Measuring listening effort expended by adolescents and young adults with a unilateral or bilateral cochlear implants or normal hearing

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Abstract

Objectives: To compare the listening effort expended by adolescents and young adults using implants versus their peers with normal hearing when these two groups are achieving similar speech perception scores. The study also aimed to compare listening effort expended by adolescents and young adults with bilateral cochlear implants when using two implants versus one. **Methods:** Eight participants with bilateral cochlear implants and eight with normal hearing aged 10 to 22 years were included. Using a dual-task paradigm, participants repeated CNC words presented in noise and performed a visual matching task. Signal-to-noise ratios were set individually to ensure the word perception task was challenging but manageable for all. Reduced performance on the visual task in the dual-task condition relative to the single-task condition was indicative of the effort expended on the listening task. **Results:** The cochlear implant group, when using bilateral implants, expended similar levels of listening effort to the normal hearing group when the two groups were achieving similar speech perception scores. For three individuals with cochlear implants, and the group, listening effort was significantly reduced with bilateral compared to unilateral implants. **Discussion:** The similar amount of listening effort expended by the two groups indicated that a higher signal-to-noise ratio overcame limitations in the auditory information received or processed by the participants with implants. This study is the first to objectively compare listening effort using two versus one cochlear implant. The results provide objective evidence that reduced listening effort is a benefit that some individuals gain from bilateral cochlear implants.

Introduction

Bilateral cochlear implants (CIs) are becoming the standard of care for children with profound hearing loss in many cochlear implant centres around the world. Although still a relatively new option, evidence regarding the advantages of two implants versus one for children has been accumulating. The perceptual benefits reported include improved speech perception in background noise (Galvin et al., 2007; Kühn-Inacker et al., 2004; Scherf et al., 2007;) and improved spatial hearing abilities (Beijen et al., 2007; Galvin et al., 2008; Van Deun et al., 2010;).

It is likely that there are additional areas of benefit from bilateral CIs which are not captured by standard tests of speech perception and spatial hearing. One potential benefit which has not yet been fully investigated is that of reduced listening effort. Reduced listening effort has been reported as a subjectively perceived benefit of receiving bilateral sound input via unaided acoustic hearing (Noble & Gatehouse, 2004), hearing aids (Noble & Gatehouse, 2006; Libby, 1980), or CIs (Kühn-Inacker et al., 2004; Noble et al., 2008). Parental reports and unpublished data collected by the present authors using a version of the Speech, Spatial and Qualities of Hearing Scale (Noble & Gatehouse 2006) adapted for parents and older children (Galvin et al., 2007) have suggested that reduced listening effort is a subjectively-perceived benefit gained by children using bilateral implants. Subjective reports by parents and clinicians of reduced listening effort for children have also been highlighted by other authors (Bohnert et al., 2006; Kühn-Inacker et al., 2004; Scherf et al., 2009; Winkler et al., 2002).

Real-life listening can be demanding and dynamic. It often occurs in noisy environments such as classrooms, tutorials and group social situations. In such environments the listener needs to switch attention between speakers whilst simultaneously processing information and formulating appropriate responses. Reports from parents and adolescents with CIs often emphasise fatigue as a consequence of the effort expended in these complex listening environments. The increased expenditure of effort on listening may result in a decrease in the cognitive resources available to attend simultaneously to other functions such as learning and maintaining social interactions. It is possible that the need to sustain high levels of listening effort may be one of the factors contributing to the poorer academic outcomes (Geers, 2003; Vermeulen et al., 2007), poorer social skills (Bat-Chava et al., 2005), and lower levels of attention and class participation (Damen et al., 2006) reported for children using unilateral cochlear implants compared to their peers with normal hearing.

A widely used method for objectively examining how effort is expended is the dual-task paradigm. This method is based on the theory of limited cognitive resources (Kahneman, 1973), which suggests that, as the demands of a task increase, additional effort may be allocated to the task to maintain performance. This allocation of additional effort results in a reduction in the cognitive resources available to simultaneously perform other tasks. In the dual-task paradigm, participants are initially required to perform two tasks individually to obtain baseline performance measures on each task. The participants are then required to complete the tasks simultaneously and are asked to prioritize the more demanding primary task, whilst attempting to maintain their performance on the easier secondary task. Secondary task performance is the main outcome measure. When the tasks are performed simultaneously, changes in performance on the secondary task are assumed to reflect effort expended on the primary task.

The dual-task paradigm has been applied in a number of studies to compare listening effort expended by groups with normal hearing and impaired hearing, or to compare effort in different noise or hearing aid conditions (see Gosselin & Gagne (2010) for a review). In these studies focusing on listening effort, the primary task involved word or sentence recognition. In some of these studies the secondary task involved digit recall (Rakerd et al., 1996; Choi et al., 2008) or word retention (Rabbitt, 1996). More often, the secondary task involved responding as quickly as possible to a visual stimulus, such as a light or picture, presented at random intervals (Downs & Crum, 1978; Downs, 1982; Hicks & Tharpe, 2002; Sarampalis et al., 2009). These studies reported increases in response times of 25 to 50ms in the dual-task condition as compared with the secondary-task-alone condition. This change reflected the listening effort expended when the word or sentence recognition task was added to the secondary visual task.

This previous research examining listening effort has demonstrated that, in comparison to their peers with normal hearing, a greater degree of listening effort was expended by both adults with moderate to profound hearing loss (Rakerd et al., 1996) and primary-school aged children with mild to moderate hearing loss (Hicks & Tharpe, 2002). Earlier studies involving adults with normal hearing indicated that a greater degree of listening effort was expended when background noise was increased (Downs & Crum, 1978; Rabbitt, 1966). A more recent study involving children with normal hearing found that higher levels of listening effort were expended when the children were listening in signal-to-noise ratios (SNRs) typically found in mainstream classrooms than when listening in quiet (Howard et al., 2010). Other studies have shown that listening effort was reduced when hearing aids were used (Downs, 1982; Gatehouse & Gordon, 1990) or when particular noise-reduction algorithms were implemented (Sarampalis et al., 2009).

None of the studies involving objective assessment of listening effort have considered the relationship between listening effort and bilateral versus unilateral sound input. Feuerstein

(1992) did consider the importance of normal bilateral hearing in relation to listening effort, but the comparative condition was asymmetrical bilateral hearing condition. The asymmetry was achieved for the normal hearing adults through a simulated mild unilateral hearing loss. Listening effort was increased in the asymmetrical condition in the most difficult speech/noise condition, with speech ipsilateral to the simulated loss and noise contralateral, but not the alternative condition with speech contralateral to the simulated loss. These results indicate that, in specific speech/noise conditions, normal bilateral hearing can provide a benefit to listening effort over asymmetrical hearing.

As noted previously, anecdotal reports from recipients, parents and clinicians suggest that one of the benefits of bilateral CIs may be reduced listening effort in complex noisy environments. Although previous studies have objectively demonstrated reduced listening effort as a result of increased/improved auditory input or easier listening condition, an objective comparison of listening effort in the bilateral versus unilateral conditions has not been made for participants with normal hearing, or for participants using hearing aids or cochlear implants. The aim of the current study was to investigate the listening effort expended in complex noisy situations by adolescents and young adults using bilateral CIs. More specifically, the study aimed to compare the listening effort expended by adolescents and young adults using bilateral cochlear implants versus their peers with normal hearing when these two groups were achieving similar speech perception scores. The study also aimed to compare the listening effort expended by adolescents and young adults with bilateral cochlear implants when using two CIs versus one.

Methodology

Participants

The eight participants with normal hearing (NH) were aged between 10 years, 9 months and 15 years, 11 months (mean: 12 years, 6 months SD: 1 year, 7 months). The CI participants were sequentially implanted with Nucleus CI22 and/or CI24 implants and were using Freedom speech processors. Details of hearing loss, age at implant, bilateral experience, and age at testing for the CI participants are presented in Table 1. There were no reports of cognitive difficulties from any professionals working with the participants. All participants used oral/aural communication and were enrolled in mainstream education settings. For these participants, a within-subject comparison of performance was made in the unilateral versus bilateral condition. Although this approach disadvantages the unilateral condition because it is not the everyday listening condition, it was considered to be the most appropriate methodology. A matched-pairs comparison was rejected due to the particular difficulty of matching adolescents and young adults on factors relevant to performance with a cochlear implant. A between-subject design was rejected due to the wide range of outcomes amongst adolescents and young adults with implants and the relatively limited sample size involved; these two factors were very likely to result in a high error variance. .

Table 1: Hearing loss, age at implant, bilateral experience, and age at testing details for the eight participants with cochlear implants.

Participant No.	Aetiology	Age at onset[1]	Age at 1st CI[2] (yr;mo)	Age at 2nd CI (yr;mo)	Time b/w CIs (yr;mo)	BiCI[3] experience (yr;mo)	Age at testing (yr;mo)
CI1	Genetic	congenital	1;4	9;1	7;9	2;4	11;5
CI2	meningitis	9 mo	5;9	16;3	10;5	3;2	19;5
CI3	WVA[4]	congenital	2;10	8;11	6;1	1;5	10;4
CI4	WVA	congenital	11;3	19;9	8;6	3;0	22;9
CI5	Genetic	congenital	3;6	12;1	8;7	1;1	13;2
CI6	WVA	congenital	2;1	9;7	7;5	1;8	11;3
CI7	WVA	congenital	9;2	15;8	6;5	0;8	16;4
CI8	WVA	congenital	0;10	7;8	6;9	2;8	10;4
Mean (SD)			4;5 (3;8)	12;4 (4;4)	7;9 (1;4)	2;0 (0;11)	14;3 (4;7)

[1] Age at onset: age at onset of profound hearing loss. [2] CI: Cochlear implant. [3] BiCI: Bilateral cochlear implants. [4] WVA: Wide Vestibular Aqueduct Syndrome.

Test apparatus

Testing was conducted in a sound-proof booth. The test set-up is shown in Figure 1. The participant was seated in front of a 180^0-array of eight Tannoy Reveal loudspeakers spaced 25.7^0 apart. The loudspeakers were positioned at ear level at a distance of 115cm and were numbered one (at 90^0 on the left) through eight (at 90^0 on the right). An ELO 17'' touch-screen was positioned on a low table in front of the participant.

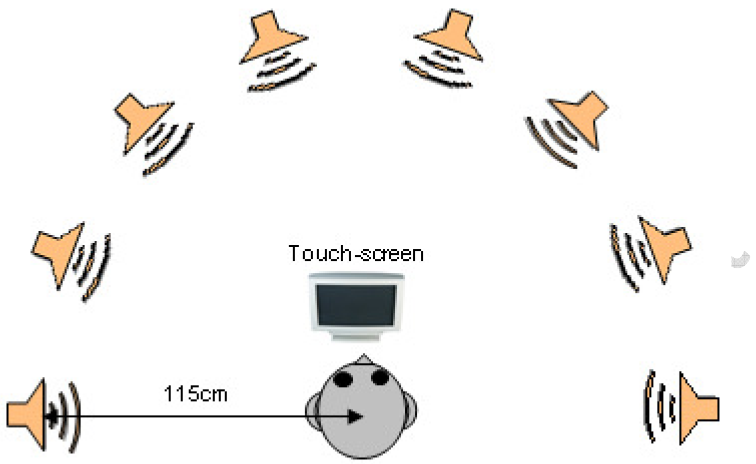

Figure 1: Schematic diagram of the test setup inside the sound-proof booth. The participant is facing a 180º 8-loudspeaker array positioned at ear level. The angle between each speaker is 25.7º.

Tasks

The dual-task paradigm consisted of a complex word-perception-in-noise task (the primary task) and a simple visual shape-matching task (the secondary task). Based on the theory of limited cognitive resources, an indication of the listening effort being expended on the word-perception-in-noise task is given by the change in response time on the visual shape-matching task when the word-perception-in-noise task is introduced.

Complex word-perception-in-noise task

The Consonant-Nucleus-Consonant (CNC) Word Test (Peterson & Lehiste, 1962) was used as the material for the primary task. The test was scored by the number of phonemes correct; phoneme scoring provides more items and therefore a more reliable measure than whole words and is less influenced by vocabulary knowledge. During the administration of each 50-word CNC list, the presenting loudspeaker was randomly selected for each word. In order that a similar number of words were presented from each of the eight loudspeakers, no more than seven words per list were presented from any one loudspeaker. Continuous 4-talker babble was presented from the seven loudspeakers not presenting a word at any one time. The SNR was set for each individual. This was an important part of the methodology aimed at ensuring that the complex word-perception-in-noise task was challenging but manageable for both the NH and CI participants. The SNR was determined for each individual by administering a practice word list in the participant's everyday listening condition (i.e., bilateral CIs or bilateral normal hearing) using an estimated SNR. The estimation was based on the experienced tester's judgment of the individual's perceptual skills. A phoneme recognition score was calculated after 25 words had been presented. If the phoneme score was below 75% or above 85%, the SNR was adjusted and a further 25 words were presented. This procedure was repeated until the participant was scoring in the range 75 to 85%. . Table 2 presents the SNR determined for each participant. The SNR thus determined for each individual was used in all test conditions for that participant. To avoid training effects, participants were exposed to each practice list or test list on only one occasion.

Table 2: Signal-to-noise ratio used for each of the 16 participants in all test conditions.

Participant	SNR (dB)	Participant	SNR (dB)
CI1	+15	NH1	0
CI2	+12	NH2	0
CI3	+15	NH3	0
CI4	+15	NH4	0
CI5	+15	NH5	0
CI6	+10	NH6	-5
CI7	+10	NH7	-5
CI8	+15	NH8	-2

Visual shape-matching task

A simple, four-alternative, forced-choice, visual shape-matching task was used for the secondary task. The materials used were squares, circles, and triangles colored red, green or yellow. One colored test shape was displayed on the touch-screen for 0.5 seconds. The image was then replaced by four colored shapes (the test item and three foils). The participant was required to select the test item from the four shapes. The delay between the original appearance of the test item and the participant's selection of the test item from the set of four was recorded by the software as the 'response time'.

Test conditions

The test conditions were a combination of task condition and listening condition. The three task conditions were: shape-matching, words-in-noise, and shape-matching + words-in-noise (the condition in which the two tasks were performed simultaneously). For the NH group there was one listening condition: bilateral hearing. For the CI group there were two listening conditions: bilateral CIs and unilateral CI. A summary of test conditions and groups assessed in the specified condition is presented in Table 3. Due to the difference in the number of listening conditions relevant to each group, the NH group was assessed in a total of three test conditions, whilst the CI group was assessed in a total of five test conditions. The purpose of the shape-matching alone and words-in-noise alone task conditions was to obtain baseline measurements in these single task conditions. This single task performance was then compared with performance on each task when the two tasks were performed simultaneously in the dual-task condition, i.e., the shape-matching + words-in-noise task condition.

In test conditions involving the words-in-noise task, one CNC list of 50 words was administered per test block. In test conditions also involving the shape-matching task, shape-matching-items were presented for the same amount of time as was taken to administer the CNC word list. This was approximately six minutes, and 48 to 52 shape-matching items were presented in this time period. In the test condition involving only the shape-matching task, shape-matching items were also presented for six minutes so that the length of testing was consistent across test conditions.

For each participant, assessment in all relevant test conditions constituted one test block. NH participants completed three tests blocks in one test session. As more test conditions were required, CI participants completed three test blocks over two to three test sessions. Due to their limited availability, participants NH7, CI1 and CI3 completed only two test blocks. In the first test block, assessment in both single task conditions was completed first to provide experience with each task individually prior to performing the tasks simultaneously. The remaining order of the task conditions, and listening conditions for the CI participants, was balanced across test blocks and participants. When the listening condition was changed, the

CI participant was engaged in five minutes of conversation to allow adaptation to the new condition.

Table 3: Task conditions, listening conditions, test conditions, and participant group assessed in each test condition.

Task condition	Listening condition	Test condition	Participant group assessed
Shape-matching	n/a	S	CI and NH
Words-in-noise	Bilateral	W:bilat	CI and NH
Shape-matching + words-in-noise	Bilateral	S+W:bilat	CI and NH
Words-in-noise	Unilateral	W:unilat	CI only
Shape-matching + words-in-noise	Unilateral	S+W:unilat	CI only

Procedure

In the S condition, participants were instructed to select the test shape from the choice of four shapes as quickly as possible. In the W:bilat and W:unilat conditions, participants were instructed to repeat the word, with guessing encouraged. In the S+W:bilat and S+W:unilat conditions, participants were instructed that repeating the words was the main task, but the test shape should also be selected as quickly as possible.

Results

Phoneme scores on the words-in-noise task

Figure 2 presents the mean individual (n = 3; n = 2 for NH7, CI1, and CI3) and mean group (n = 8)

CNC phoneme scores for the NH and CI groups in all test conditions in which the words-in-noise task was administered. As shown, the mean CNC phoneme score for each individual in each in each test condition was within, or close to, the target range of 75 to 85%. To compare CNC phoneme scores across test conditions for individual CI participants, a one-way ANOVA was conducted for each participant with test condition as the factor. These analyses indicated no significant difference between any of the four conditions assessed (W:unilat, S+W:unilat, W:bilat, and S+W:bilat) for any participant (CI1 and CI3: $F(3,4) \leq 1.08$, $p \geq 0.45$; CI2, CI4, CI5, CI6, CI7 and CI 8: $F(3,8) \leq 1.46$, $p \geq .30$). Given only two conditions were assessed for the NH participants, a two-tailed paired t-test was conducted. No significant difference was found between the two test conditions (W:bilat and S+W:bilat) for any participant (NH1, NH2, NH3, NH4, NH5 & NH6 and NH8: $t(2) \leq 1.99$, $p \geq 0.18$; NH7: $t(1) = 0.20$, $p = 0.18$). To compare CNC phoneme scores for the groups, a one-way ANOVA was conducted with participant-group/test condition as the factor. No main effect was found ($F(5,42) = 1.94$, $p = 0.108$). This result indicates that there were no differences in CNC phoneme scores between the NH and CI groups, irrespective of the test condition, and that there were no differences in scores across test conditions for either the NH or CI groups.

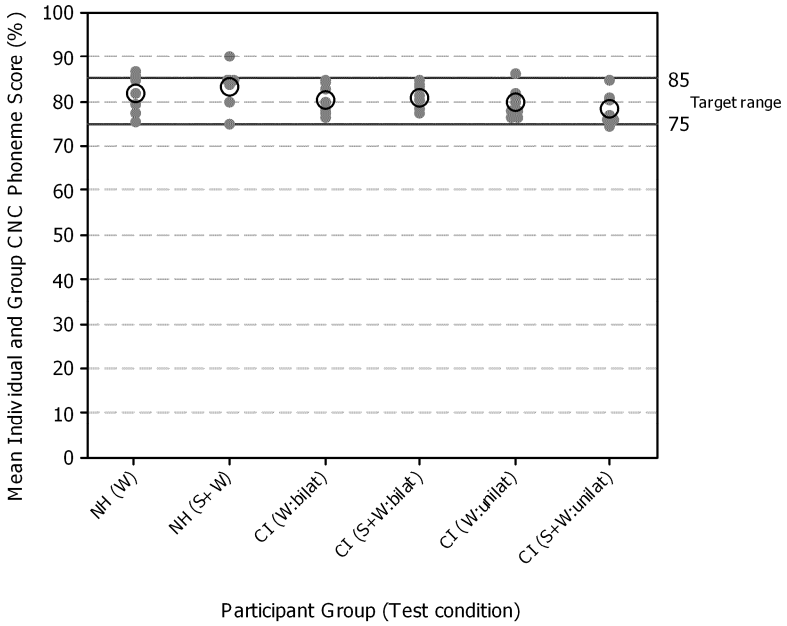

Figure 2: Mean percentage of phonemes correct on the CNC Word test. Solid circles represent mean (n = 3; n = 2 for CI1, CI3, and NH7) individual scores and open circles represent the mean (n = 8) group score in the specified condition. Results are shown for participants with normal hearing on the words-in-noise (W) and the shape-matching + words-in-noise (S+W) tasks, and for participants with cochlear implants when using bilateral implants on the words-in-noise (W:bilat) and the shape-matching + words-in-noise (S+W:bilat) tasks and when using a unilateral implant on the words-in-noise (W:unilat) and the shape-matching + words-in-noise (S+W:unilat) tasks.

Response times on the shape-matching task

The variable of most interest in this study was the change in response time on the shape-matching task when the words-in-noise task was introduced i.e., the difference in response time between the S and the S+W task conditions for each listening condition. For the NH group, the change in response time was calculated as the difference in response time between the S and the S+W:bilat tasks. For the CI group, the change in response time was calculated for two listening conditions; i.e., the difference in response time between the S and the S+W:bilat conditions, as well as the difference in response time between the S and the

S+W:unilat conditions.

Figure 3 shows the change in response time for the NH group (n = 8) and for the CI group (n = 8) in the bilateral condition. The positive mean change shown for each group represents the slower response time when the shape-matching and words-in-noise tasks were performed simultaneously compared with when the shape-matching task was performed alone. A two-tailed, Mann-Whitney test indicated no significant difference for the change in response time across the two groups ($U = 79.0$, $p = 0.27$).

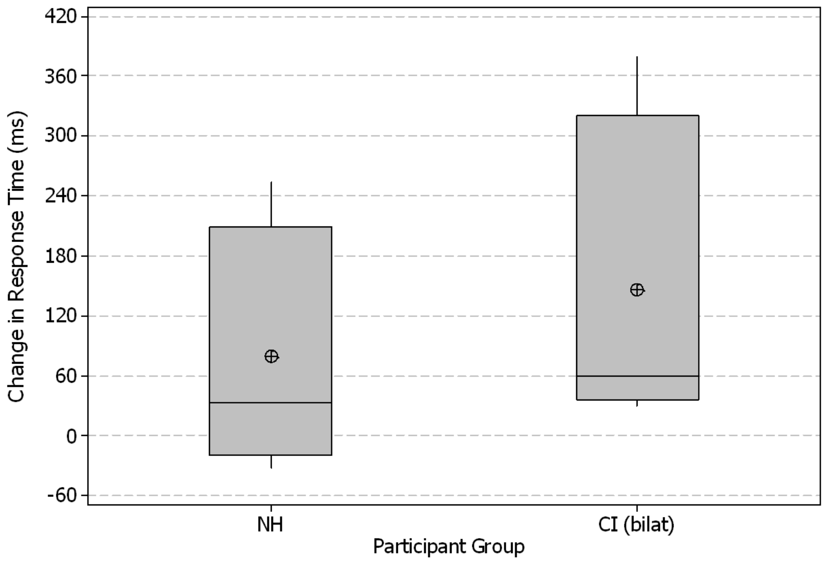

Figure 3: Change in response time (in ms) between the shape-matching (S) and shape-matching + words-in-noise conditions (S+W) for the participant group with normal hearing (n = 8) and the participant group with cochlear implants when tested in the bilateral condition (n = 8). The box represents the interquartile range, the solid line is the median, the circle is the mean, and the whiskers show the minimum and maximum vales.

Figure 4 presents the mean (n = 88 to 147) change in response time for each of the eight CI participants and for the group when using unilateral or bilateral implants. As shown, there was considerable variability across individuals in terms of the change in response time, the minimum being 31msec and the maximum 486. Again, the positive mean change shown for each individual in each condition represents the slower response time which occurred when the shape-matching and words-in-noise tasks (S+W condition) were performed simultaneously compared with when the shape-matching task (S condition) was performed alone. The change in response time as a result of the introduction of the word task in the bilateral versus unilateral conditions, Wilcoxon Signed Rank tests were conducted. The change in response time was significantly smaller in the bilateral condition for participants CI1 ($W(87) = 2367.0$, $p = 0.028$), CI2 ($W(138) = 6164.5$, $p = 0.002$) and CI3 ($W(102) = 3229.0$, $p = 0.022$) and for the group ($W(8) = 36.0$, $p = 0.007$). There was no significant difference between conditions for the remaining five individuals ($p \geq 0.056$).

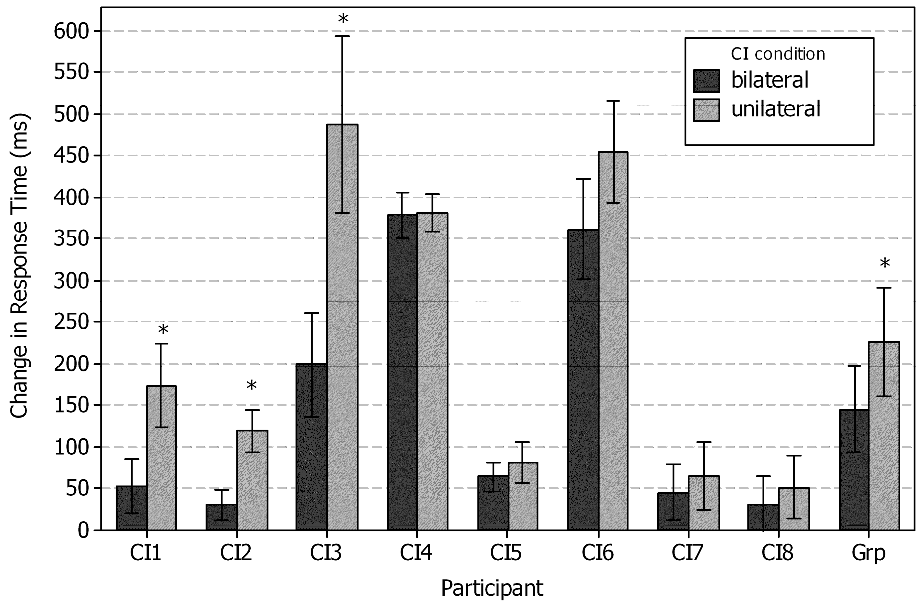

Figure 4: Change in response time (ms) between the shape-matching (S) and shape-matching + word-in-noise (S+W) conditions for the individual participants and the group with cochlear implants when tested in the bilateral and unilateral conditions. Error bars represent +/-1 standard error of the mean. Asterisks indicate a significant difference b/w conditions ($p < 0.05$).

Discussion

In a dual-task paradigm it is intended that performance on the more difficult primary task should remain the same across conditions (Downs & Crum, 1978). In the present study, the maintenance of consistent performance on CNC phoneme perception by individual participants across conditions was important to demonstrate that the participants were prioritising the main task in all conditions. Consistent phoneme scores were also important so that changes in response times reflected changes in the listening effort being expended, rather than a change in the prioritising of the tasks. For each of the 16 participants, CNC phoneme scores were not significantly different across conditions. This finding is consistent with previous dual-task work involving adults, which has shown that speech perception scores can remain unaffected by the introduction of a competing secondary task when participants are instructed that the speech perception task is the primary task which should be prioritized (Downs & Crum, 1978; Rabbitt, 1966). Previous dual-task research involving children has shown that there is some variation in the ability of children to allocate attention preferentially to a specified task. In some studies, children have not consistently directed attention towards the more difficult primary task (Choi et al., 2008; McFadden & Pittman, 2008), or extrinsic rewards have been used to ensure that attention is directed as requested (Hicks & Tharpe, 2002; Howard et al., 2010). As the present participants were older than the majority of children in these previous studies, it is likely that they had a greater ability to allocate attention and to voluntarily recruit extra resources as needed. This is consistent with previous research examining the relationship between age and the allocation of attention (Irwin-Chase & Burns, 2000; Schiff & Knopf, 1985).

One aim of the present study was to compare the listening effort expended in complex noisy environments by adolescents and young adults using CIs and those with normal hearing when these two groups were achieving similar speech perception scores. Previous research has demonstrated that, when tested under the same listening conditions, adults and children with hearing impairment expend more listening effort than their peers with normal hearing (Hicks & Tharpe, 2002; Rakerd et al., 1996). In these studies, the obvious expectation was that the task would be more difficult for the listeners with hearing impairment and it is therefore unsurprising that extra effort was required. In the current study, the response time results demonstrated that, when listening conditions were manipulated to result in similar speech perception scores, the expenditure of listening effort for the CI group and the NH was similar. Linguistic knowledge, listening experience, and the ability to use contextual cues all contribute to the processing of auditory information (Boothroyd, 1997). Due, at least in part, to their congenital or very early-onset hearing loss and the duration of profound deafness prior to first implantation (which occurred at a mean age of 4yr 5mo (SD 3yr 8mo), the CI group are likely to have had deficits in some or all of these areas. However, the provision of a higher SNR overcame any limitations in the auditory information received by the CI group, and also any limitations in their ability to process that auditory information. Unfortunately, it is not possible to routinely provide such a high SNR in the mainstream environments in which many young people with CIs are now educated (Damen et al., 2006). Typical classroom SNRs are in the range between -7dB and +5dB (Crandell & Smaldino, 2000). It would be expected that, at these low SNRs, young people with CIs would need to expend significantly greater listening effort than their NH peers, leaving fewer cognitive resources for other functions. The results highlight the need for continued support for adolescents and young adults with CIs in all educational settings. Even when age-appropriate language and good academic performance are achieved, it is important that parents and teachers are aware of the often taxing nature of mainstream education for adolescents and young adults with CIs.

The second aim of the present study was to determine whether adolescents and young adults with CIs expended less effort listening in complex, noisy environments when using two implants compared to one. The response times indicated there was a measurable reduction in listening effort for the group and for three individuals in the bilateral condition compared to the unilateral condition. This indication that bilateral implants are beneficial in reducing listening effort is consistent with reports by authors documenting anecdotal feedback (Bohnert et al., 2006; Kühn-Inacker et al., 2004) and questionnaire data (Scherf et al., 2009; Winkler et al., 2002). Although useful, such subjective data is based on observation, and may be influenced by the skills, biases, and experience of the parent, teacher, or clinician. The present study is the first objective assessment of listening effort for children using bilateral versus unilateral implants, and it is very promising that three individual CI participants demonstrated a significant decrease in listening effort when using bilateral implants. However, there was no significant difference for the remaining five participants. There are three possible interpretations of this result. Firstly, these participants were not gaining any additional perceptual benefit from their second implant, and therefore gained no benefit in the form of reduced listening effort. An alternative explanation is that, while these individuals did gain a perceptual benefit, this was not translated to a reduction in listening effort. The likelihood of this group varying in terms of the perceptual benefit gained from their second implant was high, given that the group was not homogenous with respect to factors such as age at implant and time between implants. Lastly, it is possible that the test was not sensitive enough to detect changes in expenditure of effort for these individuals.

This study was the first application of this particular combination of tasks in a dual-task paradigm. The fact that a listening effort difference was detected for at least some subjects suggests that the dual-task paradigm is a suitable method for objectively measuring if this type of benefit is provided by bilateral implants. However, primary and secondary tasks that were different in complexity and/or nature may make the test more sensitive to changes in listening effort. In the current study, a word-level task was chosen over a sentence-level task to reduce the potential impact of differences in language ability on the results. However, there is evidence from a previous study using a dual-task paradigm to suggest that a sentence-level task may be more sensitive to changes in listening effort (Gatehouse & Gordon, 1990). This type of task involves 'top-down' processing, with the listener using semantic, syntactic, and contextual knowledge. Sentence-level testing therefore involves more cognitive processing than the word perception test used in the current study. The simple, visual shape-matching task employed in the current study was suitable for this participant group, given the wide age range and therefore potential differences in cognitive ability between individuals. Nonetheless, a more challenging secondary task requiring extra cognitive resources may be another way to increase the sensitivity of the test for a less diverse participant group. For example, previous researchers have employed more complex secondary tasks involving the short-term retention of words (Rabbitt, 1966) or digits (Choi et al., 2008; Howard et al., 2010; Rakerd et al,. 1996). It is also possible that a language-based secondary task, which potentially draws on the same set of cognitive resources as the primary listening task, may be more effective in detecting subtle differences in listening effort.

Listening effort is an important area for continued study in the context of pediatric bilateral implants. Cochlear implantation is an expensive technology which requires surgical intervention and significant post-operative follow-up. Bilateral implantation is a relatively new option for those with onset of deafness in childhood, and involves additional expense and additional surgical time. The majority of research so far has focused on benefits to speech perception and spatial hearing. Objective assessment of other areas of benefit, such as a reduction in listening effort, provides a more comprehensive picture of outcomes for bilateral implant users. Future research examining the effect of bilateral implants on the reduction of listening effort for younger children, would also help to provide a more comprehensive picture of outcomes for different age groups. Clinicians need accurate information to provide pre-operative recommendations and counseling to candidates and their families. Hospitals, governments and health insurers require such information to determine policy regarding the provision of bilateral cochlear implants.

Conclusion

In an average SNR of +15dB, a group of adolescents and young adults using CIs achieved similar CNC phoneme perception scores and expended a similar amount of listening effort to a group with normal hearing who were listening in an average SNR of -2dB. This finding has particular implication for those in mainstream education, where it is not possible to routinely provide such a high SNR for young people with CIs.

This study reports the first objective assessment of listening effort for adolescents and young adults using bilateral implants. For the group, and for three individuals, listening effort was reduced when using bilateral CIs compared to a unilateral CI when phoneme perception scores remained the same. The results provide objective evidence that reduced listening effort is a benefit that some individuals gain from bilateral cochlear implants. A more sensitive assessment procedure may clarify if reduced listening effort is a benefit gained by a wider range of CI users.

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Declaration of Interest

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