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Listening Effort Measured in Adults with Normal Hearing and Cochlear Implants

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Abstract

Background: Studies have examined listening effort in individuals with hearing loss to determine the extent of the impairment. Regarding cochlear implants (CIs), results suggest that listening effort is improved using bilateral CIs compared to unilateral CIs. Few studies have investigated listening effort and outcomes related to the hybrid CI.

Purpose: Here, we compared listening effort across three CI groups, and to a normal-hearing control group. The impact of listener traits, that is, age, age at onset of hearing loss, duration of CI use, and working memory capacity, were examined relative to listening effort.

Research Design: The participants completed a dual-task paradigm with a primary task identifying sentences in noise and a secondary task measuring reaction time on a Stroop test. Performance was assessed for all participant groups at different signal-to-noise ratios (SNRs), ranging in 2-dB steps from 0 to 110 dB relative to an individual's SNR-50, at which the speech recognition performance is 50% correct. Participants completed three questions on listening effort, the Spatial Hearing Questionnaire, and a reading span test.

Study Sample: All 46 participants were adults. The four participant groups included (1) 12 individuals with normal hearing, (2) 10 with unilateral CIs, (3) 12 with bilateral CIs, and (4) 12 with a hybrid short-electrode CI and bilateral residual hearing.

Data Collection and Analysis: Results from the dual-task experiment were compared using a mixed 4 (hearing group) by 6 (SNR condition) analysis of variance (ANOVA). Questionnaire results were compared using one-way ANOVAs, and correlations between listener traits and the objective and subjective measures were compared using Pearson correlation coefficients.

Results: Significant differences were found in speech perception among the normal-hearing and the unilateral and the bilateral CI groups. There was no difference in primary task performance among the hybrid CI and the normal-hearing groups. Across the six SNR conditions, listening effort improved to a greater degree for the normal-hearing group compared to the CI groups. However, there was no significant difference in listening effort between the CI groups. The subjective measures revealed significant differences between the normal-hearing and CI groups, but no difference among the three CI groups. Across all groups, age was significantly correlated

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with listening effort. We found no relationship between listening effort and the age at the onset of hearing loss, age at implantation, the duration of CI use, and working memory capacity for these participants.

Conclusions: Listening effort was reduced to a greater degree for the normal-hearing group compared to the CI users. There was no significant difference in listening effort among the CI groups. For the CI users in this study, age was a significant factor with regard to listening effort, whereas other variables such as the duration of CI use and the age at the onset of hearing loss were not significantly related to listening effort.

Keywords

cochlear implantation; cochlear implants; deafness; hearing loss; questionnaires; reaction time

INTRODUCTION

Hearing involves more than simply hearing sensitivity and the function of the hearing mechanism. Instead, the concept of hearing also includes specific abilities important for daily life, such as listening (requiring attention and concentration), comprehending (or receiving and interpreting speech), and communicating (or allowing for exchange of ideas through conversation). In audiology, we are most often concerned with diagnosing hearing disorders and providing adequate intervention through hearing devices. However, the assessment of hearing loss should also incorporate a comprehensive evaluation of our patient’s listening effort, moving beyond conventional audiometric and speech perception testing (McGarrigle et al, 2014). Listening effort is defined as the allocation of mental resources to overcome obstacles when carrying out a listening task (Pichora-Fuller et al, 2016). There are several benefits of assessing listening effort. For example, understanding your patient’s listening effort could (a) inform your counseling sessions (e.g., discuss stress-inducing situations for patient), (b) determine the intervention strategies used with the patient (e.g., compare different hearing aid devices), and (c) provide evidence that intervention is needed (e.g., fitting an assistive listening device for borderline hearing loss).

Research studies have implemented different methodologies when assessing listening effort, including the use of objective physiological tests such as skin conductance (Mackersie and Cones, 2011) and pupillometry (see review by McGarrigle et al, 2014), behavioral or dual-task paradigms, and subjective assessments through questionnaires. In this study, we were interested in objectively measure listening effort using a dual-task paradigm, which has been widely used in previous studies (Downs, 1982; Feuerstein, 1992; Hicks and Tharpe, 2002). In these studies, participants perform a primary and a secondary task separately, then simultaneously, to assess listening effort. The primary task is always a listening activity (i.e., speech perception in quiet or noise), whereas the secondary task is either auditory (recalling digits), visual reaction time (RT) (responding to a probe light when activated), or tactile pattern recognition (identifying pulses from a bone-conduction vibrator).

For dual-task paradigms, the theory of limited cognitive resources explains how listening effort is measured on these tasks (Kahneman, 1973). Here, the cognitive system has a limited capacity of resources to use at any given point. When there is an increase in demand for attention from multiple stimuli, there is a shift in the allocation of cognitive resources available for other tasks, and listening effort increases. In dual-task paradigms, performance on the primary task (e.g., speech perception in noise) uses a majority of the mental capacity of the listener because participants are instructed to maximize their speech recognition abilities (Wu et al, 2016). As the speech perception task becomes more difficult throughout the testing situation, a change in cognitive resource allocation occurs, and fewer resources are available to perform the secondary task (Kahneman, 1973; Pashler, 1994). Subsequently, this decrease in secondary task performance is associated with increased listening effort (Downs, 1982).

Studies investigating listening effort in individuals with hearing loss using a dual-task paradigm have found that listening effort is reduced when using hearing aids compared to no hearing aid (Downs, 1982; Hornsby, 2013). For example, Downs (1982) tested 23 participants with bilateral sensorineural or mixed hearing loss and conducted a dual-task experiment immediately after fitting the participants with hearing aids. The primary task in that study was recognition of monosyllabic consonant-nucleus-consonant words (Peterson and Lehiste, 1962) in multitalker babble, presented at a +0 dB signal-to-noise ratio (SNR), and the secondary task was the response to five probe light presentations measured in reaction time. Results revealed an increase in speech recognition abilities, and a decrease in listening effort when the hearing aids were used compared to the unaided condition.

More recently, listening effort was investigated using a dual-task paradigm for 16 adults with mild-to-severe sloping sensorineural hearing loss fit with hearing aids (Hornsby, 2013). Here, the primary task was word recognition in background noise, and the secondary tasks consisted of word recall and visual RT to a visual marker. The participants were tested on the dual-task experiment in unaided and aided conditions, and subjective ratings using three questions from the Speech, Spatial, and Qualities of Hearing Scale (SSQ; Gatehouse and Noble, 2004) were completed before administration of the dual-task test. The results from the dual-task experiment revealed that secondary task performance, including word recall and reaction times to the visual task, were significantly better in the aided versus unaided conditions, suggesting that listening effort was improved when the participants were using hearing aids. By comparison, subjective measures of listening effort using the three SSQ items were not significantly different when rated in the aided versus unaided conditions, likely due to a relatively small sample size and effects of acclimatization (i.e., only 1–2 weeks of hearing aid use). Overall, Hornsby (2013) reported that the use of hearing aids improved word recognition abilities and reduced listening effort as measured using the dual-task paradigm. Therefore, these studies (Downs, 1982; Hornsby, 2013) support the use of the behavioral dual task as a sensitive measure of listening effort, showing reduced listening effort in hearing aid users when tested in the aided versus unaided conditions.

Studies have also been conducted to explore listening effort and cochlear implant (CI) performance using different methods, including dual-task paradigms (Dunn et al, 2010; Christal, 2013; Hughes and Galvin, 2013; Pals et al, 2013), pupillometry (Winn et al, 2015), and through subjective assessments (Noble et al, 2008). It has been found that, on average, adolescent CI users require a much higher SNR level compared to normal-hearing participants to achieve the same speech perception scores and use the same amount of listening effort on dual-task tests (Hughes and Galvin, 2013). Specifically, in that study, the adolescent CI users had to increase the level of the signal (speech) 13.4 dB over the noise to exert the same amount of effort as those with normal hearing using a–1.5 dB SNR (Hughes and Galvin, 2013). Similarly, normal-hearing listeners were tested under CI simulations by recording changes in speech intelligibility in degraded speech to assess listening effort (Pals et al, 2013). When the participants with normal hearing were provided with less spectral resolution via the CI simulation, equating to a finite number of electrodes in a CI, performance on listening effort tasks dropped significantly compared to performance when better spectral resolution was provided (Pals et al, 2013).

Comparisons across various CI groups have also revealed significant differences in listening effort. For example, the use of bilateral CIs contributes to a reduction in listening effort compared to unilateral CIs (Noble et al, 2008; Dunn et al, 2010; Hughes and Galvin, 2013). In studies exploring subjective outcomes among bilateral, unilateral, and bimodal users, bimodal use provides the lowest level of benefit, as bimodal users exert the highest levels of listening effort, compared to other CI users (Noble et al, 2008). Relative to combined CI and hearing aid use, bimodal users subjectively rated higher levels of benefit when both devices were being used, compared to the use of only one CI (Christal, 2013).

However, in light of studies comparing performance across CI groups, research is limited regarding listening effort for individuals with combined electric and acoustic hearing using a hybrid short-electrode CI. The short-electrode CI is an Food and Drug Administration–approved device that makes use of bilateral, residual hearing, stimulating the high frequencies via the CI, and allowing for acoustic amplification in the low frequencies via bilateral hearing aids when needed. Research has found that combining acoustic and electric hearing in the same ear via a hybrid short-electrode CI results in better speech and pitch perception compared to electric only stimulation (e.g., Gantz et al, 2004; Turner et al, 2004; Gfeller et al, 2006; 2007; Lenarz et al, 2013). Recent studies also found a significant improvement after implantation as documented on the SSQ (Lenarz et al, 2013), which includes several questions on listening effort. This suggests that there may be benefits from combined acoustic and electric hearing for listening effort, in addition to the benefits that have been reported from traditional speech perception tests.

The purpose of this study was to determine how listening effort differs among adult CI users compared to a control group of normal-hearing listeners. Specifically, we investigated the differences in listening effort measured using a dual-task paradigm across four adult participant groups: (a) normal-hearing listeners, (b) long-electrode unilateral CI users, (c) long-electrode bilateral CI users, and (d) short-electrode hybrid CI users. Finally, we were interested in determining how listener traits, such as age, length of CI use, and working memory capacity, influence one’s listening effort.

MATERIALS AND METHODS

Participants

This study included 46 adult male and female participants. Twelve of the participants presented with normal hearing (mean age = 54.8 yr, range = 47–62), 10 had uni-lateral CIs (mean age = 58.6 yr, range = 21–70), 12 had bilateral CIs (mean age = 65.7 yr, range = 49–77), and 12 used one hybrid short-electrode CI and had bilateral, residual hearing (mean age = 53.9 yr, range = 27–64). Although a one-way analysis of variance (ANOVA) comparing age across the participant groups revealed a significant difference [$F_{(3,45)} = 3.296$, $p = 0.030$], post hoc analyses using the Scheffe follow-up test showed no significant differences among any of the participant groups. All participants in the normal-hearing group were employees or faculty from Augustana College, and the CI users were patients recruited from the University of Iowa Hospitals and Clinics-Department of Otolaryngology and Head and Neck Surgery. See Table 1 for the participant demographic information. Participants had to have normal or corrected vision (i.e., no colorblindness) to be eligible for this study.

One unilateral participant (participant 2.6) did not qualify for the study as he was unable to correctly repeat ≥50% of the sentences on the dual-task test. Therefore, data for participant 2.6 are included in the analysis for the subjective questionnaires only. For the hybrid short-electrode CI users, three different electrode arrays were used by these participants that varied according to electrode length and number (see Table 1): Nucleus Hybrid S8 (6 active electrodes on a 10 mm array), S12 (10 active electrodes on a 10 mm array), or L24 (22 active electrodes on a 17 mm array) (Cochlear Corporation, Centennial, CO). The data for all hybrid users were averaged into one group because the sample was too small to evaluate any potential differences that emerge due to the internal device. The hybrid CI users, regardless of the internal device, used a combined speech processor and acoustic component in the implanted ear and a behind-the-ear hearing aid in the opposite ear. Only two hybrid CI participants (participants 4.1, 4.12) did not use a contralateral hearing aid, and instead relied on acoustic hearing only.

Hearing testing was performed first for the participants with normal hearing and the hybrid CI users to verify hearing thresholds and eligibility for the study. For the normal-hearing participants, hearing thresholds at all frequencies from 125 to 8000 Hz had to be ≤25 dB HL, and those using a hybrid CI had to have low-frequency, residual hearing in both ears. See Figure 1 for mean hearing thresholds for the hybrid short-electrode CI group. Unilateral and bilateral CI users did not have residual hearing, except for one participant (2.5), who used an ear plug and ear muff throughout the dual-task testing to insure that residual hearing did not affect the test results.

Participants were compensated for their travel and time while participating in the study. This study was approved by the Augustana Institutional Review Board.

Materials and Instrumentation

The tests were administered at the audiology laboratory in the Augustana Center for Speech, Language, and Hearing from June 2014 to August 2016. All participants signed a consent form before the start of the study. The study was conducted in a sound-treated booth, and auditory stimuli were presented in the sound field using a single, front-facing loudspeaker at 1 m distance and through a GSI-61 audiometer (Grason-Stadler; Eden Prairie, MN). Calibrations of the sound field were completed at the start of each day.

The tests were presented via E-Prime 2.0 software (Psychology Software Distribution, York, UK) in a similar manner as used in the study conducted by Wu et al (2016). These materials included the dual-task portion of the experiment, which consisted of a Hearing-in-Noise Test (HINT) along with a Stroop test. The HINT included 20 sentences combined from two lists to create one full list per condition. The sentences were presented in six noise conditions and were determined after finding the participant's SNR-50. The SNR-50 is defined as the SNR at which the participant correctly repeated 50% of the sentence. In this study, the presentation level for each participant was individually set to achieve similar speech perception scores across all normal-hearing and CI groups (similar to Hughes and Galvin, 2013). This ensured that the primary task of speech perception was difficult, yet manageable for all participants, avoiding floor and ceiling effects. The level of the speech was consistently presented at 65 dB SPL for all tests, and the starting level of the noise was 70 dB SPL for CI users and, to ensure adequate difficulty, 75 dB SPL for normal-hearing participants. During the test, level of the noise was adjusted adaptively based on the participant's response in a one-down, one-up procedure as described by Wu et al (2016). Specifically, the noise level was initially changed in 4 dB steps for the first five sentences in the list, and then was reduced to a 2 dB step size for the remaining 15 sentences. Of the 20 total HINT sentences that were presented, the SNRs of the last 16 sentences were averaged and increased by 2 dB to obtain the SNR-50. Based on the calculated SNR-50, six SNR conditions from 0 to +10 dB in 2 dB steps were created and used in the primary speech perception task.

The Stroop test is a test in which a color word is presented in a different color ink than that of the word written (Stroop, 1992). Here, the Stroop test was presented one word at a time on a computer screen that was placed in the sound booth with the participant. Four color and font colors were used: red, blue, green, and yellow. The combination of word color and font color were randomized throughout the test, but always inconsistent with one another. The computer monitor showed four boxes that contained the four colors: red, blue, green, and yellow. Participants were instructed to respond as quickly and as accurately as possible during the test. For responding to the corresponding word during the task, the participant was given a standard keyboard with four keys "D," "C," "M," and "K" labeled as red (R), blue(B), green (G), or yellow (Y). The position of the four buttons on the computer screen was consistent spatially with the four keyboard buttons in front of the participant. The Stroop data were recorded as the RT in msec following each trial and stored in the E-Prime software.

Additionally, a reading span test (Lunner, 2003) was conducted to evaluate word recall ability. Participants were given a set of sentences ranging in length from three to six sentences. The sentences were displayed on a computer screen, where the participants were then asked to recall the first or last word of each sentence after the entire set of sentences was administered. No hints were given during the test. After each sentence, the participant was asked to reply "yes" or "no" indicating if the sentence made sense or not, which was used as a distractor while the participant was recalling the words in each sentence.

A Spatial Hearing Questionnaire (SHQ; Tyler et al, 2009) was administered to all participants to evaluate their self-assessed hearing abilities in quiet and in noise. Studies investigating the SHQ have shown that it is sensitive to differences in speech perception and localization among different CI groups, and compared to individuals with normal hearing (e.g., Perreau, Ou, et al, 2014; Perreau, Spejcher, et al, 2014). Further, the SHQ is highly correlated with other measures of speech perception in quiet and in noise (Tyler et al, 2009), which relates to the primary task of speech perception in the experiment used here. Items from the SHQ specifically assess localization of sound using stimuli of different frequency content (male, female, and children's voices), speech perception in quiet and in noise, and music listening. The participants were asked to respond to each item, marking their level of difficulty in that particular listening situation, with a ranking of 0 being "very diffi-cult" and 100 being "very easy." In addition to the SHQ, participants were asked to complete three questions on perceived listening effort (PLE) experienced in everyday situations that were adapted from the existing SSQ (see Appendix). Responses on these items assessing PLE were reported using a 10-point scale, where 10 represents no listening effort.

Procedures

The order that the participants completed the objective tasks in the study was randomized for each participant and across the participant groups. The main task that all participants completed was the dual task. This task began with the SNR-50. Participants were provided with written instructions and a practice before the test began. Participants were instructed that the background noise level would vary and were encouraged to guess. Sentences were presented one at a time and the noise level increased or decreased depending on if the entire sentence was incorrectly or correctly repeated.

After the SNR-50 was determined for each participant, the secondary task, or Stroop test, was then practiced. The participants were given written instructions on a computer screen and required to practice two times, or 40 trials, until mastery of the task (i.e., responses on the Stroop test were performed with near 100% accuracy) was obtained before moving on to the next test. The participant was instructed to answer the ink color of the word displayed on the computer screen. Participants were asked to make this judgment as quickly as possible by entering their selection using the designated color keys on the keyboard provided. Once this practice of 20 trials was completed, the speech in noise task and Stroop task were completed simultaneously in the dual-task experiment. Participants were instructed to respond to the Stroop test (secondary task) first as quickly as possible, then repeat the sentence that was presented in the background noise (primary task), and then press enter to move on to the next trial. Instructions were displayed on the computer screen, and participants practiced both the speech perception and Stroop task simultaneously before the dual-task test. As with the Stroop task, practice of the dual task was performed for each participant using ≥40 trials, or more as required until mastery of the task was obtained.

For the dual-task experiment, six SNR conditions (0, +2, +4, +6, +8, and +10 dB) based on results from the SNR-50 were presented randomly to the participants. These SNR conditions were selected based on (a) previous research (Wu et al, 2016) which showed that RT on the Stroop reached a peak at the SNRs where participants' achieved 40–50% for speech recognition on the primary task and (b) our experiences with CI users that require a more positive SNR to achieve this level of speech recognition performance. In addition, one baseline condition was included to assess secondary task performance on the Stroop test in quiet, consistent with the methodology from other studies of listening effort that have also measured baseline performance in quiet (Hick and Tharpe, 2002; Gosselin and Gagne, 2011). For all conditions including the primary speech perception task, 20 sentences were presented per condition, and consequently, 20 reaction times were measured. Frequent breaks were provided throughout the dual task to each participant as needed.

Subjective measures included the 24 items from the SHQ and the three PLE questions. All participants completed these subjective measures, as well as a demographic information sheet, independently during a break or at the end of the session. Participants completed all test measures for this study in 2–2.5 h with breaks included.

Data Analysis

A power analysis (G*Power 3; Faul et al, 2007) was performed before the onset of this study to determine the number of participants that were needed for adequate statistical power, assuming a = 0.05. The result of this power analysis revealed that 12 CI users were required per participant group. This number was calculated by comparing data from Dunn et al. (2010) who used a dual-task paradigm to evaluate differences in cognitive load for bilateral and unilateral CI users. Because the actual sample size was achieved in this study for three of the four groups, and was close for the unilateral (n = 10) CI users, mixed ANOVAs were used to analyze the data. Moreover, sphericity was checked in all ANOVA tests. In cases where sphericity was not assumed, we used the Greenhouse–Geisser adjustment. Those results did not differ from the traditional ANOVA; therefore, we report the results of the ANOVA tests here.

Data for the dual task were analyzed separately for percent correct on the primary task and RT on the secondary task. A mixed ANOVA was used to compare performance on the primary speech perception task between the four-participant groups and within the six SNR conditions. For RT on the Stroop test, listening effort was determined for each participant by examining the proportion change from baseline per condition as follows: (RT on dual task – RT baseline)/RT baseline. This method of listening effort “cost” was used because it statistically controls for differences in absolute response times on the secondary task (refer to Gosselin and Gagné [2011] for more details). For all participants, listening effort was calculated using the median RT on the Stroop test across the 20 trials in each condition. A mixed ANOVA was also completed to investigate differences in listening effort between the four-participant groups and within the six SNR conditions. Main effects and interactions are reported between the normal-hearing and CI groups and across SNR conditions.

Additionally, PLE experienced in the real world was calculated from the responses to the three questions on listening effort and concentration, and averaged to represent one global PLE score. Subjective performance was also assessed using the SHQ, a 24-item questionnaire, where participants rated their spatial hearing abilities on different listening tasks. Data for the PLE and SHQ were analyzed using a one-way ANOVA to compare differences on the two subjective measures across the participant groups. Results on the reading span test were also analyzed using a one-way ANOVA to compare differences across the participant groups.

Finally, a correlation analysis was conducted to correlate performance on the dual-task paradigm test with several variables, including working memory capacity, age of participant, age of onset of hearing loss, age at implantation, and duration of CI use. For all tests, statistical significance was defined as p .>0.05. Statistical Package for the Social Sciences (SPSS; IBM Corp, 2013)v. 22 was used to analyze the data.

RESULTS

Primary Speech Recognition Task

Figure 2 shows the primary task performance on the dual-task test for the four participant groups. For the normal-hearing group, scores approximated 60% at 0 dB SNR and approached 100% at +10 dB SNR. For the CI groups, scores showed a similar trend, with the best performance for hybrid CI users, and poorest performance for the unilateral and bilateral users. Results of the mixed 4 (participant group) × 6(SNR condition) ANOVA revealed a very large, significant difference in percent correct among the six SNR conditions [$F_{(5,205)} = 78.726$, $p < 0.001$, $\eta_p^2 = 0.658$]. This is due to the increase in accuracy on the primary task with the increase in SNR. There is also a significant SNR by group interaction [$F_{(15, 205)} = 2.501$, $p = 0.002$, $\eta_p^2 = 0.155$]. This SNR by group interaction is primarily due to the change in performance of the normal-hearing group from nearly worst to best across the different SNR conditions tested (refer to Figure 2). Finally, there was a significant difference in primary task performance across the groups [$F_{(3,41)} = 4.424$, $p = 0.009$, $\eta_p^2 = 0.245$].

A Bonferroni-adjusted series of all possible pairwise comparisons for primary task performance across the six SNR conditions found that percent correct was significantly different from 0 to +10 dB SNR, and between the first four SNR conditions (0 to +6 dB SNR). There was no significant difference in percent correct on the primary task between +6, +8, and +10 dB SNR, suggesting that performance on the primary task essentially plateaus for all groups above +6 dB SNR. To further investigate differences in primary task performance across groups, we performed a second ANOVA test for the easy conditions of +6, +8, and +10 dB where performance plateaus. Results revealed that the normal-hearing group performed significantly better than unilateral ($p = 0.003$) and bilateral CI users ($p = 0.004$), and there was no significant difference in primary task performance among the normal-hearing and hybrid CI users ($p > 0.05$) in these more favorable SNR conditions.

To investigate the significant interaction between group and SNR, we conducted a separate ANOVA including only the CI participants. We found a signifi-cant main effect of SNR [$F_{(5,150)} = 49.798$, $p < 0.001$,$\eta_p^2 = 0.642$] and group [$F_{(2,30)} = 4.229$, $p = 0.024$, $\eta_p^2 = 0.220$], but no significant interaction of SNR by group [$F_{(10,150)} = 0.818$, $p = 0.612$, $\eta_p^2 = 0.052$]. This suggests that the change in percent correct on the primary task for all CI groups is similar with changing SNR. For the group differences, a post hoc analysis using a Bonferroni adjustment for multiple comparisons revealed a significant difference on primary task performance between the hybrid CI group and the bilateral CI group ($p = 0.050$), but no significant difference among the hybrid CI group and the unilateral group ($p = 0.063$), or the bilateral and unilateral group ($p > 0.05$).

Secondary Task

For RT on the secondary task, median raw scores were higher for the more difficult noise conditions (1,552–2,322 msec at 0 dB SNR) and lowest for the less challenging noise conditions (1,129–2,071 msec at 110 dB SNR). Ac curacy on the Stroop test was very high, with scores of 98.6–99.5% for all participants across all conditions tested, ensuring no significant practice or fatigue effects throughout the dual-task experiment.

Shown in Figure 3 are the results for listening effort cost for the four groups. Listening effort was high (>0.6) for all groups in the most difficult listening situations, or 0 and +2 dB SNR. With a more favorable SNR of 110 dB, listening effort improved for the normal-hearing group (cost = 0.186), remained high for the unilateral CI group (cost = 0.651), and was similar for the bilateral and hybrid CI groups (cost = 0.476 and 0.361, respectively). Results of the mixed 4 (participant group) × 6 (SNR condition) ANOVA indicated significant effects for listening effort between the SNR conditions [$F_{(5,205)} = 25.068$, $p < 0.001$, $\eta_p^2 = 0.379$], as well as for the interaction of listening effort across the six SNR conditions by hearing group [$F_{(15,205)} = 2.713$, $p = 0.001$, $\eta_p^2 = 0.166$]. Like performance on the primary task, for all groups, listening effort improved with a more favorable SNR. Additionally, the significant interaction suggests that the degree of change in listening effort with decreasing SNR was greater for the normal-hearing group compared to the CI users. Finally, there was no significant difference in listening effort among the four groups [$F_{(3,41)} = 1.604$, $p = 0.203$, $\eta_p^2 = 0.105$].

A Bonferroni adjustment for all possible pairwise comparisons of listening effort across the six SNR conditions revealed significant differences when comparing the two most difficult listening conditions, 0 and +2 dB, to the easiest listening conditions of +4 to +10 dB. There was no significant difference in listening effort for the more challenging SNR conditions of 0 and +2 dB. In other words, SNR impacts one's listening effort as a decrease in listening effort was found as the SNR improved. Additionally, we compared listening effort across the groups using a separate ANOVA for the more favorable SNR conditions of +6, +8, and +10 dB where performance on the primary task was found to be essentially stable. A significant group effect was found [$F_{(3,41)} = 3.205$, $p = 0.033$]. However, using Bonferroni adjustment for multiple comparisons, the differences in listening effort between the normal-hearing and unilateral (p 5 0.069) groups and normal-hearing and bilateral groups ($p = 0.073$) did not reach statistical significance. There was no significant difference in listening effort between the normal-hearing and hybrid CI groups ($p = 0.932$).

We also examined differences in listening effort for the CI groups only. We found a significant main effect of SNR [$F_{(5,150)} = 9.228$, $p < 0.001$, $\eta_p^2 = 0.235$], but no main effect of group [$F_{(2,30)} = 1.259$, $p = 0.298$, $\eta_p^2 = 0.007$] or interaction [$F_{(10,150)} = 0.807$, $p = 0.622$, $\eta_p^2 = 0.051$], suggesting no significant differences in listening effort among the CI participant groups.

Working Memory Capacity

Figure 4 shows the mean reading span score for the four participant groups. Scores were highest for the normal-hearing group (54.6%) and lowest for the bilateral CI group (43.1%).

A one-way ANOVA was used to compare these mean scores, and found no significant difference in working memory capacity across the four participant groups [$F_{(3,44)} = 1.880$, $p = 0.148$].

Subjective Ratings of Listening Effort

Table 2 shows the responses for the PLE and SHQ. Overall, perceived ratings from the CI users were less than the perceived ratings from the participants with normal hearing. A single measure of PLE was found by calculating the average response to all three items (columns 1–3 in Table 2). PLE was analyzed using a one-way ANOVA to compare mean responses from this single score across the four groups: (a) normal hearing (mean [M] = 8.64, standard deviation [SD] = 1.23); (b) unilateral CI (M = 4.32, SD = 2.61), (c) bilateral CI (M = 4.40, SD = 2.58), and (d) hybrid short-electrode CI (M 5 4.36, SD 5 1.71). Results revealed that PLE was significantly different across the participant groups [$F_{(3,45)} = 12.359$, $p < 0.001$]. A post hoc analysis using Bonferroni adjustment for multiple comparisons indicated a significant difference among normal-hearing and CI participants (p < 0.001), and no difference in PLE among the three implant groups ($p > 0.05$).

For the SHQ, results showed a similar pattern to the results for PLE (see right-hand column in Table 2). There was a significant difference in SHQ average scores among the groups [$F_{(3,45)} = 7.898$, $p < 0.001$]. A post hoc analysis using Bonferroni adjustment for multiple comparisons revealed that scores were significantly different between the normal-hearing group and the unilateral CI users ($p < 0.001$), and the normal-hearing group and the hybrid CI users ($p = 0.010$), but there was not a significant difference between the normal-hearing group and the bilateral CI users ($p = 0.084$). Additionally, the difference in SHQ scores among the three CI groups was not statistically significant ($p > 0.05$).

Correlational Analyses

Different listening traits were also examined in this study to determine their influence on listening effort. Here, mean scores from the reading span test, questions on perceived listening effort, and SHQ were correlated to patient demographics, including the participants' age, age at onset of hearing loss, age at implantation, and duration of implant use using Pearson correlation coefficients. Based on the significant mean differences in dual-task performance and subjective measures between the normal-hearing and CI groups, the correlational analyses were conducted using data from the three CI groups combined, and did not include data from the normal-hearing group. Results showed a significant correlation between reading span and the age at the onset of hearing loss ($r = 20.350$, $p = 0.050$), indicating a possible relationship between working memory capacity and the onset of hearing loss. However, results from the reading span and the subjective measures of listening effort were not significantly correlated to any of the demographic factors. A colinearity of PLE and SHQ was also shown ($r = 0.417$, $p = 0.014$), suggesting that these two subjective assessments measure similar attributes of hearing ability.

To compare the subjective measures with dual-task performance, the outcome measures of percent correct and RT were averaged across the six different SNR conditions to produce two groups, that is, "hard" conditions that included 0, +2, and +4 dB and "easy" conditions that included +6, +8, and +10 dB. After pooling the data in this manner, only the SHQ was found to significantly correlate with primary task performance for the easiest conditions of +6, +8, and +10 dB ($r = 0.405$, $p = 0.019$). Across the noise conditions, there was no significant correlation between SHQ and listening effort measured on the dual task, and the PLE and both speech recognition and listening effort measured on the dual task.

Next, correlations were performed to compare listening effort measured on the dual task with age of participant, age at onset of hearing loss, age at implantation, duration of implant use, and reading span score. Pearson correlation coefficients were calculated to compare the dual-task performance for the easy and hard conditions with these listening traits. Results showed that performance on the reading span test did not correlate with listening effort or speech perception as measured on the dual-task paradigm. Regarding age, the results found that age strongly influences speech perception abilities, in that older participants appeared to be less proficient on the speech perception task in the more difficult or hard noise conditions ($r = 20.355$, $p = 0.043$). For listening effort as measured from the secondary task, age also proved to be significant factor in the more favorable or easy noise conditions ($r = 0.369$, $p = 0.035$).

Finally, age at the onset of hearing loss, age at implantation, and the duration of CI use were not significantly related to listening effort as measured on the dual-task test ($p > 0.05$). In sum, this indicates that age is significantly correlated to objective measures of listening effort for the individuals in this study, but other demographics such as age at onset of hearing loss, age at implantation, and duration of CI use were not related to the participants' listening effort. Further, working memory capacity was not correlated to the subjective or objective measures of listening effort.

DISCUSSION

The purpose of this study was to examine the differences in listening effort among three different CI profiles including bilateral, unilateral, and hybrid short-electrode users, compared to a control group of normal-hearing listeners. This was assessed using a dual-task test to compare speech perception scores on the primary task and RT on the secondary task, taking into account individual differences in baseline performance, across the four groups. In similar dual-task paradigms measuring listening effort, decreases in secondary task performance are representative of less listening effort required to perform the primary task (Hick and Tharpe, 2002). In this study, we also assessed listening effort in six SNR conditions varying from 0 to +10 dB SNR that were determined for each participant individually based on their SNR-50.

For the primary task, a very large, significant difference was found for speech perception across the six SNR conditions such that it was easier to accurately repeat the sentence with lower levels of background noise, as expected. When comparing primary task performance on the dual task across groups, the normal-hearing group had significantly better speech perception scores than the unilateral and bilateral CI groups in the more favorable noise conditions of +6, +8, and +10 dB. Furthermore, there was no significant difference in primary task performance among the hybrid CI and the normal-hearing groups.

With regard to the secondary task of listening effort, this preliminary study of CI users found no difference in listening effort among the three CI groups tested: uni-lateral, bilateral, and hybrid short electrode. Previous studies of adults and children have suggested that listening effort is different across CI groups, with bilateral users having reduced effort compared to unilateral users (e.g., Noble et al, 2008; Dunn et al, 2010; Hughes and Galvin, 2013). In this study, self-assessed ability reported on the SHQ was higher for bilateral CI users than the unilateral CI group and median reaction times on the dual task were lower, but these differences were not statistically significant when controlling for individual differences in baseline performance. However, when performance on the primary task was not changing (i.e., noise conditions of +6, +8, and +10 dB), we did observe differences in listening effort between the normal-hearing versus unilateral and bilateral CI groups; however, these differences were not significant, likely due to the small sample size in the study.

Despite this lack of significance, we found a different pattern among the four groups in listening effort across the noise conditions. Specifically, the normal-hearing group showed a greater reduction in listening effort with changing SNR compared to the CI groups. On the primary speech recognition task, we also observed this change in performance with the normal-hearing group improving in percent correct from nearly worst to best across the different SNR conditions tested. However, comparing only the CI groups, the degree of change in listening effort and speech recognition performance on the dual task was similar across groups with changing SNR.

These results are in agreement with other studies, showing differences in listening effort for individuals with normal hearing than those with hearing loss. Hick and Tharpe (2002) reported significantly longer reaction times and lower speech perception scores on a dual-task test for children with hearing loss compared to a control group of children with normal hearing. In that study, listening effort was quantified by the difference in performance on the secondary task from baseline to the experimental condition (quiet, +10, +15, and +20 dB SNR). Overall, it was found that, across the four SNR conditions, the children with hearing loss exerted greater amounts of listening effort than the children with normal hearing. By comparison, other studies have found similar levels of listening effort for adolescents with CIs and normal hearing when speech perception abilities were equated across these two groups (Hughes and Galvin, 2013). As purported by Hughes and Galvin, it is likely that children using CIs would have greater listening effort than children with normal hearing, if they had to listen in environments with a low SNR, similar to more realistic everyday listening situations.

Data from the subjective measures also revealed a very interesting result. Significant differences were found on each of the subjective assessments, including the SHQ and the three questions of perceived listening effort, comparing the CI and normal-hearing groups. These results indicate that CI users put in more effort in everyday listening situations than those with normal hearing. This was similar to the objective data from this study, showing a greater improvement in listening effort and speech perception abilities with increasing SNR for the normal-hearing groups. Comparing outcomes from the SHQ, PLE, and the dual task for the CI participants, this study found no significant correlation between the subjective and objective measures of listening effort. Previous studies have been inconclusive with regard to the results obtained from objective and subjective measures of listening effort. Some studies have suggested that subjective outcomes are weaker in detecting differences in listening effort compared with objective measures of listening effort (e.g., Hornsby, 2013; Picou et al, 2013). However, a study comparing two measures of listening effort (self-report to word recall) found that, although both measures showed similar changes in listening effort as the SNR increased in the normal-hearing group, the self-report method was the most sensitive of the two measures (Johnson et al, 2015). In sum, more research is needed on subjective test measures of listening effort to ensure these are capturing true differences among listeners.

This study also contributes to a growing body of research suggesting that age is an important factor regarding listening effort. Several studies have similarly found that older adults exert more listening effort than young adults as evidenced by poorer performance on tasks of listening effort (e.g., Gosselin and Gagne, 2011; Desjardins and Doherty, 2013; Bernarding et al, 2013; Degeest et al, 2015). However, unlike age, other factors such as the age at the onset of hearing loss, age at implantation, and duration of CI use do not appear to significantly impact one's listening effort.

Limitations

There were limitations to this study that should be mentioned. First, the length of CI use varied drastically, with unilateral CI users having 17 yr of implant use, whereas hybrid CI users had z5 yr of implant use. Although we found that length of CI use did not correlate to listening effort, it is an additional variable to consider. Second, we report data from a small sample of CI users. However, the sample of CI users either met (n = 12 for the bilateral CI group and hybrid CI group) or approached (n = 10 for the unilateral group) the number that was needed for adequate statistical power. We also ensured that the statistical methods used were appropriate for the sample size (see "Data Analysis" section).

An additional limitation of this study concerns the methodology used to compare performance on the dual-task test. This study found no difference in listening effort among the three CI groups. However, the dual-task experiment used a single, front-facing loudspeaker to present the speech and the noise signals during the primary task. If the sentences and background noise for the primary task were presented using multiple speakers that were spatially separated, then there might have been differences in performance among CI users.

Future Directions and Clinical Implications

Given these results, it is important to recruit more participants using CIs to determine if there are differences in listening effort when a larger population of CI users is included. Moreover, recall that we did not evaluate differences in listening effort among the hybrid CI group with different electrode arrays (e.g., S8, S12, and L24); instead, we combined these users in one group. Future studies should investigate these differences by testing different electrode arrays within the hybrid short-electrode CI population.

Additionally, to better counsel patients on which device to select when an individual has residual hearing, it would also be important to investigate listening effort in bimodal users, or those that use combined acoustic plus electric hearing in opposite ears using a standard length CI, and compare to hybrid CI users. Some studies have suggested that bimodal users have less listening effort than unilateral and bilateral CI users before implantation as documented on the SSQ (Noble et al, 2008). Therefore, further work is needed to determine which CI configuration provides the best outcomes with the least amount of focused listening by the individual. Likewise, it is important to investigate listening effort in individuals with single-sided deafness who use CIs, which could be helpful in ascertaining the benefits of implantation in this growing population.

Finally, the relationship between subjective and objective outcomes of listening effort is important to investigate, as studies have found a weak relationship between these two measures. It would be of interest to determine the reasons for these differences in subjective versus objective outcomes, with the ultimate goal to improve the sensitivity of subjective measures of listening effort. This may lead to the development of a clinical tool that could be used to measure listening effort in patients with hearing loss in hopes to make better clinical recommendations and adjust counseling or intervention strategies as needed.

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APPENDIX

Perceived listening effort questions:

1. Using a 10-point scale, do you have to put a lot of effort into listening what is being said in a conversation? (1 = lot of effort; 10 = no effort).
2. Using a 10-point scale, how hard do you have to concentrate when listening to another person talk or when listening to a sound? (1 = concentrate hard; 10 = do not need to concentrate).
3. Using a 10-point scale, do you need to put forth more effort when listening than those around you? (1 = more effort than others; 10 = less effort than others).

Abbreviations:

ANOVA	analysis of variance
CI	cochlear implant
HINT	Hearing-in-Noise Test
PLE	perceived listening effort
RT	reaction time

SD	standard deviation
SHQ	Spatial Hearing Questionnaire
SNR	signal-to-noise ratio
SSQ	Speech, Spatial, and Qualities of Hearing Scale

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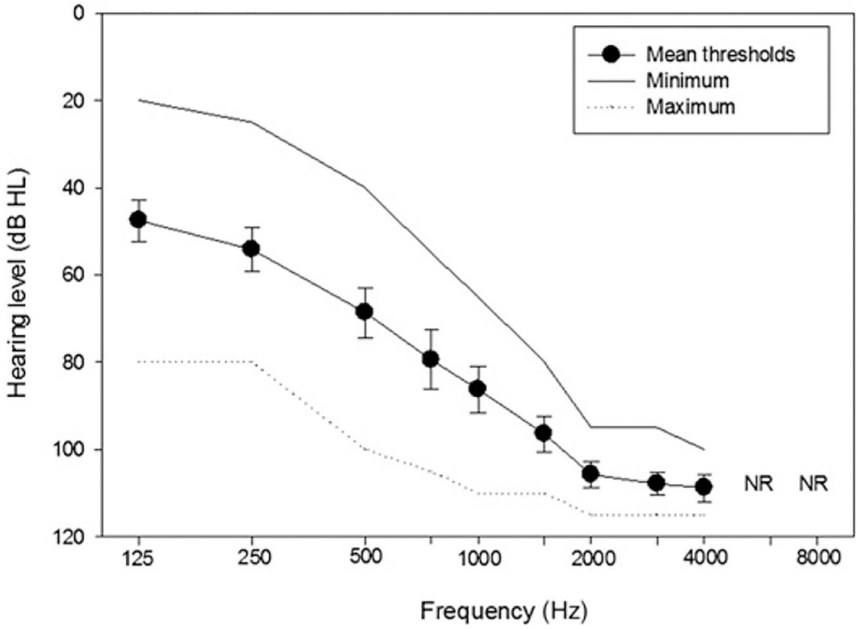

Figure 1.

Mean hearing thresholds from 125 to 8000 Hz for the participants with hybrid short-electrode CIs. Thresholds were averaged and shown for the implanted ear only. Filled circles indicate mean hearing thresholds, and there is a solid line for the minimum threshold across participants and a dashed line for the maximum threshold across participants. NR indicates no response at that frequency.

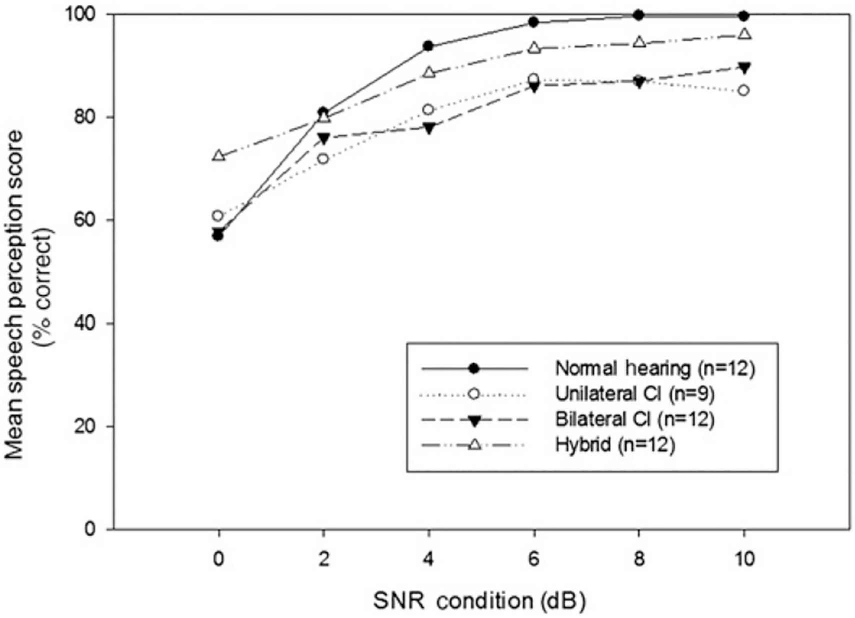

Figure 2.

Mean percent correct scores for speech perception in noise (primary task) for all participant groups. The filled circles show results for the normal-hearing group, the open circles for the unilateral CI group, the filled triangles for the bilateral CI group, and the open triangles for the hybrid short-electrode CI group. Results across the SNR conditions are displayed on the *x* axis and percent correct is displayed on the *y* axis.

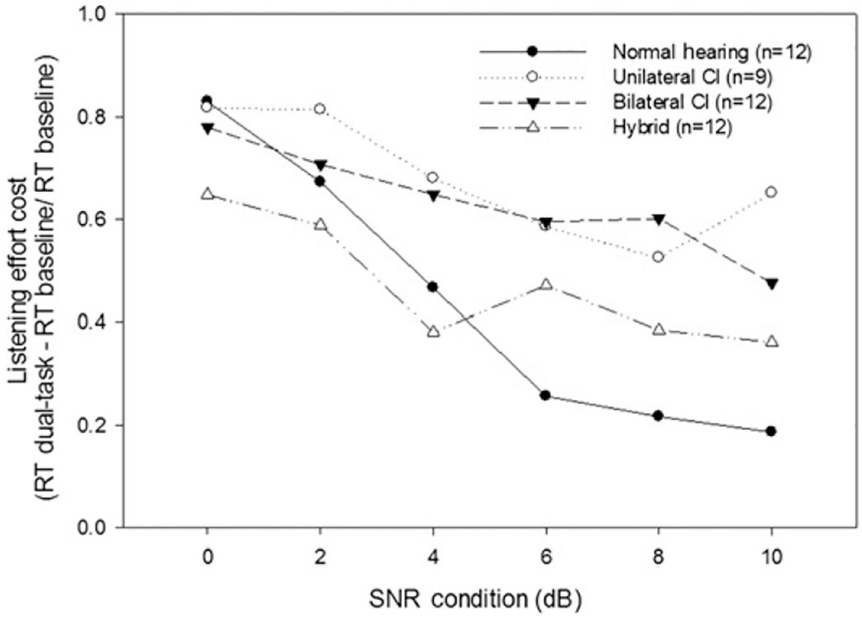

Figure 3.

Listening effort on the Stroop test (secondary task) for all participant groups. Listening effort was calculated by comparing the proportional change in median RT scores from baseline as follows: [(RT on dual task 2 RT baseline)/RT baseline]. The filled circles show results for the normal-hearing group, the open circles for the unilateral CI group, the filled triangles for the bilateral CI group, and the open triangles for the hybrid short-electrode CI group. Results for all six SNR conditions are displayed on the *x* axis and listening effort is displayed on the *y* axis.

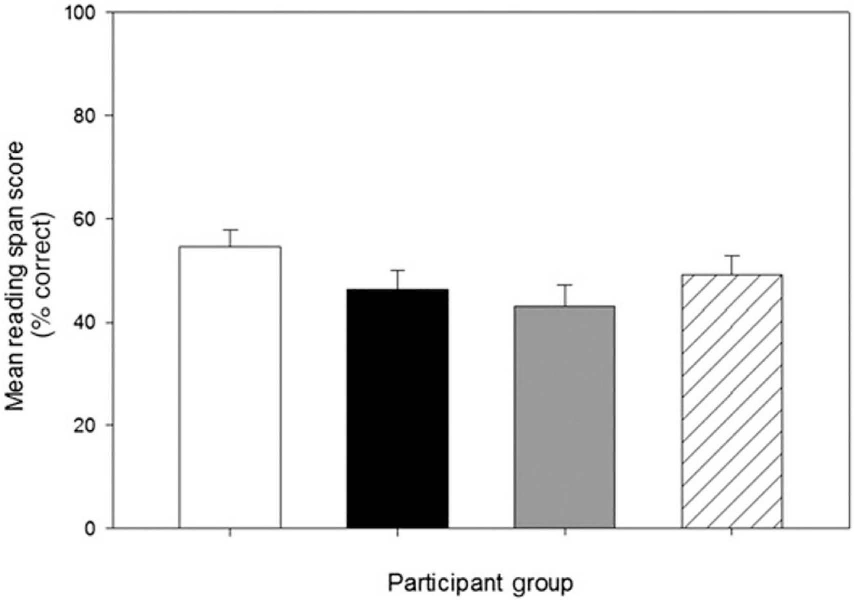

Figure 4.

Mean percent correct scores on the reading span test for all participant groups. The white bar shows results for the normal-hearing group, the black bar for the unilateral CI group, the gray bar for the bilateral CI group, and the dashed bar for the hybrid short-electrode CI group. Results by group are displayed on the *x* axis and percent correct is displayed on the *y* axis.

Table 1.

Demographic Information for All Participants (n = 46) by Group

Participant Group	Gender	Age (yr)	Education Level (yr)	Ethnicity	Age at Onset of HL (yr)	CI Type	Age at Implant (yr)	Length of CI Use
Normal hearing	F = 11; M = 1	54.75	17.00	Caucasian	—	—	—	—
Unilateral CI	F = 6; M = 4	58.60	15.80	Caucasian	18.68	N = 6; AB = 4	46.22	17.00
Bilateral CI	F = 10; M = 2	65.67	15.27	Caucasian	23.32	N = 4; AB = 8; ME = 1	56.75	8.92
Short-electrode CI	F = 4; M = 8	53.92	16.00	Caucasian	21.75	S8 = 1; S12 = 5; L24 = 6	49.67	4.75
Total	F = 31; M = 15	58.24	16.08	Caucasian	21.25	N = 22; AB = 12; ME = 1	50.88	10.22

Notes: AB = Advanced Bionics Corporation (Valencia, CA); F = female; HL = hearing loss; L24 = Nucleus Hybrid L24 (22 intracochlear electrodes on 17-mm array); M = male; ME = Med-El Corporation (Durham, NC); N = Nucleus; S8 = Nucleus Hybrid S8 (6 intracochlear electrodes on 10-mm array); S12 = Nucleus Hybrid S12 (10 intracochlear electrodes on 10-mm array).

Table 2.

Mean Scores (and SDs) across All Participant Groups for PLE and the SHQ

Participant Group	1: Effort in a Conversation	2: Concentration While Listening	3: Effort Compared to Others	SHQ Total Score
Normal hearing (n = 12)	8.67 (1.56)	8.5 (1.24)	8.75 (1.42)	83.53 (9.88)
Unilateral CI (n = 10)	5.6 (2.99)	4.6 (3.31)	2.75 (2.99)	49.61 (23.01)
Bilateral CI (n = 12)	5.83 (2.76)	4.38 (2.95)	3.00 (2.76)	64.82 (21.81)
Short-electrode CI (n = 12)	5.42 (2.27)	5.58 (2.35)	2.08 (1.73)	58.42 (11.11)