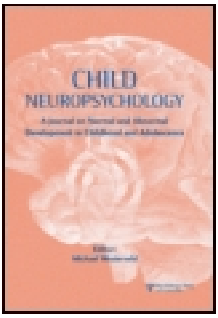

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The mathematical abilities of children with cochlear implants

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The mathematical abilities of children with cochlear implants

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Research has shown that cochlear implants give rise to improvements in speech recognition and production in children with profound hearing loss but very few studies have explored mathematical abilities in these children. The current study compared the mathematical abilities of 24 children with cochlear implants (mean age 10 years 1 month) to a control group of 22 hearing children (mean age 9 years 8 months). The math questions were categorized into questions that tapped into arithmetic or geometrical reasoning. It was predicted that the cochlear implant group would perform below the hearing group on the arithmetic questions but not the geometrical reasoning questions. Unexpectedly, the results showed that the cochlear implant group performed significantly below the hearing group on both types of math questions, but that this difference was mediated by language skill as assessed by vocabulary knowledge. The clinical implications of these results and possible future research results are considered.

Keywords: Cochlear implant; Deaf; Hearing loss; Math; Children.

Mathematical ability is increasingly essential for modern living (Nelson, Reyna, Fagerlin, Lipkus, & Peters, 2008) and directly affects employment opportunities (Rivera-Batiz, 1992). Hearing loss has long been associated with weaker performance in mathematics, but little is known about mathematical competence in children with cochlear implants (e.g., Hyde, Zevenbergen, & Power, 2003; National Council of Teachers of the Deaf Research Committee, 1957; Nunes & Moreno, 1998; Wollman, 1965; Wood, Wood, & Howarth, 1983), a group whose educational outcomes are generally improved relative to nonimplanted children with similar hearing losses. The few studies on the mathematical abilities of children with cochlear implants are so far inconclusive, and while some researchers have found that children with cochlear implants perform above average in comparison to hearing children, others report no differences or even below average performance for cochlear-implanted children. For instance, one large study presents the 4-year aggregate National Curriculum Test scores of 152 school-aged pupils with cochlear implants in

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Scottish schools (Thotenhoofd, 2006). The group comprised of 105 primary school pupils with an average age of 8.06 years and 47 secondary school pupils with an average age of 14.07 years. Whilst the cochlear implant children in the study by Thotenhoofd are reported to do well, there are unfortunately no statistical analyses. Other studies have also suggested that children with cochlear implants are performing above average in math (e.g., Mukari, Ling, & Ghani, 2007; Motasaddi-Zarandy, Rezai, Mahdavi-Arab, & Golestan, 2009), but again there has been limited statistical analysis comparing the cochlear implant with a hearing group in these studies. In contrast, in other studies, teacher ratings of the academic performance of cochlear-implanted children did not differ from ratings of their hearing classmates (Damen, van den Oever-Gotstein, Langereis, Chute, & Mylanus, 2006) and, in the study by Punch and Hyde (2010), children with cochlear implants were reported to be performing below hearing children. In addition, a 6-month follow-up of 17 children after cochlear implantation (mean age 7 years 2 months) showed no improvement in mathematics, in the context of improvements in some other cognitive skills, such as comprehension, concentration, and sequential processing, as measured by nonverbal tests (Shin et al., 2007).

In the studies where poorer performance of deaf children in mathematics has been found, it has generally been associated with reduced language abilities (e.g., Davis & Kelly, 2003; Hyde et al., 2003; Kelly & Gaustad, 2007; Kelly, Lang, & Pagliaro, 2003; Kelly & Mousley, 2001). Since the teaching of mathematics often takes the form of complex verbal explanations, it follows that children who have difficulty with complex language due to hearing loss may also have difficulty learning mathematical concepts (e.g., Nunes & Moreno, 2002). Children with cochlear implants show improvements in language abilities compared to deaf children without cochlear implants, although it is still unclear whether they reach levels comparable to their hearing peers (e.g., Geers, Nicholas, & Sedey, 2003; Mukari et al., 2007; Robbins, Bollard, & Green, 1999; Spencer, 2004; Svirsky, Robbins, Kirk, Pisoni, & Miyamoto, 2000).

Recent research has emphasized the importance of language proficiency of deaf children with cochlear implants, in cognitive abilities including analogical reasoning skills and executive functions such as impulse control, planning, problem solving, working memory, and cognitive set-shifting. Figueras, Edwards, and Langdon (2008) found strong correlations between executive function and vocabulary and grammar knowledge. Edwards, Figueras, Mellanby, and Langdon (2011) found that vocabulary and grammar skills are significant predictors of both verbal and spatial analogical reasoning abilities, but that the relationship was much stronger in the case of verbal reasoning abilities. Currently there is no empirical evidence regarding the relationship between language and numerical reasoning in deaf children with cochlear implants, in relation to different types of mathematical problems. Previous research with hearing adults and children has provided evidence for "five different cognitive systems at the core of mathematical thinking" (Spelke, 2005, p. 952). The current study will focus on two of these systems — "Arithmetic and Counting" and "Geometrical Reasoning." The former can be exemplified by addition tasks requiring accuracy, and the latter problems involve approximations, mental rotation, and spatial memory. Language proficiency and verbal associations are more closely related to arithmetic and counting than geometrical reasoning (Butterworth, 2005).

Due to the fact that language proficiency and verbal associations are more closely related to arithmetic and counting than geometrical reasoning (Butterworth, 2005), it is hypothesized that children with cochlear implants will perform below their hearing peers on arithmetic and counting mathematical questions. This has been shown previously; for example, Shin et al. (2007) found that following cochlear implantation, children with hearing loss did not show significant changes on mathematical subtests requiring verbal abilities. In contrast, it is hypothesized that children with cochlear implants will perform comparably to their hearing peers on geometrical reasoning mathematics questions. It is also hypothesized that this interaction will be removed once language ability is controlled.

METHOD

Design

A mixed-subjects design was selected as the main design of the study where two groups (Cochlear Implant group and Hearing group) were compared on their performance on different types of mathematics questions.

Participants

Cochlear Implant Group (*n* = 24). The inclusion criteria (based on Edwards, Khan, Broxholme, & Langdon, 2006) for the Cochlear Implant group were (a) aged between 7–12 years; (b) no known evidence of severe developmental delay or severe global learning difficulties; (c) no significant visual impairment (this could affect performance on some of the tasks); (d) no significant motor difficulties (this could affect performance on some of the tasks); (e) born and educated in the United Kingdom (tests are normed on UK population); and (f) severe-profound hearing loss in both ears, unaided. Fifty-three children from the Cochlear Implant Programme at Great Ormond Street Hospital met the criteria for participation and the parents/guardians of these children were sent invitation packs inviting them to take part. After parental and child consent was obtained, 24 children took part in the study (age: $M = 10$ years 1 month, range = 8.0–11.10). The group was comprised of 15 girls and 9 boys. All children were British; 20 were White British and 4 were Asian British and all used English as their first language. As a group, their mean unaided hearing level was 105.83 dBHL ($SD = 20.88$). The mean aided-hearing level was 33.44 dBHL ($SD = 2.95$). Eighteen of the children with cochlear implants had congenital deafness while the remaining 6 had acquired hearing loss. The etiologies of hearing loss for the cochlear implant group are shown in Table 1. All but three children had prelingual hearing loss.

The mean age at cochlear implantation for the group was 3 years 3 months (ranging from 1 year 5 months through to 6 years 7 months). Eighteen children had a right-sided cochlear implant and 6 had a left-sided cochlear implant. No children in the study had bilateral implants. At the time of testing, the mean length of time since implantation was 6 years 10 months (ranging from 4 years 3 months to 9 years 2 months). Twelve children in the group were attending mainstream schools, 7 children were attending schools with support units for deaf or hard of hearing children, and 5 children were attending special schools for deaf children. None of the children were using British Sign Language (BSL) as their preferred method of communication, 10 were using Sign-Supported English (SSE), and 14 preferred to use oral communication. BSL is a visual means of communicating that has its own grammatical structure and syntax. It is its own language and not closely related to spoken English. In contrast, SSE is not a language in its own right but makes use of some of the BSL signs to support spoken English and is generally used by people with hearing loss who interact mainly with hearing people.

Table 1 The Etiologies of Profound Hearing Loss in the Cochlear Implant Group.

Category	Etiology	Number of Children
Congenital	Autosomal Recessive	7
	Unknown (congenital)	4
	Ushers	2
	Waardenburg's Syndrome	2
	Autosomal Dominant	1
	Premature birth and asphyxia	1
	Rubella	1
Acquired	Meningitis – Pneumococcal	3
	Meningitis - Haemophilus	1
	Meningitis – type unknown	1
	Viral Encephalitis	1

Hearing Group (*n* = 22). Also based on Edwards et al. (2006), the inclusion criteria for the Hearing group were (a) aged between 7–12 years, (b) no known evidence of severe developmental delay or severe global learning difficulties, (c) no significant visual impairment (this could affect performance on some of the tasks), (d) no significant motor difficulties (this could affect performance on some of the tasks), and (e) born and educated in the United Kingdom (tests are normed for UK population). These participants were recruited from mainstream schools in London and South East England. Where possible, these children attended the same schools as the Cochlear Implant group. A total of 22 hearing children completed the study (9 boys). The mean age was 9 years 8 months (range 8.1–11.6). All children in this group were British (14 were White British, 5 were Asian British, and 3 were Black British) and all hearing children used English as their first language.

Measures

RM Maths (RM Maths, 2002). The computer package RM Maths (2002) was used to assess mathematical ability. This is a computer package designed for children of primary school age and is closely linked to the UK National Curriculum. RM Maths is intended as an educational tool and not a standardized clinical assessment. Therefore, it does not have published norms or data on reliability or validity. However, an evaluation of the impact of the program found a strong correlation between the number of skills mastered and the results of external tests of mathematical ability, which is a preliminary indication of validity (RM Maths, 2005). This study also demonstrated that the package benefits children falling behind in mathematics, which suggests that it is particularly attractive to children lacking confidence and skills in math. It was also chosen in the current study because of the visual presentation of questions. Each question is presented in an auditory mode through the speakers of the computer and via a written question on the computer screen. The students were expected to read the question themselves and/or to listen to the questions via the speakers. All children were asked if they could hear the speech from the computer and all children said that they could. The question could be replayed up to twice if the child needed to listen to the question again, but very few children requested to listen to the question more than once. The questions are also presented clearly with visual cues to aid understanding of the question, which seemed particularly relevant for use with children with hearing loss. Two scales of questions were created using the program (i.e., Arithmetic and Counting

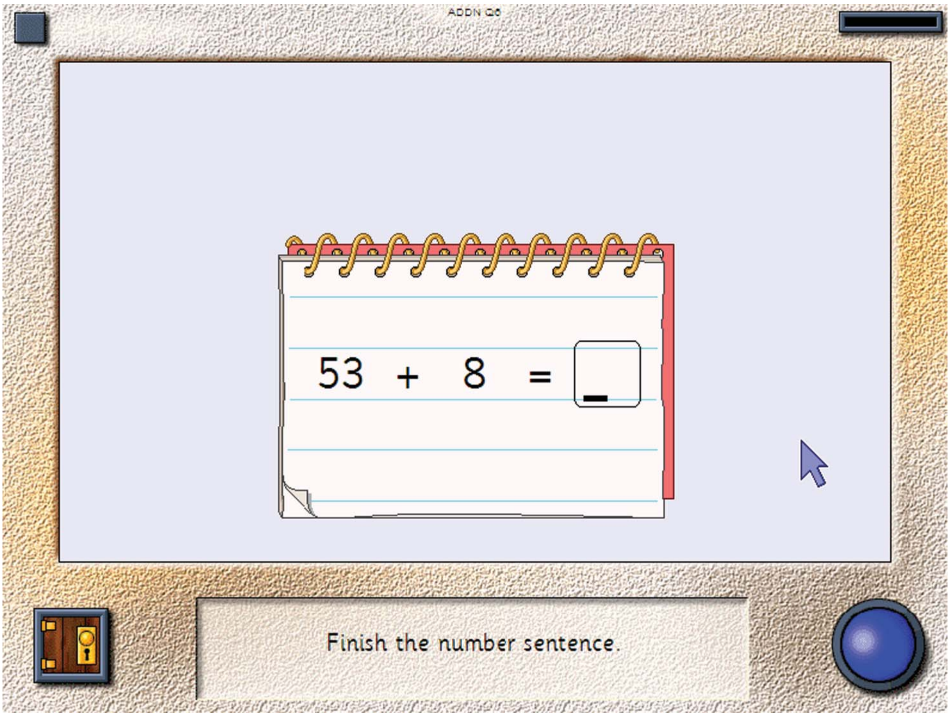

Figure 1 Example question from the RM Maths Arithmetic and Counting Scale.
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Scale and a Geometrical Reasoning Scale). The Arithmetic and Counting Scale comprised questions that required the child to accurately complete number sentences (Figure 1). The Geometrical Reasoning Scale assessed the child's ability to solve visuospatial mathematical problems. Many of these questions were presented in two parts; The first screen shot provided a visual demonstration with moving graphics while the second screen shot asked the child to select the correct response from a range of options or perform a visuospatial task relating to the demonstration (Figures 2 and 3).

Wechsler Intelligence Scale for Children, Fourth Edition (WISC-IV, UK; Wechsler, 2004) Arithmetic Subtest. Since RM Maths includes visual clues, it was felt that a "purer" measure of verbal mathematical functioning, reflecting verbal teaching and assessment methods used in the classroom, was also necessary. For this purpose, the WISC-IV Arithmetic subtest was selected, which comprises aurally presented arithmetic problems requiring a verbal response within specified time limits. For example, "If you have 3 pencils in each hand, how many pencils do you have altogether?" (Wechsler, 2004, p. 198). The WISC-IV has well-established validity and reliability. The manual does not provide norms for deaf children. However, it states that the Arithmetic subtest can be administered with few accommodations or modifications from the standardized administration procedures in aural/oral deaf children that includes those with cochlear implants.

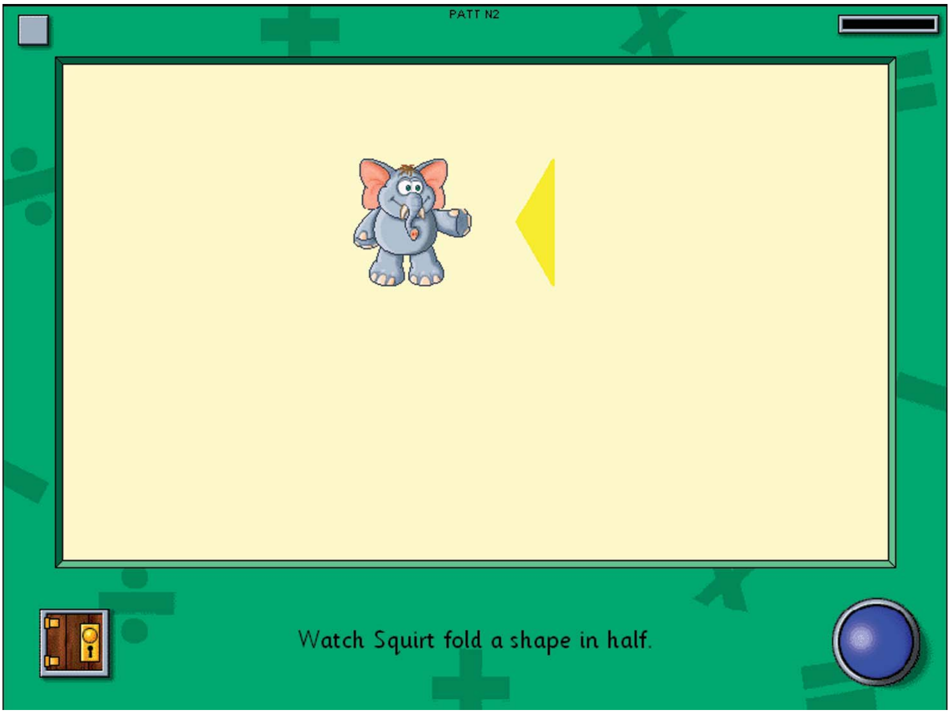

Figure 2 Example question from the RM Maths Geometrical Reasoning Scale (Step 1).
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British Picture Vocabulary Scale, Second Edition (BPVS-II; Dunn, Dunn, Whetton, & Burley, 1997). The BPVS-II assesses students' single-word receptive vocabulary. For each question, the examiner says a word and the student responds by selecting the picture (from four options) that best illustrates the word's meaning. The items sample words that represent a range of content areas such as actions, animals, toys, and emotions as well as parts of speech such as nouns, verbs, or attributes across all levels of difficulty. The BPVS-II has been used successfully in previous research with children with cochlear implants (e.g., Figueras et al., 2008; Edwards et al., 2011; James, Rajput, Brinton, & Goswami, 2008). As outlined in the BPVS-II manual (Dunn et al., 1997), the test has good reliability. The content validity and construct validity of the original BPVS has also been assessed and correlations between standard scores of the BPVS and other tests of language and grammar have been reported as ranging from .44 to .72 (Holwin & Cross, 1994).

Procedure

Testing with each child took approximately 45 minutes and took place in a quiet clinical room in the hospital outpatient clinic or in a quiet room provided by the child's school. Only the examiner and child were present during testing to avoid distraction. All children reported that they either had a computer at home and/or regularly used the computer facilities at school and were therefore familiar with their use. The RM Scales were introduced with the following instructions: "I am going to show you some adding

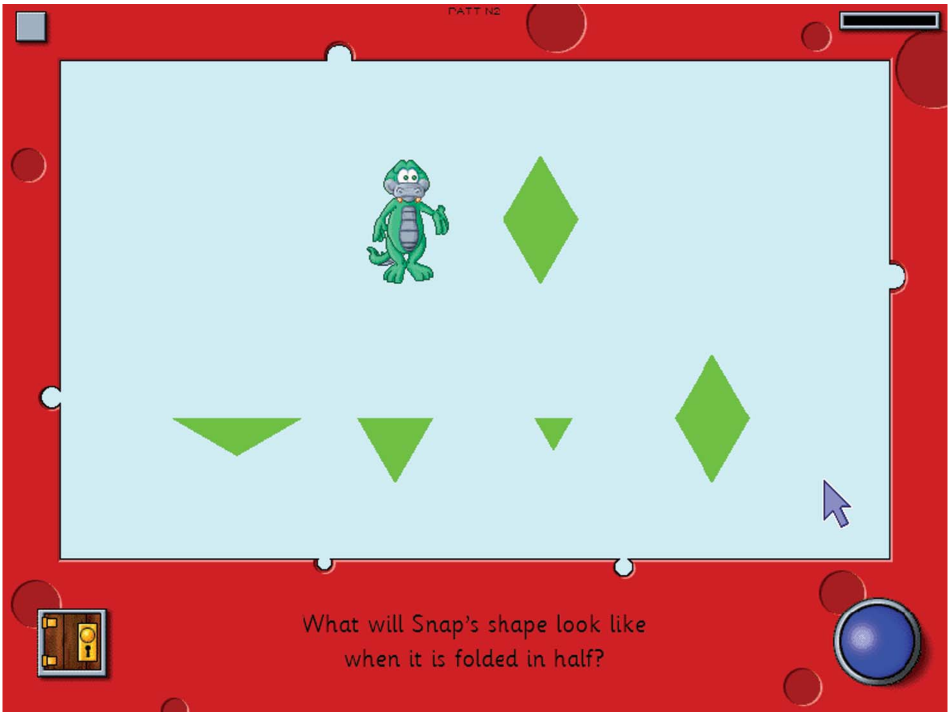

Figure 3 Example question from the RM Maths Geometrical Reasoning Scale (Step 2).
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questions/questions to do with shapes and patterns on the computer. Have a go at each question. For some questions you will need to use the mouse (examiner pointed to the mouse) and for other questions you will need to use the numbers on the keyboard (examiner pointed to the row of numbers on the keyboard). Do you understand?"

Standard administration procedures were followed for the WISC-IV Arithmetic subtest and the BPVS-II, but with adaptations to make testing possible for children using SSE as their preferred mode of communication ($n = 10$). For the WISC-IV Arithmetic subtest, this involved signing the British Sign Language (BSL) numbers. This supported the spoken instructions and ensured that the numbers had been correctly understood. Adaptation on the BPVS-II involved showing the child the first letter of the word using finger spelling to avoid confusion over similar sounding words (e.g., "bat" and "cat"). As BSL is a visual language, it was not possible to sign the word, as in many instances this would have inadvertently provided the answer. All other standard administration procedures were followed.

It was planned that the groups' scores on different measures would be compared using analyses of variance (ANOVAs) or *t*-tests. The dependent variable in each case was a child's raw score on a particular measure. The independent factor in each analysis was Group (Cochlear Implant or Hearing). When an interaction emerged, this was followed up with planned comparisons to clarify where the differences lay. To test if any differences between the groups could be accounted for by differences in language ability, BPVS-II raw scores were entered into an analysis of covariance (ANCOVA) as a covariate.

RESULTS

The mean results for each group on the measures administered are shown in Table 2 and in Figures 4, 5, and 6. A mixed ANOVA with "Measure" as the within-subjects factor with three levels (RM Maths Arithmetic and Counting score, RM Maths Geometrical Reasoning score, and WISC-IV Arithmetic raw score) and "Group" as the between-subjects factor (Cochlear Implant or Hearing) was run. There was a significant main effect of Group, $F(1, 44) = 21.41$, $p < .001$, whereby the cochlear implant group performed significantly below the hearing group. There was a significant main effect of Measure, $F(2, 88) = 18.73$, $p < .001$. There was also a significant Group by Measure interaction, $F(2, 88) = 11.03$, $p < .001$.

In order to establish the nature of the interaction, post hoc comparisons were performed. Three *t*-tests were run to compare the differences between groups on the three measures (Bonferroni correction was applied to reduce the risk of a Type 1 error). The first *t*-test revealed that there was a significant difference between the groups on WISC-IV

Table 2 Raw Scores and Standard Scores for Both Groups on Each Measure.

Measure	Cochlear Implant Group ($n = 24$)	Hearing Group ($n = 22$)	Level of Significance between Groups
RM Maths:			
Arithmetic and Counting Raw Score *M* (*SD*)	17.33 (4.07)	20.05 (1.53)	$p < .01$
Geometrical Reasoning Raw Score *M* (*SD*)	17.88 (3.33)	20.14 (1.70)	$p < .01$
WISC-IV Arithmetic Subtest			
Raw Score *M* (*SD*)	18.46 (4.68)	24.27 (2.93)	$p < .001$
Scaled Score *M* (*SD*)[a]	6.92 (2.86)	11.64 (2.11)	
BPVS-II			
Raw Score *M* (*SD*)	79.13 (20.23)	103.41 (13.60)	$p < .001$
Standardised Standardized Score *M* (*SD*)[b]	82.83 (19.00)	107.59 (9.99)	

Notes. [a] For scaled scores, the absolute average is 10 ($SD = 3$).
[b] For Standardised standardized scores, the average is 100 ($SD = 15$).

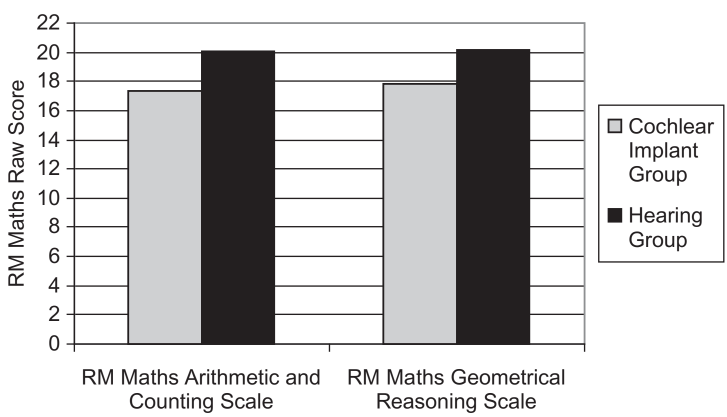

Figure 4 Raw score results for each group on the RM Maths scales.

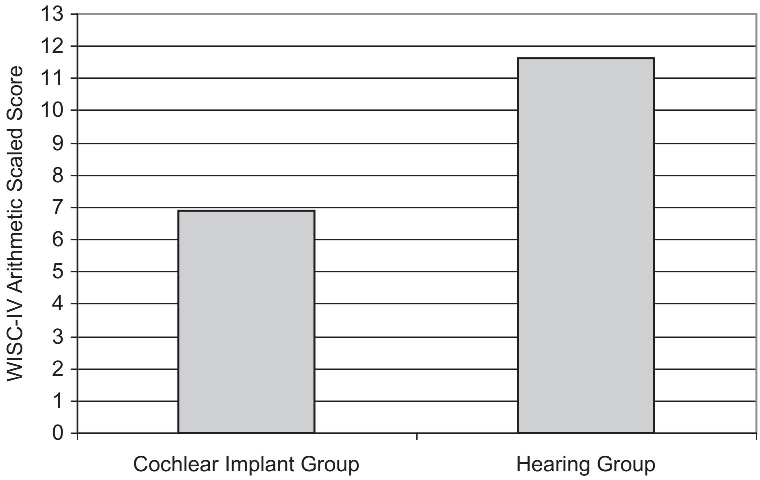

Figure 5 Scaled scores for each group on the WISC-IV Arithmetic Subtest.

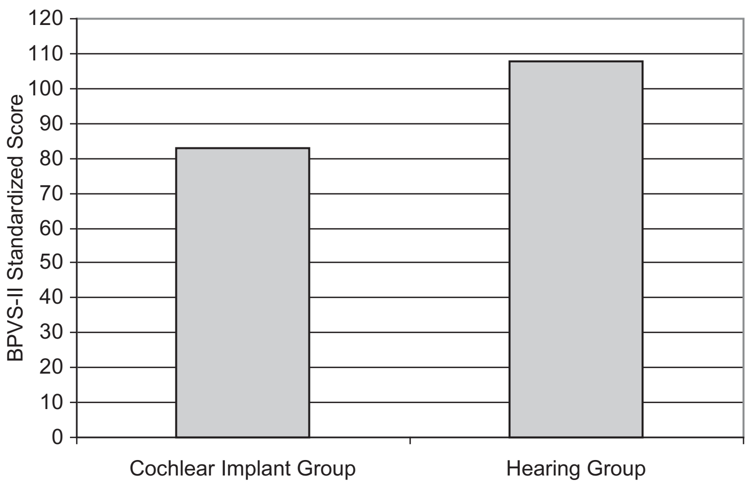

Figure 6 Standardized scores for each group on the BPVS-II.

Arithmetic raw score, $t(39) = -5.09$, $p < .001$, (separate variance estimates were used since homogeneity of variance assumptions were not met, $F = 5.19$, $p < .05$). Further t-tests also revealed that there were differences between the groups on RM Maths Arithmetic and Counting scale, $t(39) = -3.04$, $p < .01$ (separate variance estimates were again used since homogeneity of variance assumptions were not met, $F = 14.32$, $p < .05$) and RM Maths Geometrical Reasoning scale, $t(44) = -3.33$, $p < .01$ (separate variance estimates were not used since homogeneity of variance assumptions were met, $F = 0.06$, $p = .81$). In all three situations, the cochlear implant group performed significantly below the hearing group. Inspection of the data indicated that the Group by Scale interaction was a result of the cochlear implant group performing below the hearing group to a greater extent on the WISC-IV Arithmetic Scale than on the RM Maths Arithmetic and Counting scale and RM Maths Geometrical Reasoning scale.

The second part of the hypothesis proposed that this interaction would be removed after controlling for vocabulary (an indicator of language ability). BPVS-II raw scores were therefore entered into an ANCOVA as the covariate. BPVS-II raw score emerged as a highly significant covariate, $F(1, 43) = 16.52$, $p < .001$. With vocabulary controlled for, there was no longer a main effect of Measure, $F(2, 86) = 0.64$, *ns*, suggesting that all three maths measures had some overlay with vocabulary knowledge. However, the Group by Measure interaction still reached significance, $F(2, 86) = 3.67$, $p < .05$. The main effect of group also just remained significant, $F(1, 43) = 4.08$, $p = .05$, indicating that the cochlear implant group performed significantly below the hearing group on mathematics measures even after controlling for differences between the groups on vocabulary ability.

To establish the nature of the significant interaction, separate ANCOVAs were run to test for differences between the groups on each of the measures with BPVS-II raw score entered as a covariate (once again, Bonferroni correction was applied). The first ANCOVA revealed that there was a significant difference between the groups on WISC-IV Arithmetic raw scores, $F(1, 43) = 6.49$, $p < .017$, in which the cochlear implant group performed significantly below the hearing group. Again, the BPVS-II score was a significant covariate, $F(1, 43) = 11.66$, $p < .001$. However, with vocabulary ability controlled for, there were no differences between the groups on RM Maths Arithmetic and Counting scale, $F(1, 43) = 0.97$, *ns*, or RM Maths Geometrical Reasoning scale, $F(1, 43) = 0.55$, *ns*. In both instances, BPVS-II score was a significant covariate, $F(1, 43) = 7.35$, $p < .017$ and $F(1, 43) = 17.53$, $p < .001$, respectively. Thus, when vocabulary ability was controlled for, the Group by Scale interaction was due to a significant difference between the groups on the WISC-IV Arithmetic subtest.

DISCUSSION

In this study, on tests of both arithmetic and counting and geometrical reasoning, deaf children were found to perform more poorly than their hearing peers, despite information being presented visually and with spoken support. This was also the case for mathematical problems presented aurally, with no visual cues (i.e., questions from the WISC-IV Arithmetic subtest). However, when language ability was controlled for, the difference between the groups only remained for the aurally presented WISC-IV Arithmetic subtest. These mental arithmetic problems are similar to those in the RM Arithmetic and Counting scale in terms of computations but are not supported by visual cues. This finding suggests it is the deficits in language skills experienced by many deaf children that underlie their poor math performance rather than difficulties with numerical operations per se. This is consistent with the findings of Edwards et al. (2011) in relation to analogical reasoning ability. Possible explanations for the findings and supporting literature are explored below.

Shared Cognitive Demands of the Tasks

The similarity of performance of deaf children with cochlear implants and hearing children, on both the RM Arithmetic and Counting scale and the RM Geometrical Reasoning scale may be explained by the shared cognitive demands of the two types of presentation (i.e., executive functions, problem-solving ability, and working memory).

Executive functions play an important role in multiplication by hearing children (e.g., Agostino, Johnson, & Pascual-Leone, 2010) and predict mathematics achievement (Clark, Pritchard, & Woodward, 2010). On neurocognitive tests, children with cochlear implants have been shown to have less efficient executive function mediated by language skill level (Figueras et al., 2008) and are dependent on the nature of the neurocognitive test used, that is, nonverbal or verbal (Remine, Care, & Brown, 2008). Problem-solving ability has been shown to underlie both literacy and arithmetic tasks and is strongly associated across these domains in hearing children (Farrington-Flint, Vanuxem-Cotterill, & Stiller, 2009). Working memory is central to mathematical operations (DeStefano & LeFevre, 2004) and has been shown to be a major predictor of academic attainment for hearing children (Alloway & Alloway, 2010).

Working memory impairments have been demonstrated in children with cochlear implants and both reduced digit span and poor sequential memory are consistent findings (Fagan, Pisoni, Horn, & Dillon, 2007; Pisoni & Cleary, 2003; Pisoni et al., 2008). The WISC-IV arithmetic subtest, on which the two groups in our study differed, places particular demands on working memory; the child is required to hold the details of the question in short-term memory and to "manipulate" it to arrive at an answer, without the aid of visual cues to support the retention of the information.

In adults, reduced auditory digit span (short-term memory span) has been shown to occur with similar working memory capacity for linguistic material where temporal order recall was not required, in deaf signers compared with hearing speakers (Boutla, Supalla, Newport, & Bavelier, 2004). Wilson and Emmorey (1997) provide evidence to support the idea of a visuospatial "phonological loop" in working memory for American Sign Language stimuli. However, there is currently no comparable research in deaf children with cochlear implants and therefore the implications for interpreting our findings could only be speculative.

Mode of Question Delivery

Ten of our cochlear implant group were using Sign Supported English. It is interesting to note that another more detailed study comparing deaf and hearing children on software for math education found that the deaf children took more time and made more mistakes (Adamo-Villani & Wilbur, 2010). It may be that the visual aspects of RM Maths placed the cochlear implant group at a disadvantage because it has been suggested that early deafness initiates a redistribution of visuospatial attention. There is evidence that deaf children are more attentive to irrelevant peripheral stimuli than hearing children, including fMRI evidence (Bavelier et al., 2000), which explains "weaker performance" compared to norms or hearing control groups (Mitchell & Maslin, 2007). Tightly focused attention optimizes efficient experimental task performance but inevitably disregards potentially useful information from the periphery in more ecological contexts. However, the evidence regarding the visual skills of deaf children is equivocal. Thorpe, Ashmead, and Rothpletz (2002) found no differences among prelingually deaf children with either cochlear implants or conventional hearing aids and a hearing group on visual attention tasks. A study of visual attention using briefly presented numbers demonstrated poorer visual attention skills for cochlear implant groups in a vigilance task (Yucel & Derim, 2008). However, the RM Maths visual stimuli are more interesting and engaging than number sequences alone, are displayed for extended periods of several seconds and are supported by auditory input. It is also true that in some respects deaf individuals have enhanced visual skills and this makes it very hard to determine how their different visual skills profile may have influenced their performance on RM Maths and definitive conclusions await further studies (Bavelier, Dye, & Hauser, 2006).

The Language Demands of the Tasks

The varying language demands of the different tasks also seem a very important factor in the findings. By including vocabulary as a covariate, it was shown that all tasks (even Geometrical Reasoning) were affected by language ability. Many early developing skills are acquired through incidental learning, that is learning through hearing and participating in conversations about number and number games. Gregory (1998) and Kritzer (2009) argue that some deaf children may lack access to these incidental learning opportunities, limiting their early exposure to numerical concepts. For the tasks with clearer language demands (e.g., RM Maths Counting and Arithmetic and WISC-IV Arithmetic), this is even easier to apply. It also appears likely that phonological representations are important in mathematical problem solving. In hearing children, phonological representations mediate arithmetic skill (Jordan, Wiley, & Mulhern, 2010) and it has been suggested that more distinct long-term phonological representations are related to more efficient arithmetic fact retrieval (De Smedt, Taylor, Archibald, & Ansari, 2010). Phonological representations and retrieval have also been implicated in dyslexic children's calculation difficulties (Boets & De Smedt, 2010).

Limitations of the Study

The study included a narrower age band (i.e., 7- to 12-year-olds) than some previous studies of children with cochlear implants (e.g., Motasaddi-Zarandy et al. (2009) and Thoetenhoofd (2006) included children aged between 7 to 16 years). However, this age range still presents some limitations to interpretation. Firstly, the development of mathematical skills between the ages of 7 and 12 years is large. Secondly, it clearly offers no information about the development of older children's mathematics development and skills. The study also only recruited first generation deaf children (that is, those born to hearing parents), which may limit generalizability of these results. We cannot exclude selection biases at recruitment, especially as teachers selected the hearing participants. Only one measure of language was used (BPVS-II) and it may be that phonological processing would have been a useful additional variable to investigate. Many variables relating to software construction were not explored in this study and could have affected our outcome. For example, animation reduces task completion time, regardless of sound or highlighting (Adamo-Villani & Wilbur, 2010). Other cognitive functions, such as executive skills, were also not recorded in this study and may have played a part. The study would have been strengthened by the inclusion of a matched group of deaf children without cochlear implants, for comparison with the cochlear implant group; although this is a difficult sample to recruit given that the majority of deaf children with severe-to-profound hearing losses now receive cochlear implants at a very young age.

Clinical Implications

The findings show that the cochlear implant group performed significantly below the hearing group on all measures of mathematical ability administered in the current study. Consequently, it seems that more needs to be done to help children with cochlear implants perform better in mathematics. One way of achieving this may be the further development and implementation of mathematical remediation programs that rely on visual cues rather than language. This has been successfully demonstrated in children with hearing loss (Nunes & Moreno, 2002). They have developed a successful intervention program for promoting deaf pupils' achievement in mathematics based on visuospatial representations, such as graphs and tables, rather than verbal-logical explanations.

Future Research

Much future research is required in this area. Replication of this study with inclusion of a general measure of intelligence is needed in the first instance to exclude general intelligence as a possible confounding variable. However, based on the findings so far, the clinical implications suggest that it may prove very useful to develop further remediation programs for improving the mathematical abilities of children with cochlear implants. In the literature, there is disagreement as to whether teaching should focus on presenting mathematics information in a visual-spatial format or whether to actually focus on building experience with mathematical word problems. There is evidence that hearing children employ imprecise representations of large numbers to support numerical operations (e.g., McCrink & Spelke, 2010) and it may be that these intuitive processes can be usefully harnessed and developed in children with cochlear implants. Further research in this area will help to clarify which of these teaching options proves most beneficial for supporting the development of the mathematical abilities of children with cochlear implants, or whether a combination of these approaches is most helpful. In addition, the emotional and support needs of children with cochlear implants could be more systematically addressed. For example, it has been suggested that mathematics anxiety detrimentally affects mathematical performance in hearing children with calculation difficulties (Rubinsten & Tannock, 2010) and this may have implications for cochlear-implanted children with previous histories of poor mathematical skills.

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