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 heightenened 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-
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.

Table 1. Individual questionnaire items

<table>
<thead>
<tr>
<th>No.</th>
<th>Question items [16,17]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q1</td>
<td>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”)</td>
</tr>
<tr>
<td>Q2</td>
<td>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”)</td>
</tr>
<tr>
<td>Q3</td>
<td>Can you tell how far away a bus or a truck is, from the sound? (“not at all” to “perfectly”)</td>
</tr>
<tr>
<td>Q4</td>
<td>Do everyday sounds that you can hear easily seem clear to you (not blurred)? (“very much blurred” to “not blurred at all”)</td>
</tr>
<tr>
<td>Q5</td>
<td>Do you have to concentrate very much when listening to someone or something? (“concentrate hard” to “no need to concentrate”)</td>
</tr>
<tr>
<td>Q6</td>
<td>When you listen to music, can you make out which instruments are playing? (“not at all” to “perfectly”)</td>
</tr>
<tr>
<td>Q7</td>
<td>Are you able to recognize music melodies (sequences of music notes at different pitches)? (“not at all” to “perfectly”)</td>
</tr>
<tr>
<td>Q8</td>
<td>Are you able to recognize certain rhythms in music (the recurrence of music notes and silences in time)? (“not at all” to “perfectly”)</td>
</tr>
<tr>
<td>Q9</td>
<td>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”)</td>
</tr>
<tr>
<td>Q10</td>
<td>How are you satisfied with the hearing outcome of your CI, compared to your hearing before implantation? (“not satisfied” to “very much satisfied”)</td>
</tr>
</tbody>
</table>
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-
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.

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-
justing for multiple comparisons, there was difference be-
tween question items (Q10>Q2, Q3, and Q6; Q4>Q6; Q8>
Q6; Q9>Q6; all \( p < 0.05 \)). For BCI users, there was a signifi-
cant 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 ad-
justing for multiple comparisons, there was a statistical dif-
ference 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, listen-
ing 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 lin-
ear mixed model was conducted to examine the difference in
subjective binaural hearing between BCI and BMCI partici-
pants 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 mu-
sic training after CI had significantly greater subjective binau-
ral benefits than those who did not [\( F(1, 150)=5.05, p=0.03 \)].

A linear mixed effects model was used to model the subjec-
tive 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 correlat-
ed 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 listen-
ers with normal hearing (YNH, ONH) as well as the correla-
tion between composite cognitive scores and subjective eval-
uation 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 compo-
site cognitive score across domains in CI users tended to be re-
lated 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 composite score of 85 and the age for the CI user with the lowest composite score 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, im-
Cognitive Function of Cochlear Implant Users

plantation 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.

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