ORIGINAL ARTICLE
J Audiol Otol 2024 Apr 30 [Epub ahead of print]
pISSN 2384-1621 / eISSN 2384-1710
https://doi.org/10.7874/jao.2023.00276

Cognitive Functions and Subjective Hearing in Cochlear Implant Users

Fawen Zhang[1], Kelli McGuire[1], Madeline Skeeters[1], Matthew Barbara[1], Pamara F. Chang[2], Nanhua Zhang[3], Jing Xiang[3], and Bin Huang[4]

[1]Department of Communication Sciences and Disorders, University of Cincinnati, Cincinnati, OH, USA
[2]Department of Information & Logistics Technology, College of Technology, University of Houston, Houston, TX, USA
[3]Cincinnati Children's Hospital Medical Center, University of Cincinnati College of Medicine, Cincinnati, OH, USA
[4]BrainCheck, Inc., Houston, TX, USA

Received July 5, 2023
Revised September 6, 2023
Accepted September 15, 2023

Address for correspondence
Fawen Zhang, PhD
Department of Communication Sciences and Disorders,
University of Cincinnati,
3225 Eden Avenue, Cincinnati,
OH 45267, USA
Tel +1-513-558-8513
Fax +1-513-558-8500
E-mail Fawen.Zhang@uc.edu

Background and Objectives: A cochlear implant (CI) is an effective prosthetic device used to treat severe-to-profound hearing loss. The present study examined cognitive function in CI users by employing a web-based cognitive testing platform, i.e., BrainCheck, and explored the correlation between cognitive function and subjective evaluation of hearing. **Subjects and Methods**: Forty-two CI users (mean age: 58.90 years) were surveyed in the subjective evaluation of hearing, and 20/42 participated in the BrainCheck cognitive tests (immediate recognition, Trail Making A, Trail Making B, Stroop, digit symbol substitution, and delayed recognition). As controls for cognitive function, young normal-hearing (YNH, mean age=23.83 years) and older normal-hearing (ONH, mean age=52.67 years) listener groups were subjected to BrainCheck testing. **Results**: CI users exhibited poorer cognitive function than the normal hearing groups in all tasks except for immediate and delayed recognition. The highest percentage of CI users who had "possible" and "likely" cognitive impairment, based on BrainCheck scores (ranging from 0−200), was observed in tests assessing executive function. The composite cognitive score across domains tended to be related to subjective hearing (p=0.07). **Conclusions**: The findings of the current study suggest that CI users had a higher likelihood of cognitive impairment in the executive function domain than in lower-level domains. BrianCheck online cognitive testing affords a convenient and effective tool to self-evaluate cognitive function in CI users.
J Audiol Otol 2024

Keywords: REDCap; BrainCheck; Cognitive function; Cochlear implant; Auditory system.

Introduction

Normal human hearing requires interactions between bottom-up sensory encoding of sound features in dynamic sound contexts and top-down cognitive processing [1,2]. On the one hand, the bottom-up ascending system, which processes the physical sound inputs and submits this information up to the auditory cortex and beyond for further processing [3]. On the other hand, the top-down, descending pathway exerts cognitive influences on the auditory cortex and lower levels of bottom-up processing for optimal auditory perception [3,4]. This bottom-up and top-down interaction is extremely exquisite so that any disturbance in this loop may result in imbalance, which may not be compensated fully with the current treatments for hearing loss such as cochlear implantation.

A cochlear implant (CI) is an effective prosthetic device used to treat severe-to-profound hearing loss. Although most CI users have benefited from the CI for speech understanding, there is a wide range of variability among individual CI users as well as within subjects (e.g., ear difference in individuals using the CI bilaterally) [5]. Prior to implantation, long-term hearing loss can cause neural deficits in the auditory pathway, brain reorganization, increased cognitive demand and heightened listening effort, and impaired cognitive control [6,7]. After implantation, it is expected that the bottom-up and top-down interaction could be at least partially restored, but the restoration is limited mainly due to constraints of CI processing that only keeps very coarse tempo-spectral structures of sounds [8].

The top-down cognitive function consists of skills in a series of domains (e.g., memory, attention, executive function, etc.) and assessment for separate domains can reveal patterns of performance that are associated with specific neurological deficits [9,10]. Previous studies have reported significant correlations between cognitive function of some domains and speech performance in CI users [11,12]. Examining the cognitive function of different domains in CI users is important for patient consulting and the design of customized rehabilitation (e.g., identifying individuals with poor cognitive function of certain domains for targeted rehabilitation).

The current study examined CI users' cognitive function using BrainCheck (BrainCheck, Inc., Austin, TX, USA), an online software that provides self-administered cognitive tests of different domains. Recently published studies have shown high sensitivity and specificity of BrainCheck test batteries in the diagnosis of neurocognitive function deficits when compared with standard clinical assessment [13]. BrainCheck has not been used in CI users in the literature.

In the current study, we also conducted an online survey to examine CI users' subjective hearing ability using the Research Electronic Data Capture (REDCap; University of Tennessee Health Science Center, Memphis, TN, USA), a secure, web-based platform commonly used for data collection and analysis. CI users' subjective evaluation of hearing is an easy way to understand CI outcomes, which may not be fully achieved with laboratory-based testing. For instance, when assessing binaural benefits in bilaterally implanted CI users, lab settings can only allow the participants to be tested with a limited range of target-noise spatial configurations, which may result in underestimated binaural benefits [14]. Subjects' self-reported benefit of CIs has been reported to be correlated to speech perception performance tested behaviorally in high-performing CI users [15].

The research questions to be addressed in the current study include: 1) Does CI users' cognitive function show different levels of impairments in different domains including memory, attention, and executive function? 2) Is there any association between cognitive function of CI users and their subjective hearing ability? The results would provide insight for the selection of post-implantation rehabilitation programs (e.g., integrating cognitive function training).

Subjects and Methods

Subjects

Adults (>18 years of age) who wore at least one CI were recruited, including those wearing a CI unilaterally (UCI), bilaterally (BCI), and a hearing aid in the non-implanted ear (bimodal, BMCI). Forty-two (mean age: 58.90±8.36, ranging from 18 to 89 years) CI users participated including 8 UCI, 22 BCI (21 sequentially and 1 simultaneously implanted), and 12 BMCI users. All participants have used at least one CI for longer than 1 year (up to 21 years) except 3 participants for approximately 3–8 months. In terms of implant manufacturer, 3 had Advanced Bionics, 27 Cochlear Americas, and 12 Med-El devices. All BCI users had devices from the same manufacturer in both ears. In addition, 20 young (mean age: 23.83±1.34, ranging from 23 to 27 years) and 6 older (mean age: 52.67±2.16, ranging from 51–57 years) adults with normal hearing (pure tone threshold average for frequencies 0.5, 1, 2, and 4 kHz <25 dB) participated the BrainCheck tests as controls. Inclusion criteria for participants in CI, young normal hearing (YNH), and old normal hearing (ONH) included: 1) native English speaker, and 2) be able to use a computer, iPad, or smartphone. Individuals with any history of neurological disorders, psychiatric disorders, or brain injury were excluded.

The research was approved by the Institutional Research Board (IRB) office at the first author's institution (IRB number: "07-11-02-02"). The waiver of documentation of consent was approved for this study conducted online (IRB #: MOD26_2013-6396) because participants' identifiers were not needed for the research. Each participant received a gift card for their participation.

Experimental procedures

REDCap was used to collect data including CI demographic data and self-evaluation of hearing ability. Participants were told at the end of the survey they can opt to perform BrainCheck cognitive tests if they contacted the principal investigator. Twenty CI participants who contacted the researcher team after finishing the REDCap survey were sent a user-specific code to perform BrainCheck cognitive assessment. All normal-hearing listeners completed BrainCheck assessment.

REDCap survey

Demographic questions were asked about age, gender, education level, age at implantation, number of years for CI use, etc.

Participants were also asked to provide subjective evaluation of hearing in competing contexts (Q1, Q2), spatial hearing (Q3), sound quality (Q4), listening effort (Q5), music per-

Table 1. Individual questionnaire items

No.	Question items [16,17]
Q1	You are in conversation with one person in a room where there are many other people talking. Can you follow what the person you are talking to is saying? ("not at all" to "perfectly")
Q2	You are in a group of about five people in a busy restaurant. You can see everyone else in the group. Can you follow the conversation? ("not at all" to "perfectly")
Q3	Can you tell how far away a bus or a truck is, from the sound? ("not at all" to "perfectly")
Q4	Do everyday sounds that you can hear easily seem clear to you (not blurred)? ("very much blurred" to "not blurred at all")
Q5	Do you have to concentrate very much when listening to someone or something? ("concentrate hard" to "no need to concentrate")
Q6	When you listen to music, can you make out which instruments are playing? ("not at all" to "perfectly")
Q7	Are you able to recognize music melodies (sequences of music notes at different pitches)? ("not at all" to "perfectly")
Q8	Are you able to recognize certain rhythms in music (the recurrence of music notes and silences in time)? ("not at all" to "perfectly")
Q9	Can you hear the difference between a man's voice, a woman's voice, and a child's voice without looking at the speaker? ("not at all" to "perfectly")
Q10	How are you satisfied with the hearing outcome of your CI, compared to your hearing before implantation? ("not satisfied" to "very much satisfied")

ception (Q6–Q8), voice gender discrimination (Q9), and the general satisfaction level of using the CI (Q10). Most questions were selected from the Speech, Spatial, and Qualities of Hearing Scale (SSQ) and its shorter versions [16,17] to assess the subjective hearing of our interest. These questions are listed in Table 1.

For each question, the participant was allowed to move a bar to indicate his/her selected value from left to right to indicate the answer (e.g., "not at all" to "perfectly" on a 0–100 scale). For individuals with UCI users, the survey questions were asked about the CI ear; for BCI and BMCI users, the questions were asked about their individual CI ears, and binaural hearing, separately. For binaural hearing, the questions were structured in a way that they compare their binaural hearing vs. monaural CI only (for BMCI users) or the better CI ear or the right CI ear if hearing in the two ears was similar (for BCI users). The answers were from "much worse" to "much better" on a 0–100 scale in the REDCap output.

BrainCheck

BrainCheck Standard Battery tests were self-administered on participants' computer, iPhone, or iPad after the participants got access to the tests using participant-specific passcodes provided by the researchers. Once participants entered BrainCheck platform (https://client.braincheck.com), they were asked to follow the written instructions. Each test began with an interactive demo, followed by a short practice test. Once participants felt they understood what was required of the test, they then took the test. Participants were asked to perform each test as quickly and accurately as possible.

Immediate recognition test

This test assesses immediate memory. The participants were presented with 10 words on the computer screen, one at a time, and were given a few moments to memorize each word. Then the participants were presented with a series of 20 words on the next screen, including the 10 words presented previously. As each word appeared, the participants were required to identify if this word appeared previously as quickly as possible.

Trail Making Tests

Trail Making Tests A and B assess visual attention and cognitive flexibility. Trail Making Test A requires the participants to correctly sequence 25 numbered circles (1 through 25) randomly scattered on the computer screen as quickly as possible. The participant must tap the circles in a numerical order (1, 2, 3,...). Trail Making Test B consists of 24 circles including 12 numbers (1 to 12) and 12 letters (A to L). The participant must tap the circles in alternating order of numerical and alphabetical (1, A, 2, B, 3, C,…).

Stroop interference test

This test assesses the reaction time needed to overcome cognitive interference, a type of executive function. The participants were presented with the name of a color (e.g., the word "red") on the top of the screen and also presented with a series of names of colors in congruent colors (e.g., the word "red" in red color), neutral colors (all words are presented in black), and incongruent colors (e.g., the word "red" in blue color). Participants were asked to find a word in the bottom of the screen that matched the given name of a color on the top of the screen.

Digital symbol substitution test

This test assesses processing speed and accuracy, an executive function. It requires the participants to match an arbitrary correspondence of symbols to digits. When presented with a new symbol (e.g.,) on top of the screen, the participants must find the corresponding digit among all symbol-digit pairs as quickly as possible and tapping the digit.

Delayed recognition test

This test was given at the end of the test battery to assess delayed memory. It requires the participant to correctly identify the 10 words presented in "immediate recognition test" from a list of 20, without seeing the original list of words in "immediate recognition test" again.

For a convenient interpretation of the cognitive function by clinicians, BrainCheck automatically generates a score (0–200) based on the median reaction times/accuracy for each task that indicates the likelihood of cognitive impairment: 85 to 200,"unlikely"; 70 to 84, "possible"; and 0 to 69,"likely" [18]. The composite score was also generated automatically for each participant in BrainCheck using a patented algorithm that sums scaled and weighted assessment scores to represent an overall view of cognitive function [13,18]. The BrainCheck scores are accessible by all testing administers. Because the BrainCheck score is for a rough categorization of the performance ("unlikely," "possible," and "likely" to have cognitive deficit), the raw data of the reaction time of each test were also used when comparing the performance across groups. The raw data of reaction time data is only available when contacting BrainCheck, Inc.

Statistical analysis

Statistical analyses were conducted using SigmaPlot statistical package (V14.5; Systat Software Inc., Palo Alto, CA, USA) and Statistical Analysis System (SAS V9.4; SAS Institute, Cary, NC, USA). One-way analysis of variance (ANOVA) was performed to examine the effects of subject group (CI, YNH, and ONH) on the reaction time and the BrainCheck score of each test. When the normality test (Shapiro-Wilk) failed, Kruskal-Wallis one way ANOVA on ranks was performed. For the follow-up t-tests, p values were corrected for multiple comparisons.

Relationships between the composite cognitive score and demographic data were tested using Pearson's correlation analysis. A linear mixed effects model was used to model the subjective hearing on CI type (UCI, BCI, and BMCI), question item number, and BrainCheck composite score with adjustment of demographic factors, as well as the interaction between CI type and question item number; subject-specific random effect was included to account for repeated measures of the same subject on different question items. Tukey-Kramer test was used to adjust for multiple comparisons.

Results

Cognitive function in CI users

CI users' performance of all cognitive tests together with that from the ONH and YNH groups are shown in Fig. 1. CI users had a poorer performance than other two groups on all tests except immediate recognition and delayed recognition. Statistical analysis of the reaction time showed that the main effect of subject group was significant for all tests (Trail A: H=14.29; Trail B: H=21.25; Stroop: H=30.51; digit, H=24.73; immediate memory: H=18.21; delayed memory: H=23.61; $p<0.05$). Follow-up tests with adjustment for multiple comparisons showed that significant difference in performance (poor-

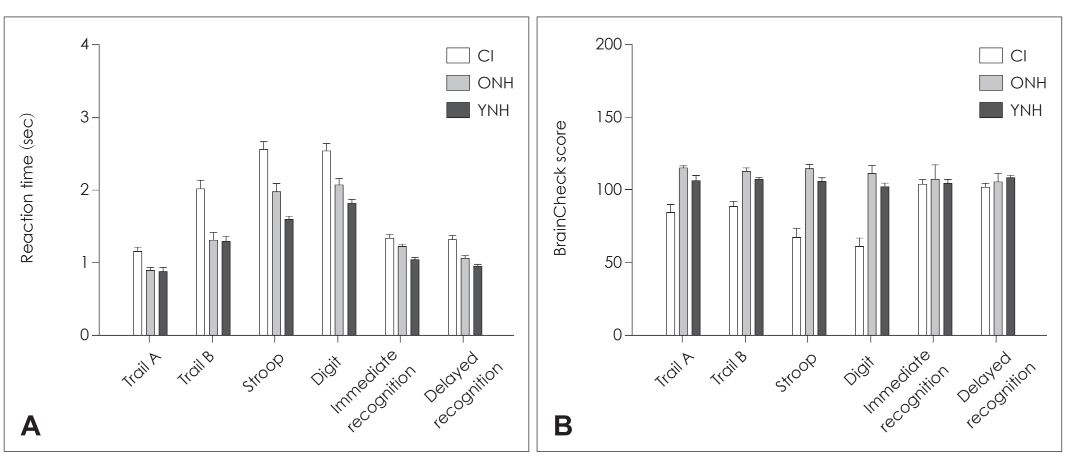

Fig. 1. Comparison of reaction time (A) and BrainCheck scores (B) on 6 cognitive tests (Trail Making A, Trail Making B, Stroop, digit symbol substitution, immediate recognition, and delayed recognition) for cochlear implant (CI) users, young normal-hearing listeners (YNH), and older normal-hearing listeners (ONH). Error bars represent standard error of the mean.

er performance corresponds to a longer reaction time) existed between the following pairs: for Trail A and Tail B tests—CI<ONH; CI<YNH; for digit symbol—CI<YNH; for Stroop—CI<ONH; CI<YNH; ONH<YNH; for immediate and delayed recognition—CI<YNH. Note that CI users' performance did not differ significantly from that of ONH on immediate and delayed recognition as well as digit symbol tests. Statistical analysis of the BrainCheck Score showed that the main effect of subject group was significant for all tests (Trail A: H=14.97; Trail B: H=26.00; Stroop: H=26.80; digit symbol: H=28.81; immediate memory: H=7.81; $p<0.05$), except delayed memory (H=1.87, $p>0.05$). Follow-up tests with adjustment for multiple comparisons showed that significant difference in performance (poorer performance corresponds to a lower BrainCheck score) existed between the following pairs: for Trail A, Trail B, digit symbol, Stroop tests—CI<YNH; CI<ONH; for immediate recognition—ONH<YNH. The results based on BrainCheck scores indicate that the CI group has significantly poorer performance than other groups except the immediate and delayed recognition tasks. In summary, results of reaction time and BrainCheck scores showed that CI users' cognitive function has a higher level of deficit at the executive function level than at the memory level.

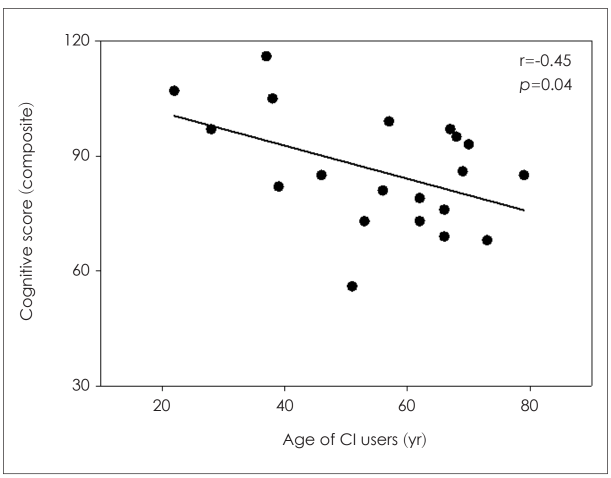

Fig. 2. Cochlear implant (CI) users' composite cognitive score as the function of age. The solid line is regression line.

Pearson's correlation analyses were conducted to examine the correlations between BrainCheck composite scores and demographic data. The results showed that age negatively affected BrainCheck composite score (r=-0.45, $p=0.04$) (Fig. 2). Other factors such as gender, education, living with a family member, paid employment, music training before CI, and music training after CI were not related to BrainCheck composite scores ($p>0.05$).

Subjective hearing

Fig. 3 shows the subjective hearing through the CI for 10 questions in UCI, BMCI, and BCI users. The scores for Q2, Q3, Q5, Q6, and Q7 were lower than those for other questions and this pattern appeared to be consistent across CI groups. However, the score for satisfaction level (Q10) was higher than the scores for other questions about hearing in specific listening scenarios.

A mixed model was used to examine the differences in the performance of all questions separately in UCI, BMCI, and BCI users, with subject effect considered and demographic data as covariates. Demographic variables were removed from the model since they were not significant. For UCI users, there was a significant effect of question items [$F_{(9, 58)}=2.24$, $p=0.03$]. After adjusting for multiple comparisons using the Tukey-Kramer test, there was no statistical difference among question items ($p>0.05$). For BMCI users, there was a significant effect of question items [$F_{(9, 72)}=5.05$, $p<0.01$]. After ad-

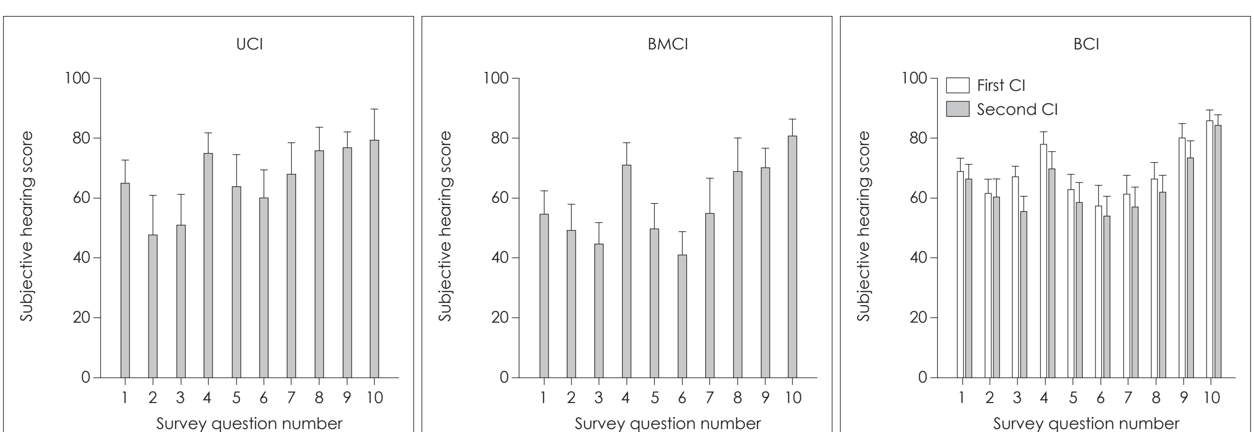

Fig. 3. Scores of subjective hearing using the cochlear implant (CI) for 10 survey questions in unilateral CI (UCI), bimodal CI (BMCI), and bilateral CI (BCI), users. For BCI users, the mean scores for the 1st CI and 2nd CI are separately plotted for individuals who were sequentially implanted (21/22 participants). Error bars represent standard error of the mean.

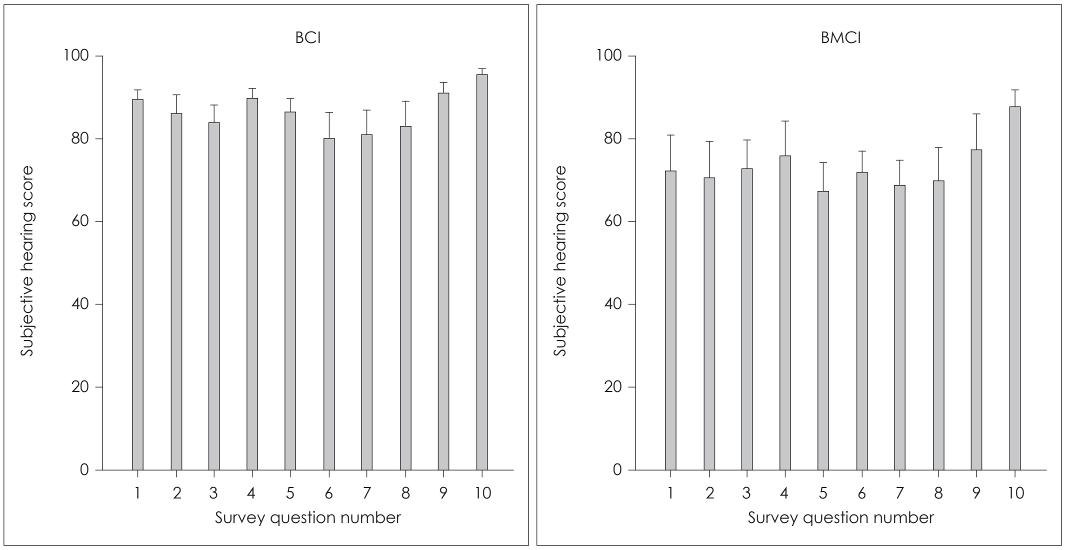

Fig. 4. Scores of subjective binaural hearing in bilateral cochlear implant (BCI) and bimodal cochlear implant (BMCI) users for 10 survey questions. Participants were asked to give a score for binaural hearing relative to monaural hearing using the cochlear implant (CI) only in BMCI users or using the best CI only or the right CI if two CIs were similar in BCI users. Error bars represent standard error of the mean.

justing for multiple comparisons, there was difference between question items (Q10>Q2, Q3, and Q6; Q4>Q6; Q8>Q6; Q9>Q6; all $p<0.05$). For BCI users, there was a significant effect of question items [$F_{(9, 379)}=9.70$, $p<0.01$], and the sequence of CI [1st or 2nd CI, $F_{(1, 379)}=5.49$, $p=0.02$]. After adjusting for multiple comparisons, there was a statistical difference between question items (Q10>Q2, Q3, Q5, Q7, and Q8; Q9>Q2 and Q3; Q4>Q3, Q6, and Q7; Q9>Q5, Q6, and Q7; all $p<0.05$). Overall, scores for questions about sound segregation in noisy environments, sound localization, listening efforts, and music timber and melody perception tended to be lower than those for other questions in BCI and BMCI users. The score for the 1st CI was significantly higher than that for the 2nd CI in BCI users ($p=0.02$).

Most BCI users (18/22) benefited from binaural hearing compared to hearing with one CI only (either the better CI ear or the right CI if they thought the two CI ears were similar in hearing ability) in all questions. A total of 8 out of 22 patients (36.36%) indicated ear differences in either pitch or loudness when hearing the same sound in front of them. Two of these participants indicated an imbalance in both dimensions.

Most BMCI users (9/12) showed binaural benefit (two ears are better than the CI ear alone) in all questions. Nine out of 12 BMCI patients (75.00%) reported ear differences in either pitch or loudness when hearing the same sound in front of them. Seven of these 9 participants indicated imbalance in both dimensions.

Fig. 4 shows the scores for subjective binaural benefits in BCI and BMCI users when they were asked to compare the binaural vs. monaural hearing for the 10 questions. BCI users had a higher score than BMCI users for all questions. A linear mixed model was conducted to examine the difference in subjective binaural hearing between BCI and BMCI participants with subject effect considered and demographic data as covariance. BCI had a significantly higher score relative to BMCI users [$F_{(1, 150)}=8.58$, $p<0.01$]. Individuals receiving music training after CI had significantly greater subjective binaural benefits than those who did not [$F_{(1, 150)}=5.05$, $p=0.03$].

A linear mixed effects model was used to model the subjective hearing for all subject groups (UCI, BCI, and BMCI), question item number, and BrainCheck composite score with adjustment of demographic factors. Results showed a trend that the BrainCheck composite score was positively correlated to subjective hearing [$F_{(1, 294)}=3.29$, $p=0.07$], after adjusting for age at implantation, a demographic factor that negatively affected the subjective hearing [$F_{(1, 294)}=44.93$, $p<0.01$].

Discussion

The current study examined cognitive function of different domains in adult CI users relative to young and older listeners with normal hearing (YNH, ONH) as well as the correlation between composite cognitive scores and subjective evaluation of hearing. It is the first to demonstrate the feasibility of using BrainCheck in CI users for online cognitive testing when in-person testing is not practical. Results from CI users showed a significantly poorer performance relative to the YNH group for all tasks, and a poor performance than ONH for only some tests (Trails A and B and Stroop). The composite cognitive score across domains in CI users tended to be related to subjective hearing after adjusting for the age at implantation, but the correlation did not reach statistical significance.

Among 20 CI users who performed BrainCheck tests, the numbers of “possible” and “likely” categories (<85/200) for the 6 tests were 7 (Trail A, 35%), 6 (Trail B, 30%), 13 (digit symbol substitution, 65%), 17 (Stroop, 85%), 1 (immediate recognition, 5%), 4 (delayed recognition, 20%), respectively. The results showed that CI users in this study had a higher likelihood of cognitive impairment at the executive function level than attention and memory levels.

Cognitive function and subjective hearing

The benefit of cochlear implantation in cognitive function has been proven [19]. The use of implantation for as short as 6 months to 1 year can result in significant improvement in cognitive function [20,21]. As to the difference between CI users and normal-hearing listeners, previous studies reported mixed results. Kaandorp, et al. [22] reported that CI users’ performance on linguistic cognitive tests such as lexical-decision test, word-naming test, and vocabulary size test, and reading span test did not differ statistically from that in young normal-hearing listeners, partially because the cognitive tests were presented visually. Kramer, et al. [23] reported that adult CI users, CI candidates, and normal-hearing peers did not differ significantly in non-auditory cognitive abilities, after controlling for confounding demographic factors. Using CI-registered database with a sample size of 145 CI users, Claes, et al. [19] reported statistically lower performance on cognitive tests (immediate memory, visuospatial/constructional, language, attention, delayed memory) presented with audiovisual stimulation in CI adults over 55 years of age and normal-hearing peers. The authors indicated that the audiovisual stimulation of the cognitive tests may have brought some disadvantage to individuals with hearing impairment during test administration; moreover, the demographic of the participants (e.g., 79% of CI users included were unilateral CI users who did not have binaural auditory inputs) may also have contributed to the group difference in cognitive function. Taken together, the discrepancy among studies could be attributed to the differences in tests used, delivery modality of the test, and demographic data of CI users.

In this study, all cognitive tests were delivered with visual presentation. Therefore, participants with hearing impairment do not have disadvantage during test administration. A previous study has reported that visual presentation is a more accurate predictor for CI speech perception outcome than the audio-visual presentation [15]. Our results showed that CI users’ cognitive function had a higher likelihood of impairment at the executive function level than attention and memory levels with stimuli presented visually. Cognitive function has been conceptualized in terms of domains of functioning that are arranged in a hierarchical structure. These domains are related to each other, and executive functioning exerts control over the utilization of cognitive processes including memory and attention [9]. CI users in this study were able to demonstrate normal performance at the memory level relative to the ONH group of a similar age, possibly because the memory tested in this study is at a relatively lower level in the cognitive hierarchy. When the cognitive need is more demanding for more complicated tests (e.g., Stroop and digit symbol tests), CI users are more likely to show cognitive deficits. This can be evidenced by the fact that CI users’ score for the listening effort question is one of the lowest among scores for all questions asked. According to cognitive reserve theory, individuals may use the cognitive function to compensate for poor lower-level performance until the cognitive resource limit is reached [24]. When task complexity exceeds cognitive reserve (e.g., challenging speech perception tasks or challenging cognitive tasks), the engagement of effortful controlled processing to compensate for deficits in lower-level auditory processing may be more pronounced in order to maximize performance [25]. Such compensation is likely to fail in low-performing CI users because their bottom-up sensory processing is so poor that they cannot use their neurocognitive skills to support speech perception [26].

Aging is an important demographic factor affecting cognitive function in CI users (Fig. 2). A normal process of aging causes anatomical changes in the human nervous system and neural inefficiency [27]. Aging causes a decline of certain cognitive functions such as processing speed and certain memory, language, visuospatial, and executive function abilities [27]. CI users’ age, which is heterogeneous, was found to significantly influence cognitive function and subjective hearing. Previous studies also reported that aging can exacerbate hearing loss-related decline of cognitive function [28].

However, aging alone cannot explain the observed cognitive deficits in CI users based on the following observations. For instance, CI users did not differ from ONH in their performance in some tests (immediate and delayed recognition, digit symbol). Moreover, the oldest CI user who participated in BrainCheck tests had a compositive score of 85 and the age for the CI user with the lowest composite score of was 51 years. Therefore, the cognitive deficit in CI users could be the combination of multiple factors such as age (some CI users are older than 60 years of age), the long-term deafness prior to implantation, and CI technology constraint.

Previous studies suggested that age alone should not be the limiting factor for cochlear implantation; on the contrary, implantation allows patients to get access to sounds which reduces the aging effect on cognitive function [29], and improves social interaction and life quality [30]. In this study, a total of 11/20 CI users had a composite cognitive score greater than 85, which indicate an "unlikely" cognitive impairment according to the BrainCheck user guide. Moreover, CI users have benefited from the CI in subjective hearing.

CI users' scores for Q2, Q3, Q5, Q6, and Q7 were lower than for other questions. The questions with poorer scores in CI users were related to sound segregation in noisy environments, sound localization, listening efforts, and music timber and melody perception, which requires fine pitch discrimination skills. This finding is consistent with the previous conclusion that poor spectral resolution due to the limited number of independent spectral channels is the main reason for poor CI performance [31,32]. There was a trend that subjective hearing was correlated with the cognitive composite score, although the correlation did not reach a statistical level (p= 0.07). Our finding indicated the possible link between cognitive top-down processing and subjective hearing. Interestingly, the score for the question about CI satisfaction (Q10) is higher than scores for questions about hearing in specific scenarios. This may be because the answers to Q10 reflect CI users' evaluation of CI benefits in both auditory and non-auditory aspects of their lives such as quality of life, which cannot be captured by hearing assessment alone [33].

Taken together, the current results indicate that cochlear implantation is an effective and satisfactory treatment for severe-to-profound hearing loss, as it results in improved cognitive function, subjective evaluation of hearing, and possibly benefits beyond hearing ability.

Ear difference in BCI users' subjective hearing

For BCI users, the ear difference might be substantial, due to differences in electrode insertion depth, neural integrity of both sides of auditory pathways, characteristics of CI hardware and software, and clinical mapping [34]. Although a few studies using behavioral assessments have shown some evidence of "right-ear advantage" [35], evidence has not been sufficient to guide clinicians in choosing which ear to implant. Comparing left vs. right ear is not meaningful in the current study because some right-ear advantage may be related to the fact that the right ear was first implanted in sequential implantation situations. Most BCI participants (21/22) in this study were sequentially implanted. However, a comparison between the 1st and 2nd CI showed a higher score of subjective hearing for the 1st CI than for the 2nd CI. Note that there was a slight difference between the 1st and 2nd ears in the age of implantation (mean 46.69 vs. 49.14 years) and duration of CI use (mean 9.82 vs. 7.28 years).

Binaural vs. unilateral hearing

Most BCI studies have used behavioral methods and modelling methods to examine binaural benefits [5,14,36]. These studies reported an overall improvement of speech in noise under binaural relative monaural listening conditions, with a high degree of variability among individuals. The amount of binaural benefit appears to be negatively related to the degree of ear difference in the monaural performance. The current study found BCI users had a greater subjective binaural benefit than BMCI users, which may be due to the greater degree of ear difference in BMCI users. Eight out of 22 BCI users (36.36%) had some degree of subjective mismatch in sound loudness or pitch. By contrast, BMCI users have a greater probability to show subjective ear difference in loudness or pitch (9/12, 75%) than BCI users, possibly because of the more drastic ear difference in hearing modality (electric vs. acoustic hearing).

Implications

First, it is critical to test cognitive function in CI users, which is not typically done in clinical practice. Some researchers have emphasized the importance of developing cognitive assessment tools specifically for hearing-impaired listeners and CI users that can avoid the bias caused by their hearing impairment [37]. The BrainCheck cognitive test battery is delivered in a non-auditory modality, avoiding confounding factors of hearing impairment in patients with hearing disorders. Moreover, BrainCheck offers a quick, effective, valid self-administered tool for identifying cognitive deficits in a domain-specific way.

Second, CI users demonstrated a higher likelihood of deficits in cognitive function at the executive function level than attention and memory levels. Cognitive composite score across domains tends to be related to subject hearing. We suggest that rehabilitation after implantation should involve training on cognitive function in patients who demonstrate cognitive deficits but receive a reasonable amount of sensory information (e.g., confirmed by good auditory evoked potentials that do not require subjects' cognitive involvement).

Finally, compared to BMCI users, BCI users have a greater degree of subjective binaural benefits and a lower probability to show ear differences in loudness and pitch; BCI users' subjective hearing is significantly better in the 1st CI than in the 2nd CI. Previous studies indicated that the perceived pitch mismatch between acoustic hearing and electric hearing in BMCI users or between two CI ears in BCI users may be reduced in some CI users over time due to brain plasticity, but this change may not be sufficient to overcome ear differences [38,39]. Our results are consistent with suggestions from previous studies that BCI should be the choice if the hearing aid does not provide sufficient acoustic hearing and BCI should be conducted with a minimal time interval between the two CIs [40].

Future studies

First, this study provided important information on the degree of cognitive deficits in CI users relative to individuals with a normal hearing, although the number of ONH was relatively small due to challenges of recruiting such participants (older adults are likely to have hearing loss). Future studies will involve CI users, age-matched normal-hearing listeners, and age-matched hearing aid users to untangle effects of age, hearing loss, and mode of hearing (acoustic hearing via hearing aids vs. electric hearing via CIs) on cognitive function and hearing ability.

Conflicts of Interest

The authors have no financial conflicts of interest.

Author Contributions

Conceptualization: Fawen Zhang. Data curation: Fawen Zhang. Formal analysis: Fawen Zhang, Nanhua Zhang, Bin Huang. Funding acquisition: Fawen Zhang. Investigation: Fawen Zhang, Kelli McGuire, Madeline Skeeters, Matthew Barbara, Bin Huang. Methodology: all authors. Project administration: Fawen Zhang, Kelli McGuire, Madeline Skeeters, Matthew Barbara. Supervision: Fawen Zhang. Validation: Fawen Zhang, Kelli McGuire, Matthew Barbara, Bin Huang. Visualization: Fawen Zhang. Writing—original draft: Fawen Zhang. Writing—review & editing: Fawen Zhang, Matthew Barbara, Jing Xiang. Approval of final manuscript: all authors.

ORCID iDs

Fawen Zhang	https://orcid.org/0000-0001-9334-0431
Kelli McGuire	https://orcid.org/0000-0003-1459-9002
Madeline Skeeters	https://orcid.org/0009-0004-3657-1005
Matthew Barbara	https://orcid.org/0009-0002-5863-8245
Pamara F. Chang	https://orcid.org/0000-0002-7676-124X
Nanhua Zhang	https://orcid.org/0000-0001-5796-3404
Jing Xiang	https://orcid.org/0000-0003-0242-5590
Bin Huang	https://orcid.org/0000-0002-0056-1794

Funding Statement

This research was partially supported by the University Research Council grant and the National Institute of Health grant to the first author. The content is solely the responsibility of the authors and does not necessarily represent the official views of the National Institutes of Health and other funding agencies.

Acknowledgments

We would like to thank all participants for their time and efforts.

REFERENCES

1) Eggermont JJ. Between sound and perception: reviewing the search for a neural code. Hear Res 2001;157:1-42.
2) Davis MH, Johnsrude IS. Hearing speech sounds: top-down influences on the interface between audition and speech perception. Hear Res 2007;229:132-47.
3) Moore DR. Listening difficulties in children: bottom-up and top-down contributions. J Commun Disord 2012;45:411-8.
4) Marian V, Lam TQ, Hayakawa S, Dhar S. Top-down cognitive and linguistic influences on the suppression of spontaneous otoacoustic emissions. Front Neurosci 2018;12:378.
5) Yoon YS, Li Y, Kang HY, Fu QJ. The relationship between binaural benefit and difference in unilateral speech recognition performance for bilateral cochlear implant users. Int J Audiol 2011;50:554-65.
6) Rakerd B, Seitz PF, Whearty M. Assessing the cognitive demands of speech listening for people with hearing losses. Ear Hear 1996;17:97-106.
7) Zekveld AA, van Scheepen JAM, Versfeld NJ, Kramer SE, van Steenbergen H. The influence of hearing loss on cognitive control in an auditory conflict task: behavioral and pupillometry findings. J Speech Lang Hear Res 2020;63:2483-92.
8) Moberly AC, Lewis JH, Vasil KJ, Ray C, Tamati TN. Bottom-up signal quality impacts the role of top-down cognitive-linguistic processing during speech recognition by adults with cochlear implants. Otol Neurotol 2021;42(10S):S33-41.
9) Harvey PD. Domains of cognition and their assessment. Dialogues Clin Neurosci 2019;21:227-37.
10) Mendelsohn D, Riedel WJ, Sambeth A. Effects of acute tryptophan depletion on memory, attention and executive functions: a systematic review. Neurosci Biobehav Rev 2009;33:926-52.
11) Moberly AC. A surgeon-scientist's perspective and review of cognitive-linguistic contributions to adult cochlear implant outcomes. Laryngoscope Investig Otolaryngol 2020;5:1176-83.
12) Zhan KY, Lewis JH, Vasil KJ, Tamati TN, Harris MS, Pisoni DB, et al. Cognitive functions in adults receiving cochlear implants: predictors of speech recognition and changes after implantation. Otol Neurotol 2020;41:e322-9.
13) Groppell S, Soto-Ruiz KM, Flores B, Dawkins W, Smith I, Eagleman DM, et al. A rapid, mobile neurocognitive screening test to aid in identifying cognitive impairment and dementia (BrainCheck): cohort study. JMIR Aging 2019;2:e12615.
14) Culling JF, Jelfs S, Talbert A, Grange JA, Backhouse SS. The benefit of bilateral versus unilateral cochlear implantation to speech intelligibility in noise. Ear Hear 2012;33:673-82.
15) Hillyer J, Elkins E, Hazlewood C, Watson SD, Arenberg JG, Parbery-Clark A. Assessing cognitive abilities in high-performing cochlear implant users. Front Neurosci 2019;12:1056.
16) Gatehouse S, Noble W. The Speech, Spatial and Qualities of Hearing Scale (SSQ). Int J Audiol 2004;43:85-99.
17) Demeester K, Topsakal V, Hendrickx JJ, Fransen E, van Laer L, Van Camp G, et al. Hearing disability measured by the Speech, Spatial, and Qualities of Hearing Scale in clinically normal-hearing and hearing-impaired middle-aged persons, and disability screening by means of a reduced SSQ (the SSQ5). Ear Hear 2012;33:615-6.
18) Ye S, Sun K, Huynh D, Phi HQ, Ko B, Huang B, et al. A computerized cognitive test battery for detection of dementia and mild cognitive impairment: instrument validation study. JMIR Aging 2022;5:e36825.
19) Claes AJ, Van de Heyning P, Gilles A, Van Rompaey V, Mertens G. Cognitive outcomes after cochlear implantation in older adults: a systematic review. Cochlear Implants Int 2018;19:239-54.
20) Mosnier I, Bebear JP, Marx M, Fraysse B, Truy E, Lina-Granade G, et al. Improvement of cognitive function after cochlear implantation in elderly patients. JAMA Otolaryngol Head Neck Surg 2015;141:442-50.
21) Sarant J, Harris D, Busby P, Maruff P, Schembri A, Dowell R, et al. The effect of cochlear implants on cognitive function in older adults:

initial baseline and 18-month follow up results for a prospective international longitudinal study. Front Neurosci 2019;13:789.
22) Kaandorp MW, Smits C, Merkus P, Festen JM, Goverts ST. Lexical-access ability and cognitive predictors of speech recognition in noise in adult cochlear implant users. Trends Hear 2017;21:2331216517743887.
23) Kramer S, Vasil KJ, Adunka OF, Pisoni DB, Moberly AC. Cognitive functions in adult cochlear implant users, cochlear implant candidates, and normal-hearing listeners. Laryngoscope Investig Otolaryngol 2018;3:304-10.
24) Stern Y, Arenaza-Urquijo EM, Bartrés-Faz D, Belleville S, Cantilon M, Chetelat G, et al. Whitepaper: defining and investigating cognitive reserve, brain reserve, and brain maintenance. Alzheimers Dement 2020;16:1305-11.
25) Smith GNL, Pisoni DB, Kronenberger WG. High-variability sentence recognition in long-term cochlear implant users: associations with rapid phonological coding and executive functioning. Ear Hear 2019; 40:1149-61.
26) Tamati TN, Ray C, Vasil KJ, Pisoni DB, Moberly AC. High- and low-performing adult cochlear implant users on high-variability sentence recognition: differences in auditory spectral resolution and neurocognitive functioning. J Am Acad Audiol 2020;31:324-35.
27) Harada CN, Natelson Love MC, Triebel KL. Normal cognitive aging. Clin Geriatr Med 2013;29:737-52.
28) Guerreiro MJS, Van Gerven PWM. Disregarding hearing loss leads to overestimation of age-related cognitive decline. Neurobiol Aging 2017;56:180-9.
29) Sorrentino T, Donati G, Nassif N, Pasini S, Redaelli de Zinis LO. Cognitive function and quality of life in older adult patients with cochlear implants. Int J Audiol 2020;59:316-22.
30) Castiglione A, Benatti A, Velardita C, Favaro D, Padoan E, Severi D, et al. Aging, cognitive decline and hearing loss: effects of auditory rehabilitation and training with hearing aids and cochlear implants on cognitive function and depression among older adults. Audiol Neurootol 2016;21(Suppl 1):21-8.
31) Litvak LM, Spahr AJ, Saoji AA, Fridman GY. Relationship between perception of spectral ripple and speech recognition in cochlear implant and vocoder listeners. J Acoust Soc Am 2007;122:982-91.
32) Gifford RH, Hedley-Williams A, Spahr AJ. Clinical assessment of spectral modulation detection for adult cochlear implant recipients: a non-language based measure of performance outcomes. Int J Audiol 2014;53:159-64.
33) Moberly AC, Harris MS, Boyce L, Vasil K, Wucinich T, Pisoni DB, et al. Relating quality of life to outcomes and predictors in adult cochlear implant users: are we measuring the right things? Laryngoscope 2018; 128:959-66.
34) Kan A, Litovsky RY. Binaural hearing with electrical stimulation. Hear Res 2015;322:127-37.
35) Garcia-Iza L, Martinez Z, Ugarte A, Fernandez M, Altuna X. Cochlear implantation in the elderly: outcomes, long-term evolution, and predictive factors. Eur Arch Otorhinolaryngol 2018;275:913-22.
36) Litovsky R, Parkinson A, Arcaroli J, Sammeth C. Simultaneous bilateral cochlear implantation in adults: a multicenter clinical study. Ear Hear 2006;27:714-31.
37) Hamerschmidt R, Santos VM, Gonçalves FM, Delcenserie A, Champoux F, de Araujo CM, et al. Changes in cognitive performance after cochlear implantation in adults and older adults: a systematic review and meta-analysis. Int J Audiol 2023;62:521-32.
38) Reiss LA, Lowder MW, Karsten SA, Turner CW, Gantz BJ. Effects of extreme tonotopic mismatches between bilateral cochlear implants on electric pitch perception: a case study. Ear Hear 2011;32:536-40.
39) Reiss LA, Ito RA, Eggleston JL, Liao S, Becker JJ, Lakin CE, et al. Pitch adaptation patterns in bimodal cochlear implant users: over time and after experience. Ear Hear 2015;36:e23-34.
40) Berrettini S, Baggiani A, Bruschini L, Cassandro E, Cuda D, Filipo R, et al. Systematic review of the literature on the clinical effectiveness of the cochlear implant procedure in adult patients. Acta Otorhinolaryngol Ital 2011;31:299-310.