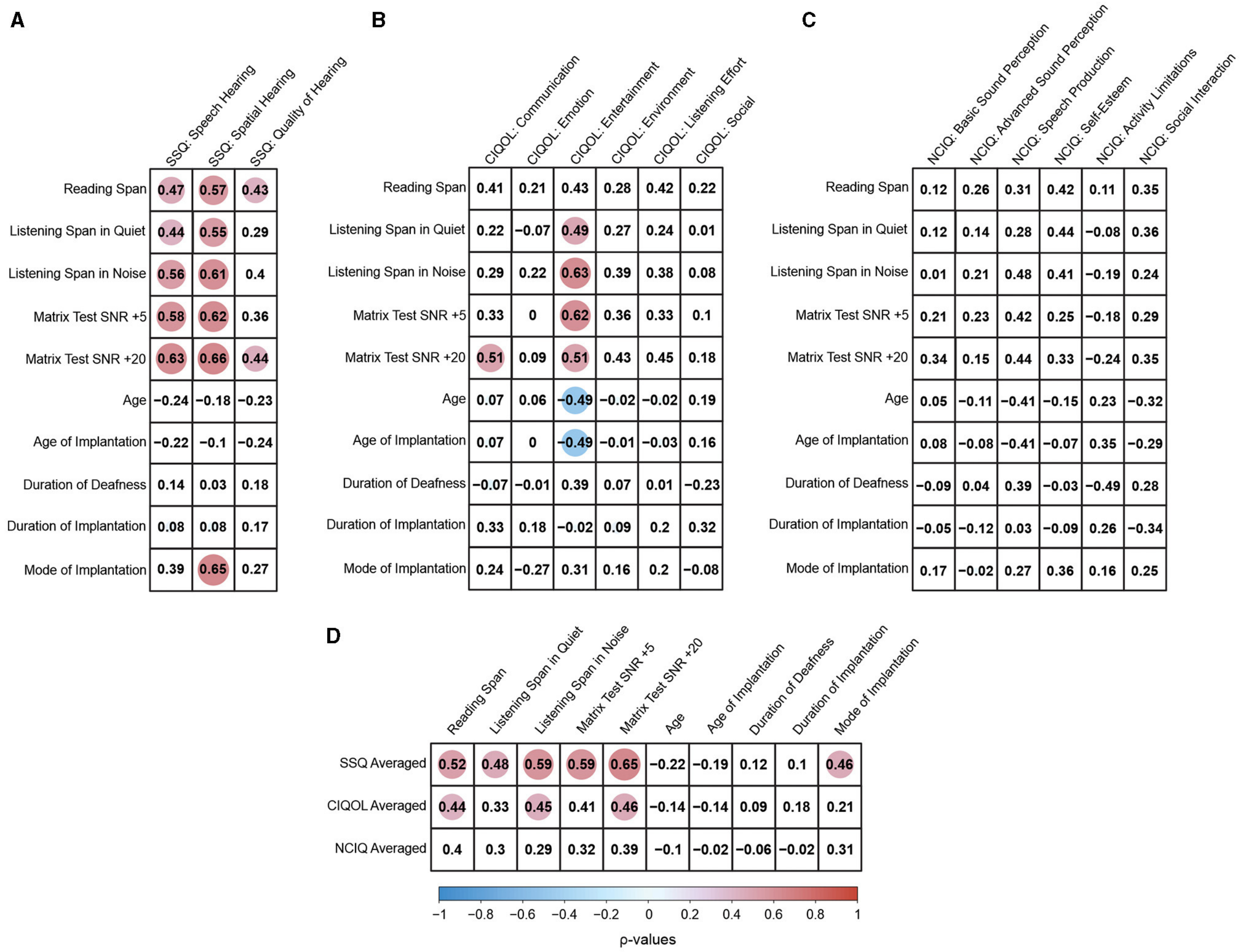


FIGURE 2
Performance and outcome comparison between groups and conditions. CI users are color coded depending on their mode of implantation from light to medium to dark blue representing unilateral, bimodal and bilateral users respectively. **(A)** Shows accuracy on recalling the sets of words in sentence span tests where TH controls outperform CI users in the listening span in quiet and in nose tasks. Within the CI group, CI users perform better on the reading span than the listening span tasks. **(B)** Shows accuracy on recalling the simple sentences in matrix sentence tests where TH controls outperform CI users on both conditions and CI users performed better on the low background noise condition. **(C)** Shows outcomes on SSQ survey measured across three subsections where TH controls report better speech, spatial and quality of hearing compared to CI users. $^{****}p < 0.0001$, $^{***}p < 0.001$, $^{**}\ p < 0.01$.

spatial hearing correlated significantly with mode of implantation ($\rho = 0.65, p = 0.004$) such that bilateral CI users rated higher spatial hearing than bimodal CI users, followed by unilateral CI users. However, considering the insufficient sample size of each group (bilateral/bimodal/unilateral) readers should consider the results as trends.

For CIQOL communication domain, only the correlation with matrix sentence test in +20 dB SNR survived FDR corrections ($\rho = 0.51$, $p = 0.003$). For the CIQOL entertainment domain, significant correlations included: listening span in quiet and noise ($\rho = 0.49$, $p = 0.005$; $\rho = 0.63$, $p = 0.0002$ respectively), matrix sentence test in +5 and +20 dB SNR ($\rho = 0.62$, $p = 0.0002$; $\rho = 0.51$, $p = 0.004$ respectively). All correlations were positive in which greater working memory and speech perception in quiet and in noise related to higher reports communication and enjoyment and clarity of TV, radio, and music. Additionally, age and age of implantation were significantly correlated to CIQOL entertainment ($\rho = -0.49$, $p = 0.006$ and $\rho = -0.49$, $p = 0.005$ respectively) suggesting that younger CI users and earlier implantation ages are associated with higher ratings of entertainment enjoyment.

To compare the correlations between each PROM, we created a composite measure for each of the PROMs which were the averaged outcomes across all subdomains (Figure 3D). This composite measure was then correlated with working memory, speech perception and demographics. FDR corrections were subsequently applied (Figure 3D). Results showed no significant correlations with the NCIQ after corrections. CIQOL outcomes correlated positively with reading span ($\rho = 0.44$, $p = 0.01$), listening span in noise ($\rho = 0.45$, $p = 0.01$) and matrix sentence test in +20 dB SNR ($\rho = 0.46$, $p = 0.009$). Similarly, SSQ correlated with reading span ($\rho = 0.52$, $p = 0.02$), listening span in quiet and noise ($\rho = 0.59$, $p = 0.0004$; $\rho = 0.47$, $p = 0.007$ respectively) and matrix sentence test in +5 and +20 dB SNR ($\rho = 0.59$, $p = 0.0005$; $\rho = 0.65$, $p < 0.0001$ respectively) and additionally, it correlated with mode of



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	SSQ: Speech Hearing	SSQ: Spatial Hearing	SSQ: Quality of Hearing
Reading Span	0.47	0.57	0.43
Listening Span in Quiet	0.44	0.55	0.29
Listening Span in Noise	0.56	0.61	0.4
Matrix Test SNR +5	0.58	0.62	0.36
Matrix Test SNR +20	0.63	0.66	0.44
Age	−0.24	−0.18	−0.23
Age of Implantation	−0.22	−0.1	−0.24
Duration of Deafness	0.14	0.03	0.18
Duration of Implantation	0.08	0.08	0.17
Mode of Implantation	0.39	0.65	0.27

B

	CIQOL: Communication	CIQOL: Emotion	CIQOL: Entertainment	CIQOL: Environment	CIQOL: Listening Effort	CIQOL: Social
Reading Span	0.41	0.21	0.43	0.28	0.42	0.22
Listening Span in Quiet	0.22	−0.07	0.49	0.27	0.24	0.01
Listening Span in Noise	0.29	0.22	0.63	0.39	0.38	0.08
Matrix Test SNR +5	0.33	0	0.62	0.36	0.33	0.1
Matrix Test SNR +20	0.51	0.09	0.51	0.43	0.45	0.18
Age	0.07	0.06	−0.49	−0.02	−0.02	0.19
Age of Implantation	0.07	0	−0.49	−0.01	−0.03	0.16
Duration of Deafness	−0.07	−0.01	0.39	0.07	0.01	−0.23
Duration of Implantation	0.33	0.18	−0.02	0.09	0.2	0.32
Mode of Implantation	0.24	−0.27	0.31	0.16	0.2	−0.08

C

	NCIQ: Basic Sound Perception	NCIQ: Advanced Sound Perception	NCIQ: Speech Production	NCIQ: Self-Esteem	NCIQ: Activity Limitations	NCIQ: Social Interaction
Reading Span	0.12	0.26	0.31	0.42	0.11	0.35
Listening Span in Quiet	0.12	0.14	0.28	0.44	−0.08	0.36
Listening Span in Noise	0.01	0.21	0.48	0.41	−0.19	0.24
Matrix Test SNR +5	0.21	0.23	0.42	0.25	−0.18	0.29
Matrix Test SNR +20	0.34	0.15	0.44	0.33	−0.24	0.35
Age	0.05	−0.11	−0.41	−0.15	0.23	−0.32
Age of Implantation	0.08	−0.08	−0.41	−0.07	0.35	−0.29
Duration of Deafness	−0.09	0.04	0.39	−0.03	−0.49	0.28
Duration of Implantation	−0.05	−0.12	0.03	−0.09	0.26	−0.34
Mode of Implantation	0.17	−0.02	0.27	0.36	0.16	0.25

D

	Reading Span	Listening Span in Quiet	Listening Span in Noise	Matrix Test SNR +5	Matrix Test SNR +20	Age	Age of Implantation	Duration of Deafness	Duration of Implantation	Mode of Implantation
SSQ Averaged	0.52	0.48	0.59	0.59	0.65	−0.22	−0.19	0.12	0.1	0.46
CIQOL Averaged	0.44	0.33	0.45	0.41	0.46	−0.14	−0.14	0.09	0.18	0.21
NCIQ Averaged	0.4	0.3	0.29	0.32	0.39	−0.1	−0.02	−0.06	−0.02	0.31

FIGURE 3
Correlation matrix for CI outcomes. Each circle represents a significant correlation after correcting for multiple comparisons using FDR for **(A)** SSQ, **(B)** CIQOL, **(C)** NCIQ, and **(D)** all PROMS averaged across domains. Red circles indicate a positive correlation while blue indicates a negative correlation. The bigger and darker the circle, the greater the correlation.

implantation ($\rho = 0.46, p = 0.009$) such that bilateral users reported higher SSQ outcomes.

4 Discussion

4.1 Summary

The objectives of this study were to investigate differences between CI users and TH controls on cognitive ability and to quantify how cognition relates to the different aspects of QOL. The main findings of this study are as follows: (1) performance on all online auditory tests (working memory span tests and matrix sentence) along with SSQ survey outcomes were significantly lower in CI users compared to TH controls. (2) Correlation results involving SSQ showed significant positive relationships between cognitive performance during visual and auditory tasks and all three domains of the SSQ (speech, spatial and quality of hearing). Additionally, only two domains in CIQOL (communication and entertainment) correlated with performance on auditory tasks. No significant correlations were observed with NCIQ. These results suggest that, compared to TH controls, CI users performed poorer on auditory working memory and speech perception and their cognitive performances on both visual and auditory tasks are related to aspects of QOL assessed through SSQ and CIQOL.

4.2 Online tests and survey outcomes between groups

In this study, CI users and TH controls did not differ in visual language working memory performance as indexed by the reading span test. This finding is consistent with previous reports comparing CI users and TH participants on visual working memory tasks (Lyxell et al., 2003; Moberly et al., 2016, 2017a,b,c; O'Neill et al., 2019; Prince et al., 2021) suggesting that these processes are intact and accessible in CI users. However, auditory working memory performance was significantly lower in CI users compared to TH in both quiet and in noise as indexed by listening span tests suggesting that sound encoding and auditory working memory are reduced in CI users. Direct comparisons between the current findings and previous literature are difficult because very few studies have directly compared CI users and TH listeners in auditory memory tasks and those that have, yielded inconsistent results. Moberly et al. (2017a) and Cleary et al. (2018) compared CI users and TH listeners on an auditory digit span test and showed no group differences for either forward or reverse digit spans. However, Tao et al. (2014) compared CI users and TH listeners on a digit span test and found that only reverse digit span scores were lower in CI users compared to TH controls while forward digit span were comparable across groups.

The auditory working memory task in the listening span test is a delayed recall task using sentences and words and therefore, vastly different from the digit span test. Caution is warranted when drawing comparisons. To our knowledge, there are no listening span test data comparing CI users and TH individuals. However, the listening span tests in people with and without hearing aids have shown increased listening span scores after amplification (Doherty and Desjardins, 2015) and have shown increased performance with noise suppression schemes (Neher et al., 2018). Taken together, the reduction in listening span we observed is qualitatively similar to previous reports on auditory working memory and hearing aids. We do not feel that reduced audibility significantly impacted performance because speech sounds were presented at suprathreshold levels. Participants adjusted volumes to comfortable level, those that reported that sounds were still too soft were not included in the analysis ($n = 4$), importantly, CI fitting is performed by adjusting electrode stimulation levels to approximate near normal free-field levels. Nonetheless, a future online test that controls for speech recognition (e.g., SWIR) is warranted.

4.3 Comparison between PROMs

In this study, we compared the effects of cognitive abilities on three commonly used QOL PROMs. The three QOL surveys differ in their domains and wording of survey items and is the likely reason why different relationships were observed with working memory and speech perception. SSQ appears to have overall stronger relationships with working memory and speech perception compared to CIQOL and NCIQ. An important caveat, however, is that this finding may be driven by the FDR correction procedure which is dependent on the number of comparisons (e.g., three domains for SSQ and six domains for both NCIQ and CIQOL). Indeed, NCIQ had several significant uncorrected correlations with working memory and speech perception. In an effort to remove the number of comparisons bias across the PROMS, we created composite PROM scores and still found a greater number of significant correlations for SSQ outcomes with all cognitive tasks compared to the other PROMs. Differences between the PROMs are discussed below.

4.4 Relationships with CIQOL entertainment

The entertainment domain of the CIQOL includes ratings of enjoyment and clarity for radio, television and music listening. NCIQ advanced sound perception domain also measured the perception and enjoyment of music however, no significant correlations were observed. Performance on the listening spans and matrix sentence tests were positively related to the CIQOL entertainment domain as well as younger CI users and CI users implanted at a younger age. The entertainment domain of the CIQOL includes prompts such as “Music sounds clear and natural to me” and “My hearing loss prevents me from listening to TV or radio” and therefore, likely qualitatively similar to the natural and actual home testing environment of the online working memory and speech perception tests that the participants performed. These positive correlations suggest that CI users with higher auditory working memory performance, greater speech perception and earlier implantation can understand and enjoy audio and audiovisual media to a larger extent. CI users have subjectively reported difficulty in understanding television speech without closed captioning especially if accompanied by background noise or music (Clark, 2003; Gfeller et al., 2019). The mechanisms relating media enjoyment and working memory/speech perception are likely related to cognitive resources and stimulus ambiguity.

Subjective music perception is another component within the CIQOL entertainment section where music perception is highly variable in CI users (Gfeller et al., 2008; Philips et al., 2012; Wright and Uchanski, 2012; Drennan et al., 2015). Our correlational results are in agreement with the recent report of D’Alessandro et al. (2021) who found significant correlations between music quality ratings and speech perception tests in noise (including the matrix test). Previous studies have shown that CI users experience difficulties listening to lyrical music; this may suggest that the instrument accompaniment of lyrical music might act as background noise while they attempt to hear and understand the lyrics (Collister and Huron, 2008; Gfeller et al., 2008, 2019; Eskridge et al., 2012). Other studies have shown that the perception of pitch and timbre in music are difficult for CI users, both of which are also elements of speech and promote pleasure and other emotions while listening to music (McDermott, 2004; Limb and Rubinstein, 2012; Moran et al., 2016). This might be why those with higher speech perception also find more pleasure with music.

Significant correlations between CIQOL entertainment with age and age of implantation is likely related to the age range of implantation (0–66 years old), the earlier implanted CI users may not be aware or have no memory of music before implantation and therefore, gain more enjoyment from it. Similar results are observed in Fuller et al. (2019) where early deafened, late implanted CI users reported a higher appreciation for music despite speech perception being lower compared to postlingual CI users.

4.5 Relationships with CIQOL communication, SSQ speech and quality of hearing

Many previous studies have reported positive correlations between speech perception with NCIQ and SSQ (Wallhäusser-Franke et al., 2018; Häußler et al., 2019; Moberly et al., 2019; Dingemanse and Goedegebure, 2020; Dietz et al., 2022; Myhrum et al., 2023) and one with CIQOL communication (McRackan T. et al., 2019). The present study however only observed speech perception relationships with CIQOL (communication), SSQ (speech hearing) and SSQ (quality of hearing) using the matrix sentence tests. The discrepancy might result from different testing conditions in which participants performed the speech perception tasks in soundproof booths or similar controlled environments in previous studies where no potential environmental distractions were perceived.

CIQOL communication consists of questions relating to receptive and expressive communication ability in different situations. Similarly, the SSQ speech hearing domain consists of questions relating to speech sound separation and segregation in presence of background talkers and selective attention to talkers and SSQ quality of hearing consists of questions relating to ability to segregate and recognize sounds, the clarity of speech, and listening effort. While the communication domain correlated with the matrix speech perception test, the speech and quality of hearing domains related to working memory and speech perception outcomes. NCIQ contained domains (basic and advanced sound perception) that somewhat coincided with these domains however, no significant correlations were observed. Given the overlap and similarity in questions between these three domains (communication, speech hearing and quality of hearing), all will be discussed below.

Individuals with lower speech perception scores have been shown, in the present and other studies, to have lower working memory capacities (Tao et al., 2014; Kaandorp et al., 2017; Moberly et al., 2017b; Hillyer et al., 2019; O'Neill et al., 2019; El Ghazaly et al., 2021) and this may contribute to the higher levels of listening effort observed in CI users (Pérez et al., 2023; Philips et al., 2023). Although the mechanisms underlying the relationship between working memory and speech perception in CI users are not clear, one possibility may be related to individual differences in cognitive capacities. CI users with larger working memory capacities have the ability to recruit more resources for selective attention (Coez et al., 2014; Kessler et al., 2020; Mertens et al., 2020) and for the comprehension and storage of speech stimuli than those with lower working memory capacity (Mortensen et al., 2006; Lee et al., 2007; Eisner et al., 2010; Lazard et al., 2010; Giraud et al., 2011; Strelnikov et al., 2015; Suh et al., 2015; Moberly et al., 2017b; Kessler et al., 2020) resulting in a lower level of listening effort. This result is better reflected in the correlations observed with SSQ.

4.6 Relationships with SSQ spatial hearing

The SSQ spatial hearing section consists of questions relating to auditory spatial judgments in common, everyday scenarios. Performance on all working memory and speech perception tasks positively related to spatial hearing. Furthermore, mode of implantation was significantly related to SSQ spatial hearing, such that bilateral users reported better spatial hearing followed by bimodal then unilateral. Therefore, bilateral users may present benefits in speech perception because of the spatial advantage that two CIs provides vs. one. This study corroborates previous findings that bilateral users receive benefits in speech perception due to better sound localization (Tyler et al., 2007; Wackym et al., 2007; Loizou et al., 2009; Dunn et al., 2010; Schäfer et al., 2011; Glyde et al., 2013; Best et al., 2015; van Hoesel, 2015; Smulders et al., 2016; Perreau et al., 2017). This study also corroborates the results of previous studies showing the advantage of bilateral CIs compared to a bimodal hearing configuration when measuring spatial hearing (Yawn et al., 2018; Gifford and Dorman, 2019).

Previous studies suggest that the benefit of bimodal and bilateral hearing configurations over unilateral hearing might stem from having the ability to segregate and attend to a target sound stimuli. This can be related to better enjoyment and clarity of media (Kong et al., 2005; Dorman et al., 2008; Gfeller et al., 2008; Veekmans et al., 2009), lower listening effort (Noble et al., 2008; Dunn et al., 2010; Hughes and Galvin, 2013; Schnabl et al., 2015; Perreau et al., 2017; Sladen et al., 2018), and better quality of hearing (Summerfield et al., 2006; Noble et al., 2008; Kocak Erdem and Ciprut, 2019). The advantage of bilateral users over bimodal users might be caused by a mismatch between listening through a CI on one side and hearing aid on the other requiring compensations in working memory and attention to combine the streams of auditory information (Gifford and Dorman, 2019; Pieper et al., 2022). Lower levels of listening effort and better quality of hearing suggests that a lower degree of cognitive resource recruitment is required for encoding stimuli perhaps due to its spatial hearing advantage (Noble et al., 2008; Schnabl et al., 2015; Hua et al., 2017) and lack of mismatched auditory information. This is corroborated by the results of this study in which CI users reporting better spatial hearing also showed greater working memory ability both in the visual and auditory modality (reading and listening spans).

4.7 Implications, future directions and limitations

This study demonstrated that greater cognitive ability is related to better outcomes of certain aspects of CIQOL and SSQ with SSQ providing more insight into the cognitive effects of QOL. Furthermore, that meaningful data can be obtained using online testing in CI users. Testing in an online environment offers several advantages for both clinicians and researchers including less burden for participants, ease of repeat testing in longitudinal studies, ability to obtain meaningful data when face-to-face interactions are impossible (e.g., during the COVID-19 pandemic). A main limitation in this study is the lack of control over stimuli presentation and environment. Since this was an online study, participants completed tasks using their own devices and in an environment of their choosing. The differences in speaker or headphone quality were not controlled for however, participants were able to hear the stimuli because before the start of the task, they were able to test the audibility of stimuli and choose the best method of listening, albeit, limited to what was available to them. In terms of environment, participants did not complete the studies in a soundproof booth and therefore, we cannot confirm that they completed the study without any external distractions. However, it can be argued that performing these tasks outside of a soundproof booth provides a more realistic representation of everyday listening. Another limitation is an insufficient sample size when modes of implantation is correlated with spatial hearing; therefore, readers should consider the results as trends.

5 Conclusion

We investigated the cognitive ability between CI users and TH controls and how they relate to commonly used PROMs in the clinical setting. Our findings support previous literature suggesting that working memory ability and speech perception are lower in CI users and is related to the communication and enjoyment and clarity of media through CIQOL and subjective reports of speech, spatial and quality of hearing through SSQ. These results suggest that detriments in cognition might create difficulties in enjoying music and listening to speech whilst in social environments. Consequences of these difficulties include psychological issues such as social isolation, depression, and anxiety (Strawbridge et al., 2000; Akeroyd, 2008; Gallacher et al., 2012; Lin et al., 2013, 2014; Gurgel et al., 2014; Fulton et al., 2015; Fritze et al., 2016; Wingfield, 2016; Golub, 2017; Loughrey et al., 2018). Additionally, our data demonstrates that, compared other commonly used PROMS, more domains assessed though the SSQ are influenced by cognitive performance.

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 Research Ethics Board (REB) at Sunnybrook Health Sciences Center. 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

PP: Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Conceptualization. JC: Writing – review & editing, Writing – original draft, Methodology, Conceptualization. TL: Writing – review & editing, Writing – original draft, Methodology, Conceptualization. VL: Writing – review & editing, Writing – original draft, Methodology, Conceptualization. AD: Writing – review & editing, Writing – original draft, Supervision, Methodology, Formal analysis, Conceptualization.

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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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