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The approximate number system and domain-general abilities as predictors of math ability in children with normal hearing and hearing loss

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Abstract

Many children with hearing loss (CHL) show a delay in mathematical achievement compared to children with normal hearing (CNH). This study examined whether there are differences in acuity of the Approximate Number System (ANS) between CHL and CNH, and whether ANS acuity is related to math achievement. Working memory (WM), short-term memory (STM), and inhibition were considered as mediators of any relationship between ANS acuity and math achievement. Seventy-five CHL were compared with 75 age and gender-matched CNH. ANS acuity, mathematical reasoning, WM, and STM of CHL were significantly poorer compared to CNH. Group differences in math ability were no longer significant when ANS acuity, WM, or STM were controlled. For CNH, WM and STM fully mediated the relationship of ANS acuity to math ability; for CHL, WM and STM only partially mediated this relationship. ANS acuity, WM, and STM are significant contributors to hearing status differences in math achievement, and to individual differences within the group of CHL.

Keywords

approximate number system; mathematics; hearing loss; deaf; working memory; short-term memory; inhibition

The numerical knowledge that young children have when they enter school has significant long term consequences on continued mathematical learning throughout school (Duncan et al., 2007; Geary, 2011; Jordan, Kaplan, Ramineni, & Louniak, 2009). Poor numeracy contributes to socioeconomic status in adulthood (Ritchie & Bates, 2013), and impacts long-term psychological well-being (see Gross, 2009, for a review). In seeking to understand why some individuals have poor numerical and mathematical skills it is important to examine core skills thought to be fundamental to their acquisition and continued development. The current study examines acuity of non-symbolic numerical representations, also known as the approximate number system (ANS), which is argued to be a central component of ‘number

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sense'. The study also considers the contribution of ANS acuity in predicting math achievement beyond domain-general abilities.

A particular focus of the current study is children with hearing loss (CHL). CHL show delays in abstract counting (counting without the support of concrete manipulatives), understanding of counting principles, and slower progress in standardised mathematic achievement tests that require more than just arithmetic (for a review see Gottardis, Nunes, & Lunt, 2011). Such delays have been ascribed to deficits in early experiences with quantitative concepts (Kritzer, 2009a, b; Nunes & Moreno, 2002), and sensory- and language-based differences in the ways that CHL and CNH process information (Marschark, Spencer, Adams, & Sapere, 2011). Whether or not CHL have a deficit in the ANS has not been considered in detail in previous studies. Furthermore, deficits in the ANS may be associated with other cognitive abilities involved in math and that have been demonstrated to differ in CHL and children with normal hearing (CNH), e.g., inhibition and memory.

ANS and Math Achievement in CNH and CHL

The ANS provides approximate abstract representations of number that enable us to make estimations of quantity and compare sets of objects for numerosity, either before we are able to count or make use of symbols or for quantities that are too large or appear too quickly to count. The accuracy of quantity discriminations is restricted by the ratio difference of the quantities being compared. For example, a comparison of 27 to 30 items (ratio of 0.9) is more difficult than a comparison of 12 to 15 items (ratio of 0.8) despite the absolute difference between them both being 3. Therefore, the closer the ratio is to 1, the more difficult the magnitude discrimination will be.

Acuity of the ANS improves throughout development; 6 month old infants can discriminate visual and auditory arrays at a ratio of 1:2 (e.g., Lipton & Spelke, 2003; Xu, Spelke, & Goddard, 2005), and by 9 months old are able to discriminate at a ratio of 2:3 (Libertus & Brannon, 2010; Wood & Spelke, 2005). Halberda and Feigenson (2008) reported discrimination limits of approximately 3:4 at age 3, 4:5 at age 4, 5:6 at age 5 to 6, and 10:11 in adults. The source of refinement of ANS acuity is widely debated, with possibilities including maturation of supporting neural structures, incidental learning opportunities, and the corresponding development of other domain-general skills that may influence math and ANS task performance (Halberda & Feigenson, 2008). Other studies suggest that differences in formal mathematics education may lead to individual differences in the refinement of the ANS (Guillaume, Nys, Mussolin, & Content, 2013; Lindskog, Winman, & Juslin, 2014; Nys et al., 2013; Piazza, Pica, Izard, Spelke & Dehaene, 2013).

In a seminal study, Halberda, Mazzocco, and Feigenson (2008) revealed a retrospective relationship between ANS acuity (measured at age 14 years) and math achievement (measured annually from the ages of 5 to 11). Subsequently, a number of studies have shown the ANS to play an important role in children's mathematical learning (e.g., Desoete, Ceulemans, De Weerdt, & Pieters, 2012; Gilmore, McCarthy, & Spelke, 2010; Inglis, Attridge, Batchelor, & Gilmore, 2011; Keller & Libertus, 2015; Libertus, Feigenson, & Halberda, 2011; Mazzocco, Feigenson, & Halberda, 2011a), and have revealed that the ANS acuity of individuals with mathematical difficulties and dyscalculia is significantly poorer than their typically achieving peers (e.g., Mazzocco, Feigenson, & Halberda, 2011b; Meijas, Gregoire, & Noel, 2012; Mussolin, Meijas, & Noel, 2010; Piazza et al., 2010). However, there are some contradictory findings (see Chen & Li, 2014 for a meta-analysis), and no robust modifier has been found to account for these differences (De Smedt, Noel, Gilmore, & Ansari, 2013).

Whilst CHL show a range of mathematical difficulties (as discussed earlier), it has been found that in tasks which require minimal counting, and where visual support is given, CHL perform as well as CNH (Zafarty, Nunes, & Bryant, 2004). From this it was concluded that delays in math achievement for CHL cannot be explained by difficulties in their early representation of number. Supporting this conclusion, Arfe et al. (2011) found that pre-schoolers with HL outperformed CNH in the comparison of non-symbolic displays, and performed as well as CNH in the comparison of Arabic digits. However, the non-symbolic task only included displays of 1–9 items; small numbers (1–4) are represented distinctly from large numbers because they fall within the limits of the brain to individuate and track simultaneously - therefore small numbers do not appear to be represented as approximate numerical magnitudes (see Hyde, 2011, for a review). Furthermore, no information was provided about the length of stimulus presentation, meaning that one cannot rule out the possibility that children had sufficient time to count the displays prior to making a magnitude decision. Finally, no measure of math ability was collected.

ANS and Domain-General Abilities

Recent evidence suggests that domain-general skills play a role in performance on ANS tasks and may account for the relationship between ANS acuity and math achievement. For example, to perform accurately in a non-symbolic numerical discrimination task it is necessary to ignore visual cues that may be confounded with numerosity, such as surface area. Fuhs and McNeil (2013) and Gilmore et al (2013) reported that whilst math ability is related to performance on tasks measuring the ANS, this relationship is no longer significant after controlling for inhibitory skills (although for contradictory evidence see Keller & Libertus, 2015).

There is more limited information on how the ANS may interact with STM or WM in the representation and processing of non-symbolic quantities. Xenidou-Dervou, De Smedt, van der Schoot, and van Lieshout (2013) found that WM was correlated with both non-symbolic and symbolic approximation, and that individual differences in WM predicted math achievement beyond the effect of approximation skills. However, they also found that symbolic approximation skill (which mediated the direct effect of non-symbolic approximation on math ability) correlated with math ability beyond the effect of WM capacity, suggesting unique contributions from both domain-specific and domain-general abilities. Other broad domain-general skills have been considered such as IQ, verbal skills, and executive control. Many studies find that even after controlling for domain-general skills, ANS acuity remains as a significant unique predictor of math achievement (Bonny & Lourenco, 2013; Halberda et al., 2008; Libertus, Feigenson, & Halberda, 2011; 2013; Lourenco, Bonny, Fernadez, & Rao, 2012; van Marle, Chu, Li, & Geary, 2014).

Consideration of the role played by domain-general factors is particularly important, because CHL are often found to perform more poorly on certain cognitive measures, and this may account for the differences between hearing status groups in math ability. There are widely reported difficulties in verbal STM and WM for individuals with HL, particularly when retention of sequential or temporal information is required (see Hamilton, 2011 for a review). For example, growth of forward and backward digit span in children with severe to profound HL is similar to that of CNH, but consistently lower at all age points (Harris, Kronenberger, Gao, Hoen, Miyamoto, & Pisoni, 2013; Harris, Pisoni, Kronenberger, Gao, Caffrey, & Miyamoto, 2011).

CHL are also reported to have some inhibitory difficulties, particularly in the allocation of selective visual attention. Dye and Hauser (2014) had CHL complete a continuous performance task (CPT) to measure sustained attention, and the same task but with flanking digits to measure selective attention. Compared to CNH, CHL showed no difference on the sustained attention task. The flanking digits in the selective attention task significantly disrupted the performance of younger CHL (6–8 years), although this disruption was reduced in older CHL (9–13 years). One explanation put forward for this poorer selective attention is that in the absence of hearing, visual attention is an appropriate adaptation to alerting to events in the environment, resulting in a redistribution of attention away from the centre to peripheral vision (see Dye & Bavelier, 2010 for a review). Dye and Hauser (2014) argue that older children can inhibit this heightened attention to the periphery when the task requires attention to the central visual field, whilst younger CHL cannot. Hence, young CHL are more likely to show distraction from irrelevant visual information.

The current study examines acuity of the ANS in CHL and CNH, and the strength of the relationship between the ANS and math achievement. Furthermore, to examine whether differences between CHL and CNH, and whether relationships of ANS acuity to math within each group, are mediated by a third factor, we include domain-general measures assessing inhibition, STM, and WM.

Method

Participants

Seventy-five CHL (42 females) with a mean age of 9 years (SD = 1 year, 9 months, range = 5 years, 1 months to 12 years, 7 months) participated in the study. CHL were recruited from mainstream schools and schools for the deaf in the UK and US. Seventy-five hearing age- and gender-matched controls were also recruited, where possible from the same schools as CHL or from schools within the surrounding area (see Table 1 for further information regarding the samples). Consent was gained from all parents prior to commencement of the study. None of the CNH had any known developmental or learning difficulty, and none of the CHL had any other diagnosed developmental difficulties.

As children were recruited from the USA and UK and differences in performance may have been influenced by differences in schooling, we initially examined whether performance on the outcome variables differed by child nationality. No differences were found on any of the measures (see Supporting Information Table S1). We also conducted a moderated multiple regression to determine whether the strength of the relationship between ANS acuity and math outcomes differed across countries. Overall, the interaction term (ANS acuity×nationality) did not add significantly to the prediction of math outcomes, suggesting that the prediction of ANS acuity to math is not moderated by nationality (see Supporting Information). We therefore proceeded to analyse the results collapsed across nationality.

Within the group of CHL, we also considered whether specific factors associated with hearing loss accounted for individual differences in performance. These factors included school type, child preferred communication, level of hearing loss, having a deaf parent, use of hearing aids vs cochlear implants, age of HL diagnosis and age of HL intervention. No significant predictors of individual differences were found (all descriptive data and statistical analyses are reported in the Supporting Information). It is possible that we have insufficient power to detect effects – for the largest effect found (level of hearing loss on digit span), the observed power is .54, and power analysis indicates that a sample size of 90 would be needed to detect this effect at power equal to .80. However, previous findings relating such factors to academic achievement in individuals with HL have also been inconclusive (see Powers, 2011 for a review), possibly due to the great heterogeneity within the HL population (Convertino, Marschark, Sapere, Sarchet, & Zupan, 2009), and the difficulty of obtaining large samples of individuals with HL.

Tasks and Procedure

All children were tested in a quiet area of the school in their preferred mode of communication (sign, speech, or both).

ANS acuity: Non-symbolic discrimination—All materials were produced using Superlab 4.0 (Cedrus San Pedro, CA). Each trial consisted of the presentation of two arrays of dots (each in a different colour). The number of dots in each array varied from 5 to 35, with each pair of arrays depicting a ratio difference of 0.91 (e.g., 10:11), 0.83 (e.g., 5:6), 0.77 (e.g., 7:9), 0.71 (e.g., 5:7), or 0.67 (e.g., 6:9). At each ratio level absolute difference between the stimulus pairings differed, but the ratio remained constant, e.g., at ratio 0.67, stimulus pairings were 6:9, 10:15, 12:18, 18:27, and 20:30. Five pairs at each level were presented four times throughout the task, the higher number appearing equally often on the left and right hand side of the screen, resulting in a total of 100 trials (20 at each ratio difference). Each stimulus pair was matched in terms of cumulative surface area of the dots. The size of individual dots was varied to ensure that items in the less numerous array were not always larger than those in the more numerous array. This ensures that individual dot size is not a predictable indicator of numerosity, although it does not preclude that other visual cues impact on numerosity comparison. Both arrays appeared simultaneously for 2000ms, after which a screen appeared showing two question marks in place of the arrays. Children were asked to indicate which array contained the most coins by pressing the corresponding left or right button on a response box. Children received visual feedback regarding their accuracy after each trial, and after every 20 trials a motivational feedback screen was presented indicating that enough coins had been collected to build part of the ‘captain’s boat’. Accuracy was used as the dependent measure as weber estimates can be difficult to calculate for children whose performance is close to chance (Inglis & Gilmore, 2014). The correlation between weber and accuracy was high ($r = -.82$, $p < .001$) and the overall pattern of results was the same using either accuracy or weber.

Standardised mathematics achievement (Wechsler Individual Achievement Test, WIAT-II, Wechsler, 2005)—Numerical Operations measures skills in identifying and writing numbers, rote counting, number production, and solving written calculation problems and simple equations that require children to use the basic operations of addition, subtraction, multiplication and division. Mathematical Reasoning is a verbal problem solving test that measures the ability to count, identify geometric shapes, and solve single and multi-step word problems. The child is required to solve problems with whole numbers, fractions or decimals, interpret graphs, identify mathematical patterns, and solve problems of statistics and probability (dependent on age and task progression).

Domain-general abilities

Inhibition: In the Flanker task (modified from Fan, McCandliss, Sommer, Raz, & Posner, 2002), children were presented with a row of five fish facing either left or right with the target fish in the center of the computer screen. A fixation cross was presented for 2000ms followed by the target fish flanked on either side by two fish facing the same or the opposite direction (congruent or incongruent conditions respectively). In each trial, children were asked to indicate, by key press, the direction the target fish was facing. A blank screen was then presented for 500ms before the next trial began. The first block consisted of 20 congruent trials, then 20 incongruent trials, and then a final block of 20 congruent trials. This final block was added to take account of any change in response time (due to practice or fatigue) during the task. For each block of trials accuracy and median RT (to correct responses only) were recorded. For purposes of analysis, a Flanker effect was calculated as {median RT incongruent block − ([median RT congruent blocks 1 + median RT congruent block 2]/2)}.

Verbal WM: In the counting recall task, the child counted the number of red circles on the screen out loud/signed and then attempted to recall in sequence the number counted on each card. The child received practice trials of 1, 2, and 3 arrays, and the test began with a block of 1 array and increased to a block of 7 arrays. Each block consisted of 6 trials (resulting in a maximum of 42 trials), and the child must achieve 4 correct trials within a block to move on to the next span level. The total number of trials recalled correctly was used as the dependent variable.

Verbal STM: In the digit recall task, children saw a sequence of between 1 and 9 digits presented sequentially on the computer screen (digits 1 to 9 presented in Tahoma font size 72). Each digit was presented for one second, and when prompted the child was required to recall (verbally or by signing) the digits in the same order as they had been presented. The child received practice trials of 1, 2, and 3 digits (depending on age), and test trials began with a block of 1 digit to recall and increased up to 9 digits to recall. Each block consisted of 6 trials (resulting in a maximum of 54 trials). The child must achieve at least 4 correct trials within a block to move to the next span level. The total number of trials recalled correctly was used as the dependent variable.

Results

Descriptive data for all measures is shown in Table 2. CHL achieved significantly lower raw scores than CNH on the Mathematical Reasoning, but not the Numerical Operations test. CHL also showed significantly poorer performance on the WM and STM tasks. On the inhibition task, CHL showed a larger Flanker effect, indicating that they showed more slowing when dealing with incongruent flanking information; however, the difference to CNH was not significant. The difference between CHL and CNH on Mathematical Reasoning remained significant after controlling for inhibition, $F(1, 145) = 5.81$, $p = .017$, $\eta_p^2 = .039$. However, controlling for either WM or STM rendered the difference between CNH and CHL in Mathematical Reasoning non-significant ($F(1, 146) = 1.95$, $p = .165$, $\eta_p^2 = .013$, and $F(1, 147) < 1$ after controlling for WM and STM respectively).

Initial analysis of the ANS task considered the change in performance associated with age for each hearing status group (see Figure 1). Increasing age was significantly related to increased accuracy on the ANS task (*r's* = .53 and .58, *p*'s < .001 for CHL and CNH respectively). Figure 1 indicates that whilst the increase in accuracy with age is similar in both groups, CHL children show consistently lower performance across the age range.

Accuracy data from the ANS task were entered into a 5 (difficulty level: 0.91, 0.83, 0.77, 0.71, 0.67) × 2 (hearing status) mixed design analysis of variance (ANOVA). This revealed significant main effects of difficulty level, $F(4, 592) = 379.44$, $p < .001$, $\eta_p^2 = .72$, and hearing status, $F(1, 148) = 10.74$, $p = .001$, $\eta_p^2 = .07$, but no significant interaction, $F(4, 592) = 1.55$, $p = .19$. Controlling for ANS acuity rendered the group difference in Mathematical Reasoning non-significant, $F(1, 147) = 1.27$, $p = .26$, $\eta_p^2 = .01$.

Relationship Between ANS Acuity, Math Achievement, and Domain-General Abilities

A partial correlation analysis (controlling for age) showed that for both CHL and CNH, better ANS acuity was correlated with higher scores on the Numerical Operations and Mathematical Reasoning tasks, although for CNH only the relation of ANS to Mathematical Reasoning was significant. The strength of the relationship between ANS and performance on the Numerical Operations task was significantly higher for CHL compared to CNH ($Z = 2.29$, $p = .02$), although there was no difference for Mathematical Reasoning ($Z = 1.48$, $p = .14$). With regard to domain-general abilities, WM and STM correlated significantly with Numerical Operations, Mathematical Reasoning and ANS acuity in CNH. For CHL, WM, STM, and inhibition were all correlated with higher ANS acuity and higher scores on Mathematical Reasoning, although only WM and STM were related to higher scores on the Numerical Operations task (see Table 3).

The next analyses considered whether the relationship between ANS acuity and math achievement is mediated by domain-general abilities. Mediation analysis was conducted with ANS acuity as the predictor variable, WM, STM, or inhibition as the mediator variable, and Mathematical Reasoning or Numerical Operations as the dependent variable. Age was included as a covariate. We followed the bootstrapping method (with 1000 iterations) advocated by Preacher, Rucker and Hayes (2007), which tests the null hypothesis that the indirect path from the independent variable to the dependent variable via the mediator does not significantly differ from zero. If zero is not contained within the confidence intervals (CI) computed by the bootstrapping procedure, one can conclude that the indirect effect is significantly different from zero.

Mediation analyses were only conducted for variables where ANS acuity, the math outcome measure, and domain-general skill were significantly correlated with each other (see Table 4). For CHL, analysis with WM as the mediator revealed a significant direct effect of ANS acuity on Mathematical Reasoning, along with a significant indirect effect via WM. WM accounted for 16% of the total effect. A similar pattern of results was found for STM; there was a significant direct effect of ANS acuity on Mathematical Reasoning, along with a significant indirect effect via STM. STM accounted for 20% of the total effect. The indirect effect of ANS acuity on Mathematical Reasoning via inhibition was not significant. With Numerical Operations as the outcome variable, there was no significant indirect effect via WM; only the direct effect from ANS acuity to Numerical Operations was significant. Therefore, WM appears to be a partial mediator of the relationship between ANS acuity and mathematical ability in CHL, but this is dependent on the type of math skill being assessed. With STM as the mediator, there was a significant direct effect of ANS acuity on Numerical Operations, and a significant indirect effect via STM. STM accounted for 21% of the total effect. Therefore, STM appears to be a partial mediator the relationship between ANS acuity and both measures of math ability.

Similar mediation was conducted for CNH using WM or STM as the mediator variable. In both cases the direct effect of ANS acuity on Mathematical Reasoning was non-significant. The indirect effects were significant, with WM accounting for 31% of the total effect, and STM accounting for 39% of the total effect.

Discussion

Previous studies have reported that poorer math skills of CHL were not the result of delays in the representation of numerical information (e.g., Arfe et al., 2011). However, as highlighted earlier, a number of methodological issues (e.g., the use of subitizable numerosities, and uncertainty regarding whether counting could have occurred) make these findings inconclusive. Using a method more likely to detect subtle individual differences in acuity of the ANS, in the current study we find that CHL have poorer numerical discrimination skills compared to CNH. The lack of interaction between difficulty level and hearing status suggests that CHL are showing the usual signature ratio discrimination limits but that this is delayed in its development. CHL also showed significantly lower performance on the Mathematical Reasoning task. Controlling for group differences in ANS acuity rendered the difference between CHL and CNH in Mathematical Reasoning non-significant. These results support the conclusion that CHL have less acuity in the ANS compared to CNH, and that this contributes to lower performance in mathematics.

With regard to domain-general skills, there was no difference between CHL and CNH on the inhibition task. CHL did show significantly poorer performance than CNH on the counting recall and digit recall tasks, replicating previous findings showing poorer performance on serial recall STM and WM tasks (Harris et al., 2011; Harris et al., 2013). Controlling for group differences in either STM or WM rendered the difference between CHL and CNH in Mathematical Reasoning non-significant. In summary, poorer domain general skills (STM and WM) and poorer ANS acuity may both account for lower math performance of CHL compared to CNH.

To some extent, we replicate previous findings showing that better ANS acuity is associated with better mathematical skills. For both CHL and CNH, higher ANS acuity was correlated with better performance on both the Numerical Operations and Mathematical Reasoning subtests, although for CNH only the latter relationship was found to be significant. There is ongoing debate within the literature about the relationship between ANS acuity and mathematical ability as findings have been inconsistent. This relationship has been replicated in some studies (e.g., Gilmore et al., 2010; Inglis et al., 2011; Libertus et al., 2011; Mazzocco et al., 2011a; Meijas, Mussolin, Rouselle, Gregoire, & Noel, 2012; Mussolin et al., 2010; Piazza et al., 2010), but not others (De Smedt & Gilmore, 2011; Gobel, Watson, Lervag, & Hulme, 2014; Holloway & Ansari, 2009; Iuculano, Tang, Hall, & Butterworth, 2008; Landerl & Kolle, 2009; Mundy & Gilmore, 2009; Rouselle & Noel, 2007; Sasanguie, Gobel, Moll, Smets, & Reynvoet, 2013). Differences in the findings might be explained by methodological characteristics, e.g., the use of stimulus displays within a subitizable range or the collapse of results across subitizable and non-subitizable ranges, the presentation of easily discriminable ratio differences which would not have detected subtle differences in ANS acuity, differences in the paradigms to assess ANS acuity, differences in the math outcomes being measured, differences in the age groups tested, or differences in the inclusion of other predictor variables in the analytical model (see Schneider et al, 2016 for a recent meta-analysis).

Some of these factors are addressed in the current study. Firstly, it is possible that the relationship of ANS acuity to math ability is most likely to be observed when studying groups with poorer mathematical skills (Bonny & Lourenco, 2013). We find this here in the comparison of CHL and CNH, where the strength of the relationship between ANS acuity and math achievement is higher in CHL who are lower achieving in mathematical ability. Secondly, the mediation analysis showed that both STM and WM fully mediate the direct effect of ANS on Mathematical Reasoning in CNH. This supports the idea that whilst there may be a significant bivariate correlation between ANS acuity and math ability in CNH, this is rendered non-significant when other explanatory variables are considered in the analysis (Lyons, Price, Vaessen, Blomert, & Ansari, 2014). However, this same pattern of results does not hold up for children (CHL) who have compromised STM/WM skills, and where non-symbolic numerical representations still appear to play an important and direct role in supporting mathematical skills. Clearly, further research is needed to examine the relative contribution of ANS versus domain-general skills to math ability in children of different ages, and with different levels of both math and domain-general abilities.

There are a number of mechanisms by which STM and WM might mediate the relationship between ANS acuity and math ability. Gullick, Sprute, and Temple (2011) demonstrated that during non-symbolic and symbolic comparison tasks, brain activity differences related to WM are seen across individuals, and Kolkman, Hoijtink, Kroesbergen, and Leseman (2013) argue that even very simple tasks, like magnitude comparison, impose a memory load as they require simultaneous and sequential processes of perceiving, coding, interpreting, and comparing information. Therefore, one explanation of the significant mediation is that good memory skills are required to successfully complete the ANS task and for general math ability.

Another mechanism may be the accuracy with which the ANS is mapped on to symbolic numbers. Mazzocco et al. (2011b) suggested that the relationship between ANS acuity and computational skills may be mediated by the mapping of the ANS and the verbal number system, e.g., the ease and precision of accessing quantity representations from abstract symbols. Furthermore, they argue that domain-general skills like WM may mediate this mapping precision, since WM is responsible for storing, processing, retrieving, and combining information to yield meaningful quantitative representations (see also Hornung, Schiltz, Brunner, & Martin, 2014; Lyons & Beilock, 2011; Xenidou-Dervou et al., 2013). Similarly, Kolkman, Kroesbergen, and Leseman (2014) found that WM predicted the development of number-magnitude skills. They argued that while number-magnitude skills may arise from an innate system dedicated to process numerical information, WM might be needed to construct the connections between numbers and magnitudes.

Finally, it is possible that domain-specific elements of the domain-general tasks are important. The counting span task requires symbolic quantitative knowledge and counting skill, and these skills may mediate the relationship of ANS acuity and math ability. Van Marle et al. (2014) found a significant relationship between ANS acuity and math achievement, but children's knowledge of number words (measured by counting tasks) fully mediated this relationship. Other studies have similarly found that the relationship between non-verbal number sense and math achievement is completely mediated by symbolic number skills (Bartelet, Vaessen, Blomert, & Ansari, 2014; Hornung et al., 2014). Our finding that digit recall (which does not require counting) also acts as a full or partial mediator suggests that the mediation of the relationship between ANS and math ability is not just something to do with counting, but we still cannot rule out the possibility that domain-specific processing of numerical information, rather than memory (ST or WM) is the mediating mechanism.

With regard to inhibition, for CHL inhibition was correlated with Mathematical Reasoning and ANS acuity. In line with the findings of Keller and Libertus (2015), inhibition was not significantly correlated with math ability or ANS acuity in CNH, and inhibition did not significantly mediate the direct relationship of ANS acuity to Mathematical Reasoning in CHL. Whilst it is not possible to perfectly control for non-numerical parameters such as dot size, density, and total area (Gebuis & Reynvoet, 2012), we deliberately constructed stimuli in the ANS task such that cumulative surface area of the dots in the two arrays are equated regardless of number. Moreover, individual dot size was varied so that it could not be used as a reliable predictor of numerosity (i.e., stimuli in the more numerous array were not of a constant smaller size; rather they were a combination of smaller and larger dots). Therefore, we attempted to create a stimulus set where performance would be negatively affected if a visual cue other than numerosity were considered (see Smets, Sasanguie, Szucs, & Reynvoet, 2015 for a detailed discussion of how ANS stimuli construction may influence performance). However, other visual cues, such as *average* dot diameter, are a congruent cue in our stimulus set – increased numerosity is always associated with lower *average* dot diameter. Therefore, we cannot rule out the possibility that the predictability of this visual cue limited to need to inhibit completely incongruous or unpredictable cues to numerosity. Hence, inhibitory skill might not be so important for accurate performance in our ANS task. This is in contrast to some previous studies where stimuli are constructed so that number and area are correlated or anti-correlated to specifically examine for a bias to respond to stimulus parameters other than numerosity (Fuhs & McNeil, 2013; Gilmore et al., 2013) and where inhibition may be necessary to inhibit a consistent but inaccurate cue to numerosity (in anti-correlated conditions). However, the inconsistency in findings across studies highlight that the method by which stimuli for ANS tasks are constructed may impact on overall accuracy and subsequently the relationship of ANS to math ability and domain-general measures, and represents a methodological confound when comparing across studies in the field (Dietrich, Huber, & Nuerk, 2015; Smet et al., 2015).

There is clearly something about having HL that puts children at risk of having poorer ANS acuity. Studies examining representation and retrieval of basic numerical information in adults with HL suggest that whilst numerical information might be represented in a similar manner in NH and HL adults (as shown by SNARC, distance, and size effects), the efficiency with which individuals with HL process that basic numerical information is poorer (Bull, Marschark, & Blatto-Vallee, 2005), and the accuracy with which that information is represented (as shown in a number-line task) is less precise (Bull, Marschark, Sapere, Davidson, Murphy, & Nordmann, 2011). More recently, Convertino, Borgna, Marschark, and Durkin (2014) reported that college students with HL were significantly less accurate in magnitude estimation (weight, size, quantity, or length) of real-world things (e.g., height of a basketball hoop) and things directly in front of them at laboratory stations (e.g., the number of marbles that would fit in a displayed shoe box). Furthermore, for students with cochlear implants, college entrance scores in mathematics were significantly related to performance on the estimation tasks. This suggests that individuals with HL may continue to have difficulties in a range of quantitative estimation tasks, and that for some individuals with HL, this may relate to mathematics achievement.

In looking for the source of this risk, we consider Bahrick and Lickliter’s (2012) intersensory redundancy hypothesis, which argues that information simultaneously available in temporal and spatial synchrony across two or more modalities is highly salient and may be attended to, learned, and remembered better than the same information presented to only one modality or presented to two modalities in a temporally and spatially asynchronous fashion. Multisensory information has been found to facilitate early numerical learning; the presentation of redundant, synchronous visual and auditory information about number resulted in infants making highly precise numerical discriminations at an earlier age (Jordan, Suanda, & Brannon, 2008). Jordan and Baker (2011) similarly revealed that preschool children showed more sensitive numerical discrimination ability if given numerical information in in auditory and visual synchronised displays.

Many CHL lack intersensory redundant information about numerosity from the moment they are born, and as such, may not develop (or will develop at a slower rate) as precise a representation of number as CNH. Gregory, Bishop, and Sheldon (1995) documented that there is a lack of simultaneous visual and auditory information in the interactions between CHL and their parents. For example, whilst parents of hearing children count or label their actions as they carry them out (e.g., counting steps as they climb the stairs), parents of [some] CHL cannot do so. This lack of simultaneous visual and auditory information may subsequently interfere with CHL's informal math experience and learning (Gregory, 1998) and may result in a lack of intersensory redundant information that is important for the fine tuning of the ANS and subsequently mathematical ability. We cannot rule out the reverse explanation that differences in math ability between CNH and CHL account for differences in the refinement of ANS acuity, but the finding that there are differences in ANS acuity between CNH and CHL (and individual variability within each group) even at a young age before there has been much exposure to formal education, suggests that this is not the fundamental explanation for differences in ANS acuity.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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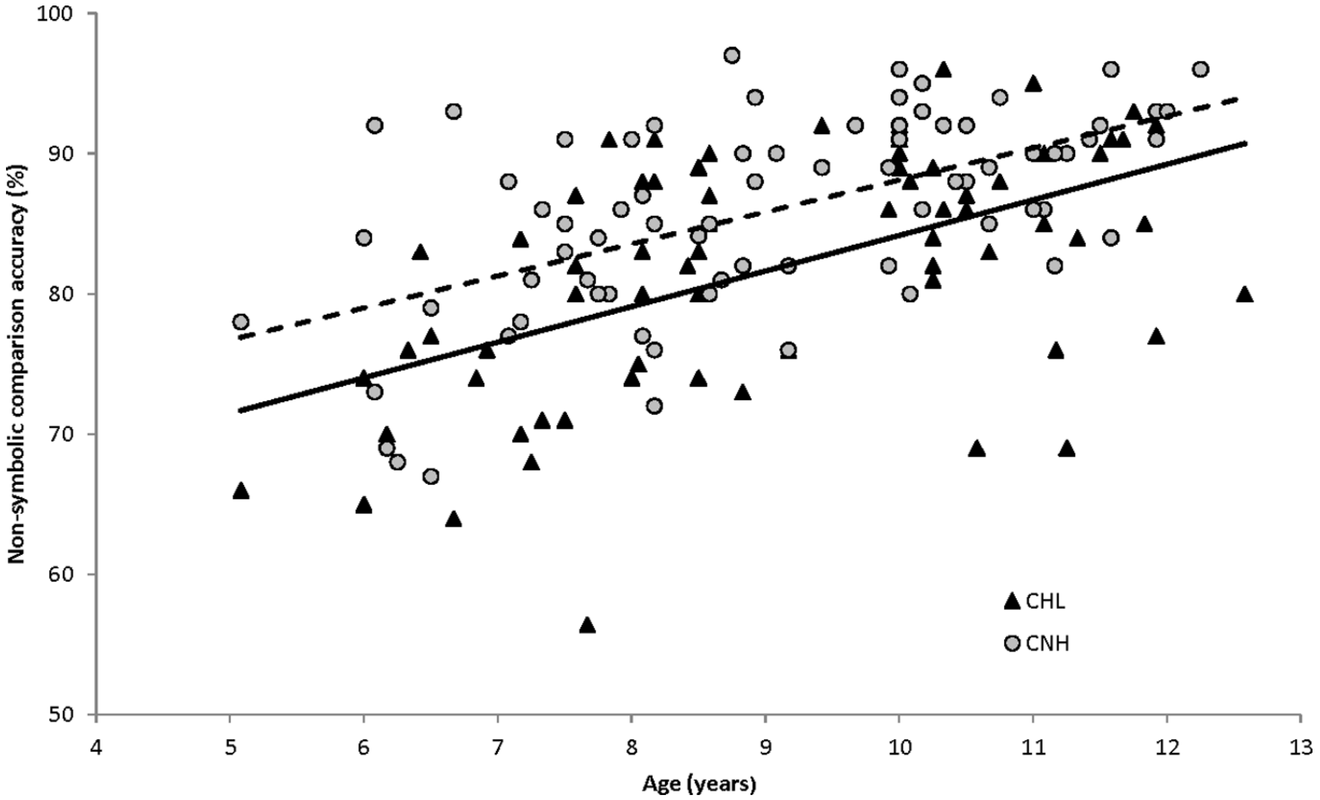

Figure 1.

Acuity of the approximate number system (% accuracy) for CHL and CNH across the age range.

Table 1

Descriptive Information for CHL and CNH Samples.

	CHL	CNH
Level of hearing loss		
Mild to Moderate	19 (25.3%)	
Severe	8 (10.7%)	
Profound	33 (44%)	
Missing	15 (20%)	
Hearing devices		
Hearing aid	46 (61.3%)	
Cochlear implant	24 (32%)	
No device reported	5 (6.7%)	
Communication preference		
Signed language	19 (25.3%)	
Spoken language	33 (44%)	
Sign/spoken language mix	20 (26.67%)	
Missing	3 (4%)	
SES classification[1]		
High	38 (50.75%)	45 (60%)
Medium	11 (14.75%)	18 (24%)
Low	16 (21.3%)	5 (6.7%)
Missing	10 (13.3%)	7 (8.3%)
Parental education		
Secondary school or lower	6 (8%)	10 (13.3%)
High School	18 (24%)	18 (24%)
Undergraduate	23 (30.7%)	20 (26.7%)
Postgraduate	19 (25.3%)	21 (28%)
Missing	9 (12%)	6 (8%)

[1] Based on parental reports of household income and occupation (using the National Statistic Socio-Economic Classifications, NS-SEC)

Table 2

Descriptive Data (means, SD) and Comparison of Group Differences.

	CNH	**CHL**	***t***	***p***	**d**
ANS accuracy (% correct)	85.86 (6.97)	81.71 (8.48)	3.27	= .001	.52
Numerical Operations	18.64 (7.27)	17.33 (6.87)	1.13	= .260	.19
Mathematical Reasoning	36.68 (11.45)	31.43 (10.05)	2.99	= .003	.49
Inhibition (Flanker Effect)	350.95 (362.54)^{74}	515.62 (691.70)^{74}	1.81	= .072	.30
Verbal WM (Count recall)	19.82 (6.35)	17.26 (5.53)^{72}	2.61	= .010	.43
Verbal STM (digit recall)	21.74 (5.15)	26.09 (6.49)	4.54	< .001	.74

Note: Where N is not equal to 75, the sample size is indicated in superscript.

Table 3

Partial Correlations (Controlling for Age) Between Domain-Specific and Domain-General Measures (CHL = Below Diagonal, CNH = Above Diagonal).

	1	2	3	4	5	6
1. Numerical Operations	--	$.66^{***}$	.21	.05	$.44^{***}$	$.34^{**}$
2. Mathematical Reasoning	$.46^{***}$	--	$.28^{*}$	−.09	$.34^{**}$	$.45^{***}$
3. ANS accuracy	$.53^{***}$	$.49^{***}$	--	.13	$.30^{*}$	$.26^{*}$
4. Inhibition	−.18	$-.31^{**}$	$-.39^{**}$	--	.07	−.02
5. Verbal WM	$.24^{*}$	$.41^{***}$	$.33^{**}$	−.21	--	$.37^{**}$
6. Verbal STM	$.50^{***}$	$.44^{***}$	$.31^{**}$	$-.23^{*}$	$.40^{***}$	--

* $p < .05$,

** $p < .01$,

*** $p < .001$.

Table 4

Mediation Analyses Examining Domain-General Factors as a Mediator of the Relationship Between ANS Acuity and Math Outcomes.

		beta	**p**	**CI**	**Percent mediation (P_M)**
Outcome: Mathematical Reasoning CHL					
Mediator: WM	Total effect	.43	.00	.27, .59	
	Direct Effect	.36	.00	.19, .53	
	Indirect Effect	.07		.01, .18	.16
Mediator: STM	Total effect	.40	.00	.23, .57	
	Direct Effect	.32	.00	.15, .49	
	Indirect Effect	.08		.03, .16	.20
Mediator: Inhibition	Total effect	.41	.00	.24, .58	
	Direct Effect	.36	.00	.18, .55	
	Indirect Effect	.05		−.01, .02	.11
Outcome: Numerical Operations CHL					
Mediator: WM	Total effect	.31	.00	.19, .43	
	Direct Effect	.30	.00	.17, .43	
	Indirect Effect	.01		−.01, .06	.05
Mediator: STM	Total effect	.31	.00	.20, .43	
	Direct Effect	.24	.00	.13, .36	
	Indirect Effect	.07		.02, .14	.21
Outcome: Mathematical Reasoning CNH					
Mediator: WM	Total effect	.29	.02	.05, .53	
	Direct Effect	.20	.10	−.04, .44	
	Indirect Effect	.09		.02, .21	.31
Mediator: STM	Total effect	.29	.02	.05, .53	
	Direct Effect	.18	.12	−.05, .40	
	Indirect Effect	.11		.02, .26	.39