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Examining the Development and Functional Role of Spatial-Numerical Representations

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An abstract of

A thesis submitted to the Faculty of the James T. Laney School of Graduate Studies of Emory University in partial fulfillment of the requirements for the degree of Master of Arts in Psychology, 2017

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Abstract

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Spatial-numerical associations (SNAs) have been documented across development and species. Yet the functional significance of such ubiquitous associations remains unclear. To test the prominent hypothesis that SNAs are related to mathematical proficiency, we examined the relation between SNAs and math proficiency in 5- to 8-year-old children. We found evidence of SNAs with two paradigms, a magnitude comparison task and the place-the-number task, a novel paradigm for examining SNAs with minimal task demands, with a significant correlation between the two, suggesting they measure a stable SNA (e.g., left-to-right oriented mental number line). Although there were no correlations between children's SNAs on the place-the-number task and any measure of math ability, children's SNAs on the magnitude comparison task were negatively correlated with their performance on a measure of cross-modal arithmetic, suggesting that children with stronger SNAs were less competent at cross-modal arithmetic, an effect that held when controlling for age and general cognitive abilities. Despite some evidence for a negative relation between SNAs and math ability in adulthood, we argue that the effect here may reflect task demands specific to the magnitude comparison task and not an impediment of the mental number line. Moreover, we suggest that differences in task demands could account for contradictory findings in the literature. We conclude with a discussion of the multi-faceted nature of the mental number line and how these different features may relate to mathematical ability.

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Examining the Development and Functional Role of Spatial-Numerical Associations

Interest in the spatial nature of numerical representations can be traced back to as early as 1880 to Francis Galton's work on 'number forms' (Galton, 1880). However, it was not until the discovery of the SNARC (Spatial Association of Response Codes) effect that there was an empirical account of these representations (Dehaene, Bossini, & Giraux, 1993). In this paradigm, participants made parity judgments (odd/even) to Arabic numerals using left and right response keys. Participants responded significantly faster to smaller numbers when using the left key and to larger numbers when using the right key, providing evidence of a left-to-right spatial representation of number, the so-called mental number line. In the 25 years since this discovery, many researchers have aimed to understand the ontogenic and phylogenic origins of these spatial-numerical associations (SNAs). Because early work regarding the mental number line dealt primarily with symbolic numerical stimuli and was shown to be shaped by reading direction (Dehaene et al., 1993; Shaki, Fischer, & Petrusic, 2009), it was initially hypothesized that SNAs arose from experience with linguistic conventions (i.e., reading/writing). Although cultural experience certainly modulates the directionality of SNAs (McCrink, Shaki, & Berkowitz, 2014; Zebian, 2005), recent research has provided evidence for the existence of SNAs in nonhuman animals (Drucker & Brannon, 2014; Rugani, Vallortigara, Priftis, & Regolin, 2015) and preliterate children (de Hevia, Addabbo, Girelli, & Macchi-Cassia, 2014; Opfer, Thompson, & Furlong, 2010) using non-symbolic stimuli. Nevertheless, despite accumulating evidence for the prevalence of SNAs, there are open questions regarding both their developmental trajectory and functional significance.

Development of SNAs

Assessing SNAs developmentally has proven difficult, as most paradigms utilize relatively advanced numerical judgments (e.g., parity), bimanual responses, and/or reaction time data, which are generally unsuitable for use with young children. To combat these difficulties, several researchers have devised alternative paradigms to assess SNAs in children. For example, when making magnitude judgments (i.e., is the presented Arabic numeral larger or smaller than 5?), as opposed to parity judgments, van Galen and Reitsma (2008) found evidence of SNAs in 7- to 9-year old children. Patro and Haman (2012) further addressed these concerns by using a non-symbolic magnitude comparison task and unimanual responses. In this paradigm, 2- to 4-year-olds judged which of two simultaneously presented arrays contained more items by selecting the array with larger numerosity. They found evidence for SNAs, with significantly faster responses when the target array was on the right than on the left. They also showed a similar, although weaker, effect when children had to select the array which was smaller in numerosity, such that children exhibited marginally faster responses when the target array was on the left than on the right. This provided further support for the existence of SNAs prior to extensive experience with reading or mathematics. Even with some evidence for spatial organization of number throughout development, however, it is unclear how reliable these effects are given the limited research in this area thus far. Moreover, and critically, little is known about functional significance of these associations. Are SNAs simply reflective of how numerical representations are organized in the mind and brain? Or do they provide support for quantitative reasoning, particularly in the domain of mathematics?

Functional Significance of SNAs

One prominent hypothesis is that SNAs may be related to mathematical reasoning, such that stronger SNAs would be accompanied by better math abilities (Opfer, Thompson, & Furlong, 2010; Fischer & Shaki, 2014). Yet previous research in fact found evidence for negative relations in adults, such that stronger SNAs are associated with poorer math ability. Importantly, however, this has only been observed in extreme populations, with participants with math difficulties showing stronger SNAs than controls (Hoffman et al., 2014) and controls showing stronger SNAs than professional mathematicians (Cipora et al., 2016). Furthermore, although there is some evidence for a negative relation, several studies have reported no relationship between SNA and math competence (Bull, Cleland, & Mitchell, 2013; Cipora & Nuerk, 2013). Nevertheless, considering the early emergence of SNAs and the known relations between spatial and mathematical skills during development (Lauer & Lourenco, 2016; Mix & Cheng, 2012; Uttal et al., 2013; Veridine, Golinkoff, Hirsh-Pasek, & Newcombe et al., 2017), it is important to examine the potential functional role of SNAs at this time. Given the abstract nature of numerical and mathematical concepts, spatial instantiation of these concepts would likely be of maximum utility when these difficult concepts are initially being acquired (Barsalou, 2008; Lakoff & Núñez, 2000).

As highlighted above, SNAs have been difficult to assess in children, impeding study of their potential utility in the critical early stages of mathematical development. As a result, only a few studies have assessed the relation between SNAs and math ability in childhood. And like the work on SNAs and math ability in adulthood, the findings thus far are mixed. Using the same paradigm as van Galen and Reitsma (2008), Hoffman, Hornung, Martin, and Schiltz (2013) had 5-year-olds complete color and magnitude judgments on Arabic numerals. Children also complete measures of numerical competence (verbal counting, digit writing, or number line estimation). Although children showed evidence of SNAs when judging the color of Arabic numerals, replicating van Galen and Reitsma (2008), with younger children, individual performance did not correlate with any measure of numerical competence. When SNAs were indexed using a magnitude judgment task, there was a correlation between children's SNAs and some of the measures of numerical competence (verbal counting and Arabic digit writing). However, the SNA effect on this task was not significant at the group-level, raising questions about the reliability of children's SNAs in this study and, thus, the reported correlations with numerical competence.

In other work, Bachot, Gevers, Fias, and Roeyers (2005) examined a group of 16 children from ages 7 to 12 years with visuospatial deficits, some of whom also had dyscalculia, an arithmetic disorder. They found that these children did not exhibit SNAs on a symbolic magnitude comparison task, whereas a control group of children, matched for age and gender, did exhibit display evidence of SNAs. However, children with visuospatial and math deficits were not differentiated and thus, it is unclear whether the lack of a significant SNA was driven by poor math ability or by more general visuospatial deficits. In another study with a larger sample (N = 429), Schneider, Grabner, and Paetsch (2009) found evidence of SNAs in 5th and 6th graders, but no relation between SNA strength and mathematical achievement, assessed by a measure of conceptual knowledge of decimals/fractions and by the grade received in their mathematics class. Given the age of these children (M = 11.3 years) and their relatively advanced mathematical ability, however, it is unclear whether this finding is informative regarding the role of SNAs in mathematical development.

Altogether, the findings on the relation between SNAs and math abilities are inconclusive and difficult to interpret for multiple reasons. First, it is unclear which SNA paradigms are developmentally appropriate and, further, what, if any, comparisons can be made across these different paradigms. Thus far, there lacks strong evidence that these tasks measure the same construct, as evident by the inconsistent findings. Furthermore, although previous research has operated under the broad assumption that SNAs may be related to math ability, few targeted predictions have been made regarding the specific age at which this relation would be most expected and what specific components of math ability might benefit. Consequently, the variability in age range examined and math measures administered has only furthered the difficulty in drawing conclusions from the literature in this area. Even in cases where a potential link between SNAs and math ability has been found, it remains possible that this connection can be accounted for by more general cognitive abilities such as working memory. Overall, the limitations of previous work in this area necessitate a comprehensive examination of the validity of our developmental paradigms for assessing SNAs and their potential relation to math performance.

Present Study

In the present study, we assessed performance on two SNA tasks and multiple measures of mathematical competence in children from ages 5 to 8 years. This age range was selected because it is a time when children understand number concepts but have not yet mastered basic arithmetic. Because previous research suggests that not all SNA paradigms may be related (Cheung, Ayzenberg, Diamond, Yousif, & Lourenco, 2015; Hoffman et al., 2013), one possibility is that the inconsistent findings in the literature may be due to differences in the SNA paradigms used. Thus, we included two different SNA tasks, one non-symbolic and one symbolic, to assess whether they are in fact evaluating the same construct. The first SNA task, a non-symbolic magnitude comparison task, was implemented based on previous research suggesting this task can measure SNAs in children as young as preschool age (Patro & Haman, 2012). Patro and Haman (2012) compared performance on 'More' and 'Less' conditions of this task across participants, but, here, all children completed both conditions. The second SNA task was a novel paradigm, the place-the-number task (adapted from Aulet, Yousif, & Lourenco, 2017), implemented to examine SNAs with reduced task demands. In contrast to the magnitude comparison task, this task was designed to evaluate SNAs for symbolic numbers (Arabic numerals). With the inclusion of non-symbolic and symbolic SNA paradigms, we not only aimed to assess the relation between these two tasks, but also to non-symbolic and symbolic measures of mathematical ability.

Because there has been little research on the link between SNAs and math ability thus far, it is possible that inconsistent findings regarding this relation are a result of differences in the math measures used. Mathematical skill is not monolithic; thus, it is necessary first to make predictions regarding what component(s) of math ability are most likely to be related to SNAs. As there are different mechanisms by which SNAs could facilitate mathematical understanding, different hypotheses have been put forth to explain this potential connection. For this reason, in the present study, children were administered three tasks implemented to target specific areas of an emerging math competency. One possibility is that grounding numerical concepts in a common visuospatial organization may support children's understanding of number as an abstract concept (Cipora, Patro, & Nuerk, 2015). To this end, children completed a cross-modal arithmetic task (adapted from Barth, Beckmann, & Spelke, 2008) to assess the extent to which children's numerical representations are modality independent. Another, though not mutually exclusive, possibility is that since approximate arithmetic operations are associated with spatial-directional biases (i.e., 'operational momentum'; Knops, Viarouge, & Dehaene, 2009), the strength of children's SNAs may relate to their performance on tasks relying on these operations. Thus, children completed an approximate symbolic arithmetic task (adapted from Gilmore, McCarthy, & Spelke, 2007). We also included a standardized measure of exact symbolic arithmetic, namely the Woodcock Johnson Calculation subtest (WJ; Woodcock, McGrew, & Mather, 2001a), as a general measure of symbolic mathematical understanding. Lastly, because previous work reporting a relation between SNAs and math ability (e.g., Hoffman et al., 2013) did not control for age or general intelligence, the specificity of this potential relation remains unclear. To ensure that any relation found was not the result of general cognitive abilities, we included several control measures assessing verbal proficiency (WJ - Picture Vocabulary subtest; Woodcock, McGrew, & Mather, 2001b), verbal working memory (WJ - Auditory Working Memory subtest; Woodcock et al., 2001b), and spatial short-term memory (Kaufman Assessment Battery for Children; Kaufman & Kaufman, 1983).

Method

Participants

Sixty-six children (28 female) between the ages of 5 and 8 years of age (*M* = 74.65 months, *SD* = 9.62) from the greater Atlanta area participated in this study. One child was excluded from the analyses for failing to complete multiple tasks. Caregivers provided written informed consent on behalf of their children. All children received stickers throughout the session to maintain motivation, as well as a small gift at the end of the session for participating. Experimental procedures were approved by the local ethics committee.

Tasks and Procedure

Place-the-number Task

In this task (adapted from Aulet, Yousif, & Lourenco, 2017), children viewed an Arabic numeral (1-9) presented in black font within a rectangle (white fill with black outline; 918 × 495 pixels). At the start of a trial, the number appeared within the rectangle (the "whiteboard") and children were instructed to press a virtual button located at the bottom of the screen, which resembled a whiteboard eraser with the word "START" written on it. At this time, the "whiteboard" disappeared and an image of a dry-erase marker appeared on the center of the screen. Children then tapped this image, at which time the "whiteboard" reappeared. They were instructed to tap the location on the screen where the number had previously appeared. The number spawned at the tapped location. Adjustments to responses could be implemented by tapping and dragging the number to a new location. When satisfied with the placement of the number, children pressed a button located at the bottom of the screen to confirm their response and proceed immediately to the next trial. At the start of the task, children received the following instructions: "In this game, you'll see a number written on the whiteboard. Your job is to remember exactly where it was. We will erase the number by pressing the eraser button. Then, we can tap the marker button to pick up the marker. Now your job is to tap the screen to put the number back exactly where it was on the whiteboard."

Presentation of numbers and duration of response window were untimed. Children completed 72 trials total (each numeral, 1-9, presented 8 times each). To ensure children remained focused, these trials were split into four blocks consisting of 18 trials each (each number presented twice; random order), administered at fixed points in the session (see General Procedure below for more details). At the beginning of the remaining three blocks, the experimenter stated: "Remember, your job is to place the number back exactly where it was." Following the completion of each block, children were given a sticker.

As a measure of children's spatial-numerical associations, the primary variable of interest was children's bias along the horizontal axis. For each trial, we calculated the difference between the x-coordinate of the children's final placement and x-coordinate of the number's original location, such that a negative value represents a more leftward placement in comparison to the original location, and a positive value represented a more rightward placement. For each participant, we then calculated the mean bias for each number and calculated a slope by regressing these values onto their corresponding numerical value. Thus, in this paradigm, a positive slope represents the canonical left-to-right mental number line.

Magnitude Comparison Task

Because of previous research suggesting that children perform differently on magnitude comparison tasks when asked to select the numerically larger array compared to when asked to select the numerically smaller array (Patro & Haman, 2012), we had all children complete both 'More' and 'Less' conditions of this task (order counterbalanced across children). In the 'More' condition, they were asked to judge which of two dot arrays was larger in numerosity. In the 'Less' condition, they were asked to judge which of two arrays was smaller in numerosity. SNAs on this task were measured by a congruency score: the difference in accuracy on congruent and incongruent trials (congruent trials were those where the array containing more dots was presented on the right).

Dot arrays were generated with a script created by Gebuis and Reynvoet (2011). For each pair of arrays, this script generates the non-numerical properties of the arrays according to one of four possible configurations: (1) larger number has a larger average dot diameter and a larger convex hull, (2) larger number has a larger average dot diameter but a smaller convex hull, (3) larger number has a smaller average dot diameter and a smaller convex hull and (4) larger number has a smaller average dot diameter but a larger convex hull. The configuration for each pair was chosen at random. These arrays (5.4 x 5.4 in) were arranged horizontally on screen, each below an image of a Star Wars character (BB-8 and R2D2).

Prior to beginning the practice trials, children were told: "BB-8 and R2D2 are on a quest to explore the galaxy. In this game, you will see that both BB-8 and R2D2 have found some stars. In this game, your job will be to pick which has more (/less) stars." Children were then shown an example of a trial and asked to indicate which had more (/less) stars to ensure they understood the concept of more (/less) before proceeding. In each condition, children completed three practice trials, during which they were given corrective feedback. In the practice trials, the two arrays differed by a 1:2 ratio (i.e., arrays of 4 and 8, 5 and 10, and 8 and 16). In all test trials, the two arrays differed by a 4:5 ratio (i.e., arrays of 4 and 5, 8 and 10, 12 and 15, 16 and 20). Each ratio pair was presented a total of four times; twice in the congruent and twice in the incongruent positions. Children completed 16 test trials per condition, for a total of 32 test trials. Based on previous research (Mazzocco, Feigenson, & Halberda, 2011), arrays were visible for 1200 ms before being occluded; arrays remained occluded until children made a response. All responses were made on the touchscreen. After the children made a response, there was a 1500 ms ISI before proceeding to the next trial.

Cross-modal Arithmetic Task

In this task (adapted from Barth et al., 2008), we assessed children's ability to add/subtract a sequence of sounds to/from an array of dots. First, children were familiarized with an example animation where the appearance (addition condition) or disappearance (subtraction condition) of blue dots, one-by-one, was paired with a sound. After this animation, children were shown a new array of blue dots that was subsequently occluded by a matching blue occluder. They were told that if they listened carefully, then they could hear more blue dots "appear" (or "disappear"), at which time they heard a sequence of sounds. The experimenter then asked the children whether there would be more or less dots behind the occluder. If children answered correctly ("more" for addition and "less" for subtraction) in these demonstrations, then the experimenter proceeded to the practice trials. If children answered incorrectly, then the experimenter repeated the previous animations again[1].

Children were given two practice trials in which they were shown an array of blue dots (7.6 x 5.6 in) on the left side of the screen, which was then occluded. After occlusion, children heard a sequence of sounds, representing the appearance/disappearance of blue dots. While the blue occluder remained on screen, an array of red dots appeared (7.6 x 5.6 in) on the right side of the screen, and was then covered by a matching red occluder. Children were then asked whether blue or red had more dots. After their response, the experimenter removed the occluders to reveal both arrays, providing children corrective feedback. In both practice trials, blue and red dots differed by a 1:2 ratio (one practice trial with more blue dots and one with more red). The timing of these practice trials was controlled by the experimenter to ensure maximum comprehension. In all stages of this task, the blue arrays/occluders and red arrays/occluders were matched for luminance.

Following the practice trials, children completed 12 test trials (randomly ordered). In these trials, blue and red dots differed by one of three ratios: 4:5, 4:6, or 4:7. Children completed four trials of each ratio (two trials where blue array was more numerous and two where red array was more numerous). Element size was held constant across all arrays/trials. Thus, an array which was larger in numerosity was also larger in total surface area. However, because the task required the addition/subtraction of elements across modality, reliance on non-numerical cues alone could not result in successful

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[1] If children answered incorrectly a second time, then the experimenter discontinued testing of this task. This only occurred for one child, who was removed from all analyses for failing to complete multiple tasks.

(above chance) performance on this task. In accordance with the original task (Barth et al., 2008), the same individual sound (duration = 15 ms) was used in all sound sequences. The sounds in each sequence were presented in an irregular rhythm. Total duration of the sequences ranged from approximately 1 to 3 s. In the addition condition, final set sizes ranged from 16 to 54 (*M* = 35). In the subtraction condition, final set sizes ranged from 7 to 30 (*M* = 16).

At the start of each test trial, an array of blue dots (against a solid black background) appeared and remained visible for 3 s. Then, the blue array was occluded and remained occluded for 6 s while the sequence of sounds played. Following this presentation, an array of red dots appeared and remained visible for 3 s and then was occluded. Children could only respond to select which array was more numerous once both arrays were occluded. Responses were made using the touchscreen. Immediately after children made their response, the experimenter pressed a key to proceed to the next trial. After children completed the addition condition, the same procedure was completed for the subtraction condition. All children completed the addition condition prior to the subtraction condition. Recent research suggests that the presentation of relatively difficult trials at the start of a task negatively impacts performance on subsequent (easier) trials (Odic, Hock, & Halberda, 2014). Thus, to avoid such carryover effects, the order was set as fixed, with addition prior to subtraction given evidence of better performance on addition than subtraction (Barth et al., 2008).

Approximate Symbolic Arithmetic Task

In this task (adapted from Gilmore et al., 2007), children were asked to solve approximate addition or subtraction problems, presented verbally with corresponding visual displays (i.e., images of cartoon children with corresponding Arabic numerals). An example problem is: “Sarah has twenty candies in her bag, and then she gets twenty-five more. John has thirty candies. Which one of them has more candies?” Following the reading of the quantities, the corresponding visual displays containing the Arabic numerals were occluded to discourage exact calculation. After the experimenter finished presenting the problem, children responded by pointing to, or naming, the character who they believed had more candies. Children completed two conditions: addition and subtraction. Within each condition, children completed 12 trials, with comparisons within each trial consisting of one of three possible ratios: 4:5, 4:6, or 4:7 (equal number of ratios across trials). In the addition condition, final set sizes ranged from 12 to 58 (M = 30). In the subtraction condition, final set sizes ranged from 10 to 56 (M = 28). Numerosities were matched as closely as possible across the three ratios. Trials were randomly ordered. As with the cross-modal arithmetic task, the order was fixed (Odic et al., 2014), such that the addition condition was administered before the subtraction condition. This task was untimed.

Exact Symbolic Arithmetic Test

Children completed the Woodcock Johnson Calculation subtest, a standardized assessment of symbolic arithmetic ability (WJ; Woodcock et al., 2001a). Specifically, the WJ – Calculation test measures participants’ ability to perform exact computation using addition, subtraction, multiplication, and division with whole numbers, rational numbers, and variables. This test is untimed and administered in paper-and-pencil format following a standard protocol, such that testing was discontinued once the child answered six consecutive questions incorrectly. This test has good internal consistency, as measured by a split half procedure (Calculation, $r = .85$; McGrew, Woodcock, & Schrank, 2007).

Control Measures

Children completed two subtests from the Woodcock Johnson (WJ; Woodcock et al., 2001a; 2001b) that served as controls for general cognitive functioning: verbal proficiency (WJ – Picture Vocabulary) and verbal working memory (WJ – Auditory Working Memory). Additionally, children also completed the Spatial Memory subtest from the Kaufman Assessment Battery for Children (K-ABC; Kaufman & Kaufman, 1983) as an assessment of spatial short-term memory and to serve as another non-math control measure. Each test has good internal consistency, as measured by a split half procedure (Picture Vocabulary, $r = .81$; Auditory Working Memory, $r = .96$; K-ABC-Spatial Memory, $r = .80$; Kaufman & Kaufman, 1983; McGrew et al., 2007).

General Procedure

All computerized tasks were presented on a Hewlett Packard Compaq Elite 8300 23” all-in-one desktop computer. Children sat approximately 40 cm from the screen for all computerized tasks. For ease of administration, a fixed order of tasks was used such that tasks requiring similar materials were administered consecutively, with computerized tasks preceding paper-and-pencil tasks. Of the computerized tasks, all children first completed the magnitude comparison task, followed by the cross-modal arithmetic and approximate symbolic arithmetic tasks (order-counterbalanced). Of the paper-and-pencil tasks, all children first completed WJ – Calculation. Then, children completed all control measures in a randomized order. All three control measures were untimed (for details on the procedure for each task, see Kaufman & Kaufman, 1983; McGrew et al., 2007).

Children completed four blocks of the place-the-number task, administered at fixed points in the session: at the start of the session (block 1), after completion of the magnitude comparison task (block 2), after the completion of cross-modal arithmetic and approximate symbolic arithmetic tasks (block 3), and after the completion of all standardized tasks (block 4).

Results

SNA Tasks

Place-the-number Task

Of the total sample (*N* = 65), five children were excluded from the analyses of the place-the-number task for failing to complete all four blocks of this task due to time constraints or fussiness (see Table 1 for descriptive data on all measures). In all analyses of this task, data from all four blocks were combined[2]. Furthermore, two children were excluded from these analyses due to poor accuracy (> 2.5 SD from the group mean), where accuracy was calculated as the absolute distance between the number's original location and the child's final placement. The remaining children (*N* = 58) had a mean accuracy of 63.02 pixels (SD = 24.32).

As described above, to test for an SNA on this task, the variable of interest was children's bias along the horizontal axis[3]. As is typical in SNA paradigms (Fias et al.,

[2] Comparisons of performance across blocks were not conducted due to insufficient data per block (18 trials; 2 trials per numeral).

[3] Analysis of children's bias along the vertical axis yielded no evidence of a significant SNA, *p* > .7. Previous research suggests SNAs in the vertical axis may be less reliable (Holmes & Lourenco, 2012). However, it is also possible that the rectangular space used here constrained bias in the vertical dimension.

1996), for each child, a slope was calculated by regressing mean bias for each number onto the corresponding numerical value. Children's slopes were significantly greater than zero, $t(57) = 2.02$, $p < .05$, $d = .26$ (see Figure 1), and the majority of children (37 of 58) exhibited a positive slope (binomial test, $p < .05$), consistent with the canonical left-to-right mental number line.

Magnitude Comparison Task

Of the total sample, all children ($N = 65$) were included in analyses of the 'More' condition. One child was excluded from the analyses of the 'Less' condition due to experimenter error. Children's accuracy revealed performance above the chance level of .50 in both conditions ('More': $M = .71$, $SD = .15$, $t[64] = 11.41$, $p < .001$, $d = 1.42$; 'Less': $M = .70$, $SD = .12$, $t(63) = 13.72$, $p < .001$, $d = 1.71$), with no significant difference between conditions, $t(63) = .008$, $p > .99$. Furthermore, a zero-order correlational analysis showed that children's accuracy in these two conditions was significantly correlated, $r(62) = .27$, $p < .05$. Consequently, all further analyses utilizing this task were conducted using composite scores. For each child, we calculated overall accuracy (percent total trials correct across both conditions). To assess children's SNAs on this task, we calculated a total congruency score as the difference between correct congruent and incongruent trials (see Figure 2), such that a positive congruency score represented a stronger SNA (greater accuracy on congruent than incongruent trials). Children exhibited average congruency scores significantly greater than zero, $M = .60$, $SD = 2.23$, $t(63) = 2.13$, $p < .05$, $d = .27$, here, again, suggesting a significant left-to-right mental number line

Relation Between SNA Tasks

To test the relation between the two SNA tasks (place-the-number and magnitude comparison), we conducted a correlational analysis between children's slopes on the place-the-number task and total congruency scores on the magnitude comparison task, while controlling for accuracy on the two tasks to account for differences in task demands. There was a significant correlation between children's performance on the two SNA tasks, $r_p(53) = .30$, $p < .05$, suggesting that these two tasks tap a common construct (see Figure 3). Further, they remained significantly correlated after additionally controlling for age, $r_p(52) = .30$, $p < .05$. To ensure that these correlations were not the result of undue influence from a subset of data points, we examined the data for outliers. No data points qualified as bivariate outliers using the criterion of 2.5**SD* from the mean.

Math Tasks

Cross-modal Arithmetic Task

Nine children were excluded from the analyses for failing to complete one or both conditions of this task (see below for exclusion criteria). With the remaining sample (N = 56), performance was significantly above the chance level of .50 (M = .66, SD = .11), $t(55) = 10.50$, $p < .001$, $d = 1.41$. Of this sample, 51 children exhibited above chance performance.

A repeated measures analysis of variance (ANOVA) with operation (addition and subtraction) and ratio (4:5, 4:6, and 4:7) as within-subject variables found a marginal effect of operation, $F(1, 55) = 3.81$, $p = .06$, $\eta^2 = .03$, suggesting that children may have had greater difficulty with subtraction. There was also a significant effect of ratio, $F(2, 110) = 7.11$, $p < .01$, $\eta^2 = .06$, and a linear contrast analysis revealed that performance improved as ratio decreased, $F(1, 55) = 11.64$, $p < .01$, $\eta^2 = .07$. There was no interaction between operation and ratio, $p > .94$. Although the effect of operation/condition was only marginal, we conducted subsequent analyses on each condition separately for completeness and consistency with previous research.

Addition. Five children were excluded from analyses of the addition condition (three failed to provide correct responses during the second repetition of the practice phase; two always chose the left array). Of the remaining sample ($N = 60$), performance was significantly above the chance level of .50 ($M = .68$, $SD = .13$), $t(59) = 10.62$, $p < .001$, $d = 1.37$, consistent with the original findings of Barth et al. (2008). Moreover, performance was above chance at each ratio, *p*s < .001 (see Figure 4). A repeated measures ANOVA revealed that although there was no significant effect of ratio ($p > .13$), a linear contrast analysis yielded a marginal linear trend, such that performance improved as ratio decreased, $F(1, 59) = 3.67$, $p = .06$, $\eta^2 = .03$.

Subtraction. Nine children were excluded from analyses of the subtraction condition (five were not administered the task after failure to complete the addition task; three children always chose the right array; one child was excluded due to experimenter error). As in the addition task, the remaining children ($N = 56$) performed above chance on the subtraction task, $M = .64$, $SD = .16$, $t(55) = 6.37$, $p < .001$, $d = .85$. Again, performance was above chance at all three ratios (see Figure 5). A repeated measures ANOVA revealed a significant main effect of ratio, $F(2, 110) = 5.12$, $p < .01$, $\eta^2 = .04$, and a linear contrast analysis further revealed a significant linear trend, $F(1, 55) = 7.67$, $p < .01$, $\eta^2 = .05$, such that performance improved as ratio decreased, consistent with previous findings and the addition condition.

Approximate Symbolic Arithmetic Task

Thirteen children were excluded from the analyses for failing to complete one or both conditions of this task (see below for exclusion criteria). With the remaining sample (N = 53), performance was significantly above the chance level of .50 (M = .76, SD = .15), $t(52) = 12.56$, $p < .001$, $d = 1.72$. Of this sample, 50 children exhibited above chance performance. A repeated measures analysis of variance (ANOVA) with operation (addition and subtraction) and ratio (4:5, 4:6, and 4:7) as within-subject variables found a significant effect of operation, $F(1, 52) = 4.66$, $p < .05$, $\eta^2 = .02$, such that children were more accurate for addition than subtraction. There marginal effect of ratio, $F(2, 104) = 3.02$, $p = .05$, $\eta^2 = .02$. A linear contrast analysis showed a significant linear trend, such that performance improved as ratio decreased, $F(1, 55) = 11.64$, $p < .01$, $\eta^2 = .07$. There was no interaction between operation and ratio, $p > .13$. Due to the significant effect of operation, we conducted subsequent analyses on each condition separately.

Addition. Three children were excluded from analyses of the addition task for always choosing the left array. With the remaining sample (N = 62), performance on this task was significantly above the chance level of .50, M = .77, SD = .19, $t(61) = 11.14$, $p < .001$, $d = 1.42$. Performance was above chance at all three ratios (see Figure 6). A repeated measures ANOVA revealed a significant main effect of ratio, $F(2, 122) = 3.64$, $p < .05$, $\eta^2 = .02$, though there was not a significant linear trend ($p > .27$).

Subtraction. Twelve children were excluded from analyses of the subtraction task for always choosing the right array. With the remaining sample (N = 53), performance on this task was significantly above chance, M = .73, SD = .17, $t(52) = 9.76$, $p < .001$, d = 1.34. Performance was above chance at all three ratios (see Figure 5). A repeated measures ANOVA showed no effect of ratio and no significant linear trend (ps > .11).

Exact Symbolic Arithmetic Test

Children's raw scores on the Woodcock Johnson Calculation Subtest ranged from 0 to 14 (M = 6.71, SD = 4.21). Because several children (N = 9) received a score of zero on this test we were unable to calculate a standardized score for these children. Of the children who received standardized scores, the mean score (M = 115.20, SD = 11.95) is classified as high average (Schrank, Mather, & Woodcock, 2004).

Relation Between Math Tasks

To assess the relation between the math tasks, we first conducted a series of zero order correlations (see Table 2). Because the difference in accuracy between cross-modal addition and subtraction did not reach statistical significance (p = .06; η^2 = .03), correlation analyses were conducted with a measure of overall accuracy across these conditions, which also served to maximize power. Further, because several children did not receive a standardized score on the WJ – Calculation subtest, correlation analyses utilized the raw scores on this measure, controlling for age separately.

Performance on the cross-modal arithmetic task[4] and the addition condition of the approximate symbolic arithmetic task were significantly positive correlated, $r(52) = .34$, $p <.05$, such that children who performed better on cross-modal arithmetic also performed better on approximate symbolic addition. Further, performance on these tasks remained significantly correlated after controlling for age, $r_p(51) = .29$, $p < .05$. This relation likely reflects the common calculation type (approximate, as opposed to exact,

[4] Correlations were also conducted for cross-modal addition and subtraction conditions separately (See Table 2). These were not reported in the main text due to reduced power when evaluating these conditions separately.

arithmetic) across the two tasks, despite differences in numerical format (non-symbolic vs. symbolic). We also found a significant correlation between approximate symbolic arithmetic and WJ – Calculation, $r(51) = .64$, $p < .001$, such that children who performed better on approximate symbolic arithmetic also performed better on WJ – Calculation, a measure of exact symbolic arithmetic. Subsequent analyses, however, revealed only a marginal relation between these two measures after controlling for age, $r_p(50) = .27$, $p < .06$, suggesting that this relation is likely largely explained by age.

Control Measures

Mean scores and other descriptive data on all control measures are presented in Table 1. 22

Is There a Relation Between Children's SNAs and Math Performance?

The primary aim of the present study was to examine the potential links between individual differences in the strength of children's SNAs and their mathematical performance. To test this possibility, we first conducted zero order correlations between children's SNAs and performance on each math tasks. We found no significant relationship between children's slopes on the place-the-number task and accuracy on any of the math tasks (*p*s > .15). In particular, there were no correlations between place-the-number and cross-modal arithmetic, regardless of whether the analyses were conducted with the measure of overall accuracy or split by condition (addition vs. subtraction). Further, there were no significant correlations between place-the-number and approximate symbolic arithmetic or exact symbolic arithmetic (WJ – Calculation). Thus, when using the place-the-number task to evaluate SNAs, there is no apparent relation between SNA strength and mathematical ability.

When we used congruency scores on the magnitude comparison task as a measure of SNAs, we found a significant correlation with performance on only one measure of math ability: cross-modal arithmetic, $r(53) = -.33$, $p < .05$ (all other ps $> .07$). This negative correlation revealed that stronger SNAs were related to poorer non-symbolic arithmetic with stimuli in different modalities (visual and auditory). To ensure that this effect was not the result of undue influence from a subset of data points, we examined the data for outliers. No points qualified as bivariate outliers using the criterion of 2.5*SD from the mean.

In the Introduction, we suggested that poor math understanding could be accompanied by stronger SNAs in adults (Cipora et al., 2016; Hoffman et al., 2014). However, it remains unclear to what extent such a relation is or could be accounted for by more general cognitive factors. In a subsequent analysis, we examined the relation between children's congruency scores on the magnitude comparison task and their accuracy on cross-modal arithmetic when controlling for age, verbal proficiency (WJ – Picture Vocabulary), working memory (WJ – Auditory Working Memory), and short-term memory (K-ABC). We found that the relation between SNAs as measured by congruency scores on the magnitude comparison task remained significantly correlated with cross-modal arithmetic[5], $r_p(48) = -.30$, $p < .05$, even when controlling for these general factors.

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[5] Partial correlations were also conducted separately for cross-modal addition and subtraction conditions. We found no significant relations between either condition and congruency scores on the magnitude comparison task after controlling for age and general cognitive ability. These were not reported in the main text due to reduced power when evaluating these conditions separately.

General Discussion

Our findings demonstrate stability in the strength of children's SNAs across two paradigms, a magnitude comparison task and the place-the-number task, despite robust differences in the nature of these tasks. Of particular interest, we found evidence for a relation between children's performance on these tasks, even though the tasks varied in the type of numerical stimuli used (non-symbolic vs. symbolic) and in numerical salience (explicit vs. implicit). This correlation is important as it provides evidence for the construct validity of these tasks. This is especially critical given that previous studies have rarely examined the relation between paradigms (for exception, see Cheung et al., 2015 for an assessment with adults). Importantly, the relation found here suggests that the SNAs exhibited on these tasks reflect an integral aspect of number representations, as opposed to a transient association generated on-line in response to the demand characteristics of each paradigm (for review of this position, see Abrahamse, van Dijck, & Fias, 2016).

Because previous research regarding the relation between SNAs and mathematical skill in adulthood is inconclusive, it is important to shed light on this link during early childhood when math skills are initially being acquired. Specifically, we hypothesized that the spatial grounding provided by SNAs would facilitate understanding of number as an abstract concept and, thus, stronger SNAs would relate to better performance on math, such as cross-modal arithmetic (Barsalou, 2008; Lakoff & Núñez, 2000). Although we found no link in the case of one SNA task (place-the-number), our results with a second SNA task (magnitude comparison) suggest the opposite. Stronger SNAs on magnitude comparison were associated with worse performance on cross-modal arithmetic, even after controlling for age, verbal proficiency, working memory and short-term memory. As discussed in the Introduction, previous research on this relation in adults has also found a negative relation between SNA strength and mathematical ability. Given this support from previous work, it is certainly possible that this finding reflections a true link, such that having a stronger spatial representation for number hinders children's ability to represent and compare numerosity across modalities, at least at this stage in development.

Importantly, however, we do not find any correlation between SNAs on the place-the-number task and math skill. In light of this, we suggest an alternative interpretation: the negative correlation observed between SNAs and mathematical ability, as measured by the magnitude comparison task and cross-modal arithmetic (the only significant correlation between SNAs and math found here), is a reflection of demands of the magnitude comparison task. In this task, the strength of children's SNAs are not orthogonal to accuracy. In other words, a complete bias towards the left array in the 'Less' condition and the right array on the 'More' condition, consistent with a left-to-right mental number line, would result in 50% total accuracy on the task. Thus, this may not be a 'pure' measure of children's SNAs, but rather, a reflection of their ability to suppress such an SNA when doing so is required to complete the task. That is, weak inhibitory control may result in an inability to inhibit an SNA on the magnitude comparison task, and also, in poorer performance on the cross-modal arithmetic task (for review of the link between inhibitory control and mathematics achievement, see Cragg & Gilmore, 2014).

Critically, previous research corroborates this explanation. Hoffman, Pigat, & Schiltz (2014) found that participants with weaker inhibitory control, as measured by a Stroop paradigm, exhibited stronger SNARC effects. Further, inhibitory control explained a significant amount of the variance in SNARC strength even when controlling for age and other general factors such as processing speed and working memory, perhaps explaining why the relation found in the present study remains significant after controlling for working memory. Conversely, on our place-the-number task, evaluation of children's SNAs are essentially orthogonal to accuracy. A child with a strong, consistent SNA might place all small numbers slightly leftward and all large numbers slightly rightward of their original location, and yet, can still maintain a high level of overall accuracy due to the relatively small bias in terms of absolute distance. Consequently, we urge future research to remain cautious in interpreting relations between SNAs and math performance unless they are using a measure with minimal task demands. For those who continue to use tasks such as the classic magnitude comparison task, it may be crucial to account for individual differences in inhibitory control when evaluating SNAs.

Is there truly no relation between SNA strength and math ability? In the Introduction, we highlighted the need to examine this potential relation when math concepts are initially being acquired. With this in mind, one possibility is that a relation may nevertheless exist in younger children than those tested in the present study. Furthermore, even for their age group, the children in the present study had relatively advanced mathematical abilities, evidenced by their higher than average scores on the WJ – Calculation subtest. Consequently, future work should examine this relation in younger children, such as preschoolers, to test this relation truly at the onset of emerging mathematical ability. Given the need to assess this link in younger children, the construct validity confirmed here between the non-symbolic (magnitude comparison) and symbolic (place-the-number) SNA paradigms is critical, as younger children will not yet be familiar with symbolic numerals, necessitating the sole use of non-symbolic measures.

Nonetheless, many other components of the mental number line, besides directionality, may be related to math competence (for review, see Cipora et al., 2015). For example, another aspect of interest is the dynamic nature of the mental number line, as evidenced by operational momentum effects, in which participants systematically overestimate the results of addition and multiplication problems and underestimate the results of subtraction and division problems (Katz & Knops, 2014; Knops, Viarouge, & Dehaene, 2009; McCrink, Dehaene, & Dehaene-Lambertz, 2007). Particularly, it is argued that these arithmetic biases are a result of spatial overestimation, akin to representational momentum (Freyd & Finke, 1984). Representational momentum is a perceptual phenomenon where participants, when shown a moving object that then vanishes or is occluded, misjudge the object's final location to be slightly further along its trajectory. Likewise, it has been suggested that arithmetic over/underestimations are a result of overestimations of "movement" along a mental number line, such that addition and multiplication cause rightward shifts in attention and subtraction and division cause leftward shifts in attention. Evidence utilizing eye-tracking has further supported this claim, showing that arithmetic involving these operations result in saccades in the corresponding direction (Holmes, Ayzenberg, & Lourenco, 2016; Klein, Huber, Nuerk, & Moeller, 2014). Given the known relation between mental rotation, another kind of dynamic representation, and mathematical ability (Cheng & Mix, 2014; Thompson, Nuerk, Moeller, & Cohen Kadosh, 2013), there is good reason to predict a relation between operational momentum and mathematical ability, such that one's ability to dynamically manipulate the mental number line may lead to greater fluency when completing arithmetic calculations. Further, previous research has found evidence for operational momentum for non-symbolic number already present in infancy (Macchi Cassia et al., 2016; McCrink & Wynn, 2009), making this an optimal SNA to examine during early mathematical development.

Another critical feature of the mental number line is the extent to which numbers are mapped to space in a linear or logarithmic fashion. Many have argued that these mappings reflect the precision of underlying non-symbolic numerical representations, as in the approximate number system (Dehaene, Izard, Spelke, & Pica, 2008; Laski & Siegler, 2007). Most commonly, these mappings are measured by a number line estimation task, where participants designate the position of a numerical value on a number line (Siegler & Opfer, 2003). For linear representations, a change in numerical distance corresponds to an equivalent change in spatial distance; in other words, across the entire range of the number line, numerical values are represented with consistent spatial intervals. Conversely, for logarithmic representations, often observed in young children, the spatial distance between two small numbers is larger than the spatial distance between two respective larger numbers (e.g., children will designate the numbers 5 and 15 as being spatially further apart than 75 and 85). Not only has the linearity of one's number line been shown to correlate positively with math proficiency, as measured by a variety of math tasks (Booth & Siegler, 2006, 2008; Siegler & Booth, 2004), but causal evidence has also been put forth, showing that after children received training to increase the linearity of their numerical representations, their math performance improved compared to children who received non-numerical (control) training (Ramani & Siegler, 2008; Siegler & Ramani, 2009). However, others have argued that this linearity does not reflect greater precision of underlying numerical representations, but rather reflects measurement skills or proportional reasoning. Thus, from this perspective, these findings do not reflect a relation between SNAs and math performance, but rather, a more direct relation between two measures of mathematical ability (Barth, Slusser, Cohen, & Paladino, 2011; Cohen & Blanc-Goldhammer, 2011; Cohen & Quinlan, 2017; Cohen & Sarnecka, 2014; Rouder & Geary, 2014; Slusser, Santiago, & Barth, 2013).

In conclusion, our results do not provide strong support for a relation between the directional nature of SNAs and mathematical ability in 5- to 8- year-old children (Cipora et al., 2015). Contrary to our initial prediction, the one significant relation, between SNAs on the magnitude comparison task and cross-modal arithmetic, suggest a negative relation between SNAs and math ability. While we have suggested that this link is likely due to individual differences in inhibitory control, consistent with previous research (Hoffman et al., 2014), we acknowledge the speculative nature of this claim given that the present study did not include a direct measure of inhibitory control. As a result, we urge future research to provide insight on this connection. Lastly, given the multi-faceted nature of the mental number line, it is of the utmost importance to consider the ways in which these different aspects of number-space interactions may differentially relate to mathematical performance.

References

Abrahamse, E., van Dijck, J. P., & Fias, W. (2016). How does working memory enable number-induced spatial biases? *Frontiers in* Psychology, *7,* 977.

Aulet, L. S., Yousif, S. R, & Lourenco, S. F. (2017). Numbers uniquely bias spatial attention: A novel paradigm for understanding spatial-numerical associations. *Proceedings of the 39th Annual Conference of the Cognitive Science Society*.

Bachot, J., Gevers, W., Fias, W., & Roeyers, H. (2005). Number sense in children with visuospatial disabilities: Orientation of the mental number line. *Psychology Science, 47*, 172–183.

Barsalou, L. W. (2008). Grounded cognition. *Annual Review of Psychology, 59*, 617–645.

Barth, H., Beckmann, L., & Spelke, E. (2008). Nonsymbolic, approximate arithmetic in children: Evidence for abstract addition prior to instruction. *Developmental Psychology, 44,* 1466–1477.

Barth, H., Slusser, E., Cohen, D., & Paladino, A. M. (2011). A sense of proportion: Commentary on Opfer, Siegler, & Young. *Developmental Science, 14,* 1205–1206.

Booth, J. L., & Siegler, R. S. (2006). Developmental and individual differences in pure numerical estimation. *Developmental Psychology, 42*, 189–201.

Booth, J. L., & Siegler, R. S. (2008). Numerical magnitude representations influence arithmetic learning. *Child Development, 79,* 1016–1031.

Bull, R., Cleland, A. A., & Mitchell, T. (2013). Sex differences in the spatial representation of number. *Journal of Experimental Psychology: General*, *142*, 181–192.

Butterworth, B. (2005). Developmental dyscalculia. In Campbell, J.I.D. (Ed.), *Handbook of Mathematical Cognition*. (pp. 455-467). Hove: Psychology Press.

Cheng, Y. L. & Mix, K. S. (2014). Spatial training improves children's mathematics ability. *Journal of Cognition and Development, 15,* 2-11.

Cheung, C. –N., Ayzenberg, V., Diamond, R. F. L., Yousif, S. R., & Lourenco, S. F. (2015). Probing the mental number line: A between-task analysis of spatial-numerical associations. *Proceedings of the 37th Annual Conference of the Cognitive Science Society* (pp. 357-362). Hillsdale, NJ: Lawrence Erlbaum Associates.

Cipora, K., Hohol, M., Nuerk, H. -C., Willmes, K., Brożek, B., Kucharzyk, B., & Nęcka, E. (2016). Professional mathematicians differ from controls in their spatial-numerical associations. *Psychological Research, 80,* 710–726.

Cipora, K., & Nuerk, H. -C. (2013). Is the SNARC effect related to the level of mathematics? No systematic relationship observed despite more power, more repetitions, and more direct assessment of arithmetic skill. *Quarterly Journal of Experimental Psychology, 66,* 1974–1991.

Cipora, K., Patro, K., and Nuerk, H. -C. (2015). Are spatial-numerical associations a cornerstone for arithmetic learning? The lack of genuine correlations suggests no. *Mind Brain Education, 9,* 190–206.

Cohen, D. J., & Blanc-Goldhammer, D. (2011). Numerical bias in bounded and unbounded number line tasks. *Psychonomic Bulletin & Review, 18,* 331–338.

Cohen, D. J., & Quinlan, P. T. (2017). The log–linear response function of the bounded number-line task is unrelated to the psychological representation of quantity. *Psychonomic Bulletin & Review*, 1-8.

Cohen, D. J., & Sarnecka, B. (2014). Children's number-line estimation shows development of measurement skills (not number representations). *Developmental Psychology, 50,* 1640–1652.

Cragg, L., & Gilmore, C. (2014). Skills underlying mathematics: The role of executive function in the development of mathematics proficiency. *Trends in Neuroscience and Education, 3,* 63–68.

de Hevia, M. D., Addabbo, M., Girelli, L., & Macchi-Cassia, V. (2014). Human infants' preference for left-to-right oriented increasing numerical sequences. *PLoS ONE, 9*, e96412.

Dehaene, S., Bossini, S. & Giraux, P. (1993). The mental representation of parity and number magnitude. *Journal of Experimental Psychology: General*, *122*, 371–96.

Dehaene, S., Izard, V., Spelke, E., & Pica, P. (2008). Log or linear? Distinct intuitions of the number scale in western and Amazonian indigene cultures. *Science, 320,* 1217-1220.

Drucker, C. & Brannon, E. M. (2014). Rhesus monkeys (Macaca mulatta) map number onto space. *Cognition*, *132*, 57–67.

Fias, W., Brysbaert, M., Geypens, F., & d'Ydewalle, G. (1996). The importance of magnitude information in numerical processing: Evidence from the SNARC effect. *Mathematical Cognition*, *1*, 95-110.

Fischer, U., Moeller, K., Bientzle, M., Cress, U., & Nuerk, H. C. (2011). Sensori-motor spatial training of number magnitude representation. *Psychonomic Bulletin & Review*, *18*, 177-183.

Fisher, M. H. & Shaki, S. (2014). Spatial associations in numerical cognition – From single digits to arithmetic. *Quarterly Journal of Experimental Psychology, 67*, 1461-1483.

Freyd, J. J. & Finke, R. A. (1984). Representational momentum. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *10*, 126–132.

Galton, F. (1880). Visualised numerals. *Nature*, *21*, 252–256.

Gebuis, T. & Reynvoet, B. (2011). Generating non-symbolic number stimuli. *Behavior Research Methods*, *43,* 981-986.

Gilmore, C. K., McCarthy, S. E., & Spelke, E. S. (2007). Symbolic arithmetic knowledge without instruction. *Nature*, *447*, 589–591.

Hoffman, D., Hornung, C., Martin, R., & Schiltz, C. (2013). Developing number-space associations: SNARC effects using a color discrimination task in 5-year-olds. *Journal of Experimental Child Psychology*, *116*, 775–791.

Hoffmann, D., Mussolin, C., Martin, R., & Schiltz, C. (2014). The impact of mathematical proficiency on the number-space association. *PLoS ONE*, *9*, e85048.

Hoffmann, D., Pigat, D., & Schiltz, C. (2014). The impact of inhibition capacities and age on number–space associations. *Cognitive Processing*, *15,* 329–342.

Holmes, K. J., Ayzenberg, V., & Lourenco, S. F. (2016). Gamble on gaze: Eye movements reflect the numerical value of blackjack hands. *Psychonomic Bulletin & Review, 23*, 1974–1981.

Holmes, K. J. & Lourenco, S. F. (2012). Orienting numbers in mental space: Horizontal organization trumps vertical. *Quarterly Journal of Experimental Psychology*, *65*, 1044-1051.

Katz, C. & Knops, A. (2014). Operational momentum in approximate multiplication and division? *PLoS One*, *9*, e104777.

Kaufman, A. S., & Kaufman, N. L. (1983). *Kaufman Assessment Battery for Children*. Circle Pines, MN: American Guidance Service.

Klein, E., Huber, S., Nuerk, H. -C., & Moeller, K. (2014). Operational momentum affects eye fixation behaviour. *Quarterly Journal of Experimental Psychology, 67*, 1614–1625.

Knops, A., Viarouge, A., & Dehaene, S. (2009). Dynamic representations underlying symbolic and nonsymbolic calculation: Evidence from the operational momentum effect. *Attention, Perception, and Psychophysics*, *71*, 803–821.

Knops, A., Zitzmann, S., & McCrink, K. (2013). Examining the presence and determinants of operational momentum in childhood. *Frontiers in Psychology*, *4*, 325.

Lakoff, G., & Núñez, R. E. (2000). *Where mathematics comes from: How the embodied mind brings mathematics into being*. Basic books.

Laski, E. V., & Siegler, R. S. (2007). Is 27 a big number? Correlational and causal connections among numerical categorization, number line estimation, and numerical magnitude comparison. *Child Development, 78*, 1723-1743.

Lauer, J. E., & Lourenco, S. F. (2016). Spatial processing in infancy predicts both spatial and mathematical aptitude in childhood. *Psychological Science, 27*, 1291–1298.

Macchi Cassia, V., McCrink, K., de Hevia, M. D., Gariboldi, V., & Bulf, H. (2016). Operational momentum and size ordering in preverbal infants. *Psychological Research*, *80*, 360-367.

Mazzocco, M. M., Feigenson, L., & Halberda, J. (2011b). Preschoolers' precision of the approximate number system predicts later school mathematics performance. *PLoS One*, *6*, e23749.

McCrink, K., Dehaene, S., & Dehaene-Lambertz, G. (2007). Moving along the number line: Operational momentum in nonsymbolic arithmetic. *Perception and Psychophysics*, *69*, 1324-1333.

McCrink, K., & Opfer, J. E. (2014). Development of spatial-numerical associations. *Current Directions in Psychological Science*, *23*, 439–445.

McCrink, K., Shaki, S. & Berkowitz, T. (2014). Culturally-Driven Biases in Preschoolers' Spatial Search Strategies. *Cognitive Development*, *30*, 1-14.

McCrink, K., & Wynn, K. (2009) Operational momentum in large-number addition and subtraction by 9-month-old infants. *Journal of Experimental Child Psychology*, *104*, 400-408.

Mix, K. S. & Cheng, Y. L. (2012). The relation between space and math: developmental and educational implications. *Advances in Child Development and Behavior*, *42*, 197-243.

Odic, D., Hock, H., & Halberda, J. (2014) Hysteresis affects number discrimination in young children. *Journal of Experimental Psychology: General, 143,* 255-265.

Opfer, J. E., & Furlong, E. E. (2011). How numbers bias preschoolers' spatial search. *Journal of Cross Cultural Psychology*, *42*, 682–695.

Opfer, J. E., Thompson, C. A., & Furlong, E. E. (2010). Early development of spatial numeric associations: evidence from spatial and quantitative performance of preschoolers. *Developmental Science, 13*, 761–771.

Patro, K., & Haman, M. (2012). The spatial–numerical congruity effect in preschoolers. *Journal of Experimental Child Psychology*, *111*, 534–542.

Ramani, G. B., & Siegler, R. S. (2008). Promoting broad and stable improvements in low-income children's numerical knowledge through playing number board games. *Child Development*, *79*, 375–394.

Rouder, J. N., & Geary, D. C. (2014). Children's cognitive representation of the mathematical number line. *Developmental Science, 17*, 525-536.

Rugani, R., Vallortigara, G., Priftis, K., & Regolin, L. (2015). Number-space mapping in the newborn chick resembles humans' mental number line. *Science*, *347*, 534–536.

Schneider, M., Grabner, R. H., & Paetsch, J. (2009). Mental number line, number line estimation, and mathematical achievement: Their interrelations in Grades 5 and 6. *Journal of Educational Psychology*, *101*, 359–372.

Schrank, F. A., Mather, N., & Woodcock, R. W. (2004). *Woodcock Johnson III Diagnostic Reading Battery: Comprehensive manual*. Itasca, IL: Riverside.

Shaki, S., Fischer, M. H., & Petrusic, W. M. (2009). Reading habits for both words and numbers contribute to the SNARC effect. *Psychonomic Bulletin & Review, 16*, 328–331.

Siegler, R. S., & Booth, J. L. (2004). Development of numerical estimation in young children. *Child Development, 75*, 428–444.

Siegler, R. S., & Opfer, J. E. (2003). The development of numerical estimation: Evidence for multiple representations of numerical quantity. *Psychological Science*, *14*, 237–243.

Siegler, R. S., & Ramani, G. B. (2009). Playing linear number board games— but not circular ones—improves low-income preschoolers' numerical understanding. *Journal of Educational Psychology*, *101*, 545– 560.

Slusser, E. B., Santiago, R. T., & Barth, H. C. (2013). Developmental change in numerical estimation. *Journal of Experimental Psychology: General*, *142*, 193–208.

Thompson, J., Nuerk, H., Moeller, K., & Cohen Kadosh, R. (2013). The link between mental rotation ability and basic numerical representations. *Acta Psychologica, 144*, 324-331.

Uttal, D. H., Meadow, N. G., Tipton, E., Hand, L .L., Alden, A. R., Warren, C., & Newcombe, N. S. (2013). The malleability of spatial skills: A meta-analysis of training studies. *Psychological Bulletin*, *139*, 352-402.

van Galen, M. S., & Reitsma, P. (2008). Developing access to number magnitude: A study of the SNARC effect in 7- to 9-year-olds. *Journal of Experimental Child Psychology*, *101*, 99–113.

Verdine, B., Golinkoff, R. M., Hirsh-Pasek, K., & Newcombe, N. (2017). Links between spatial and mathematical skills across the preschool years. *Society for Research in Child Development Monograph, 82*.

Woodcock, R. W., McGrew, K. S., & Mather, N. (2001a). *Woodcock-Johnson III Tests of Achievement*. Itasca, IL: Riverside.

Woodcock, R. W., McGrew, K. S., & Mather, N. (2001b). *Woodcock-Johnson III Tests of Cognitive Abilities*. Itasca, IL: Riverside.

Zebian, S. (2005). Linkages between number concepts, spatial thinking, and directionality of writing: The SNARC effect and the reverse SNARC effect in English and Arabic monoliterates, biliterates, and illiterate Arabic speakers. *Journal of Cognition and Culture, 5*, 165–190.

Table 1. Descriptive statistics for all measures administered. For all Woodcock-Johnson tasks (WJ: normed, *M* = 100, *SD* = 15), values represent standardized scores.

Type	Task		N	Mean	SD
SNA	**Place-the-number**				
		Accuracy	58	63.02	24.32
		Slope (Horizontal bias)	58	1.07	4.06
	Magnitude Comparison				
		Accuracy	64	0.70	0.10
		Congruency Score	64	0.59	2.23
Math	**Cross-modal Arithmetic**				
		Total Accuracy	56	0.66	0.11
		Addition Accuracy	60	0.68	0.13
		Subtraction Accuracy	56	0.64	0.16
	Approximate Symbolic Arithmetic				
		Total Accuracy	53	0.76	0.15
		Addition Accuracy	62	0.76	0.19
		Subtraction Accuracy	53	0.73	0.17
	WJ - Calculation		54	115.20	11.95
Control	**WJ - Picture Vocabulary**		65	108.81	10.23
	WJ - Auditory Working Memory		65	116.66	16.11
	K-ABC - Spatial Memory		65	11.11	3.10

Table 2. Above the dark gray diagonal are zero-order correlations. Below the dark gray diagonal are partial correlations, controlling for age.

Task			1	2	3	4	5	6	7
Cross-modal Arithmetic	**1**	Total				.20	.34*	.03	.13
	2	Addition			.22	.20	.29*	.03	.09
	3	Subtraction		.21		.12	.26	.02	.09
Approximate Symbolic Arithmetic	**4**	Total	0.14	.15	.07				.64***
	5	Addition	0.34*	.29*	.25			.44**	.53***
	6	Subtraction	-0.06	-.04	-.04		.21		.45**
WJ - Calculation	**7**		0.06	.02	.03	.27	.12	0.18	

*$p < .05$, **$p < .01$, ***$p < .001$

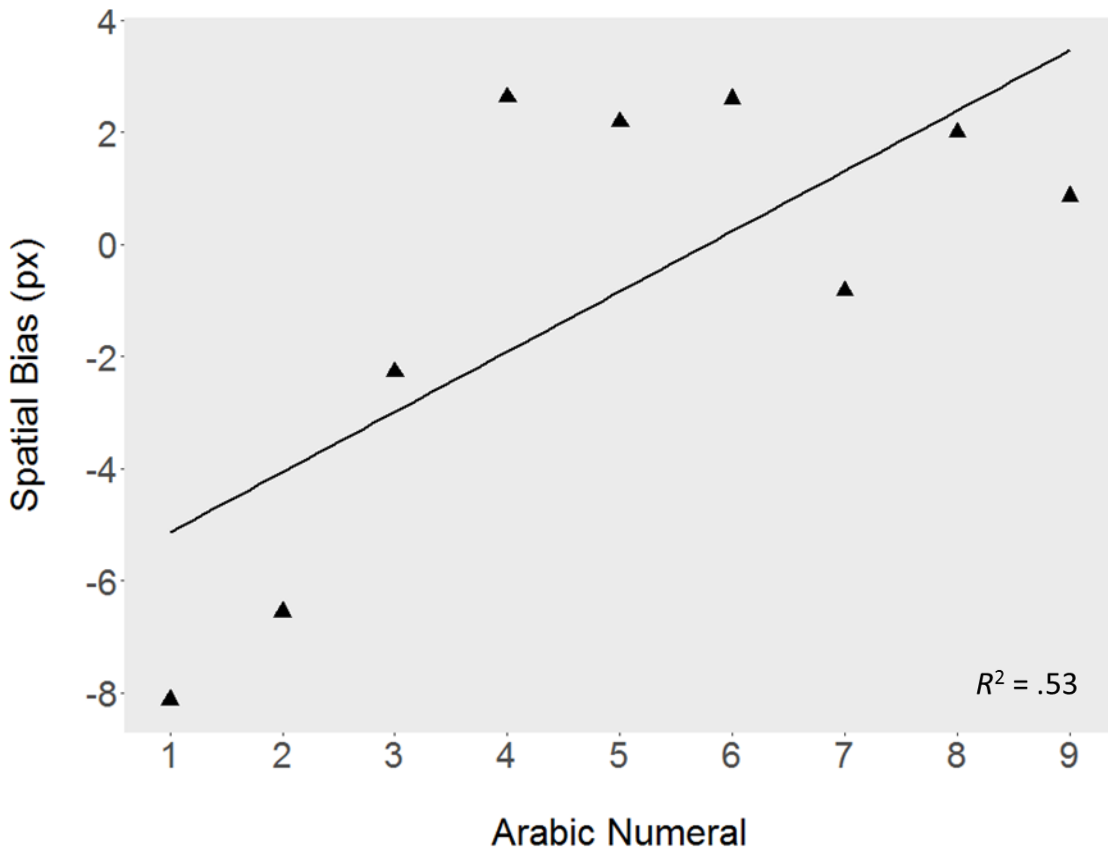

Figure 1. SNA on the place-the-number task. Regressing the group mean bias for each numeral on their corresponding value revealed numerical value to be a significant predictor of mean bias for each number, R^2 = .53, $t(8) = 2.78$, $p < .05$, providing evidence of an SNA on a novel task for children.

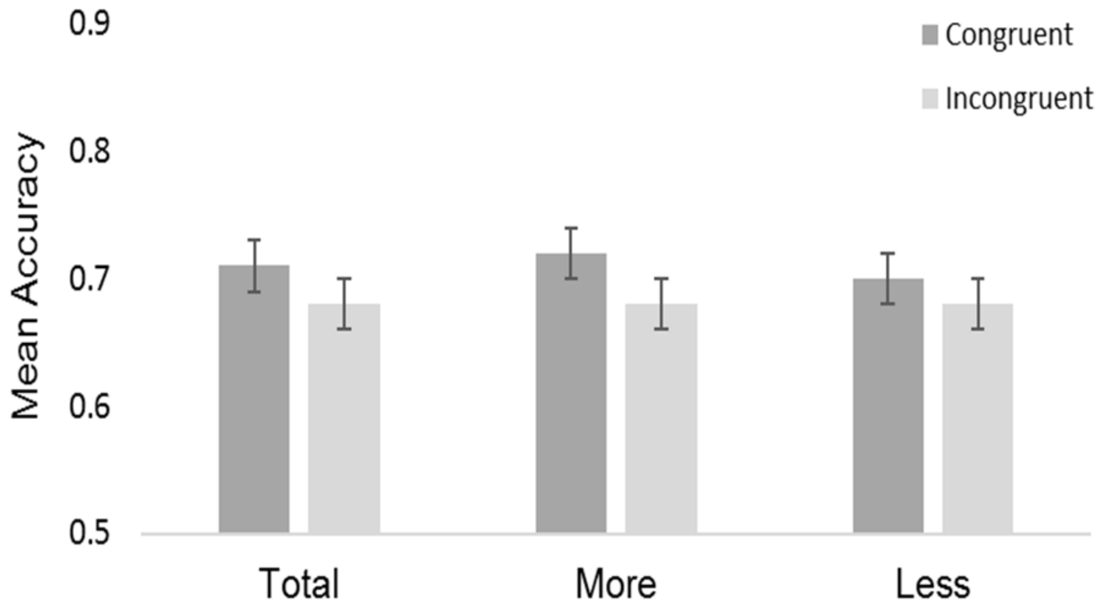

Figure 2. Mean accuracy (i.e., proportion correct) on the magnitude comparison task as a function of condition (Total, More, and Less) and trial type (incongruent or congruent). Children had significantly greater total accuracy on congruent than incongruent trials, $t(63) = 2.13$, $p < .05$, $d = .27$, providing evidence for a significant SNA. Error bars represent +/- 1 SEM.

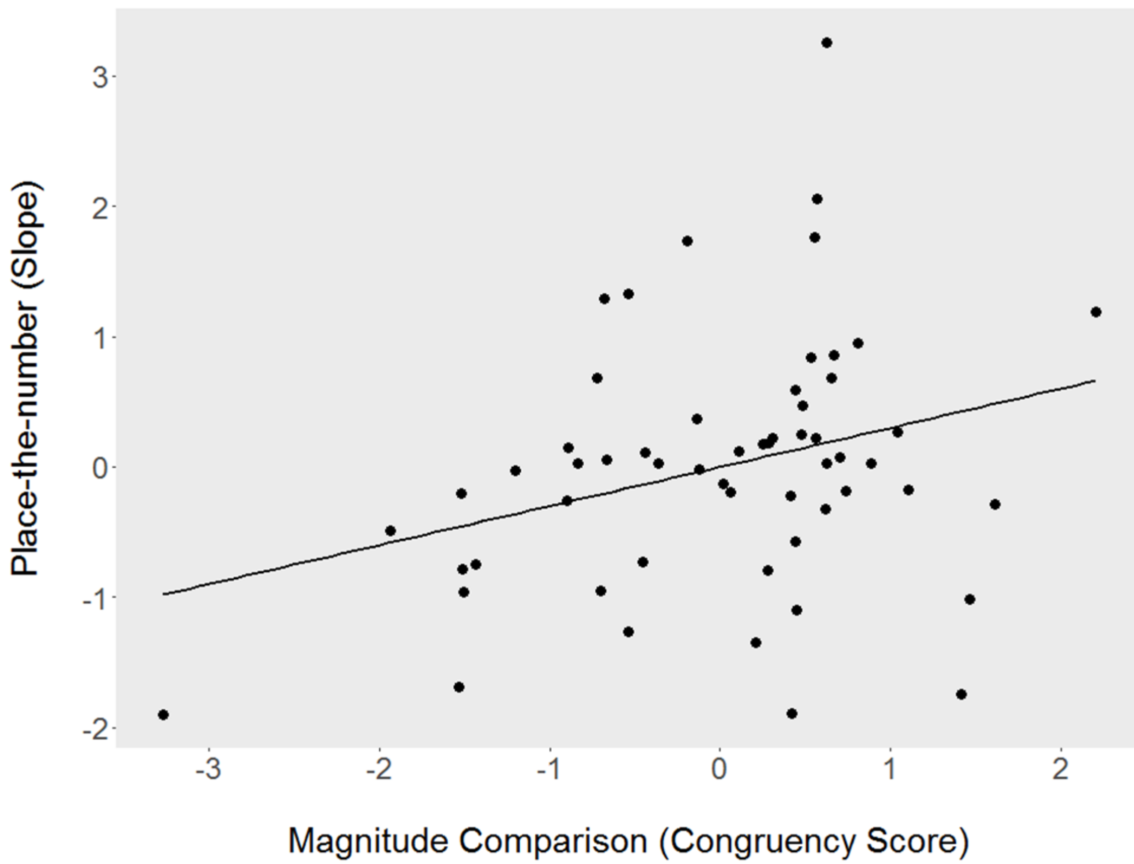

Figure 3. Partial correlation scatterplot between both SNA tasks (magnitude comparison and place-the-number), when controlling for overall accuracy on both tasks, $r_p(53) = .30$, $p < .05$. No data points qualified as bivariate outliers using the criterion of 2.5**SD* from the mean.

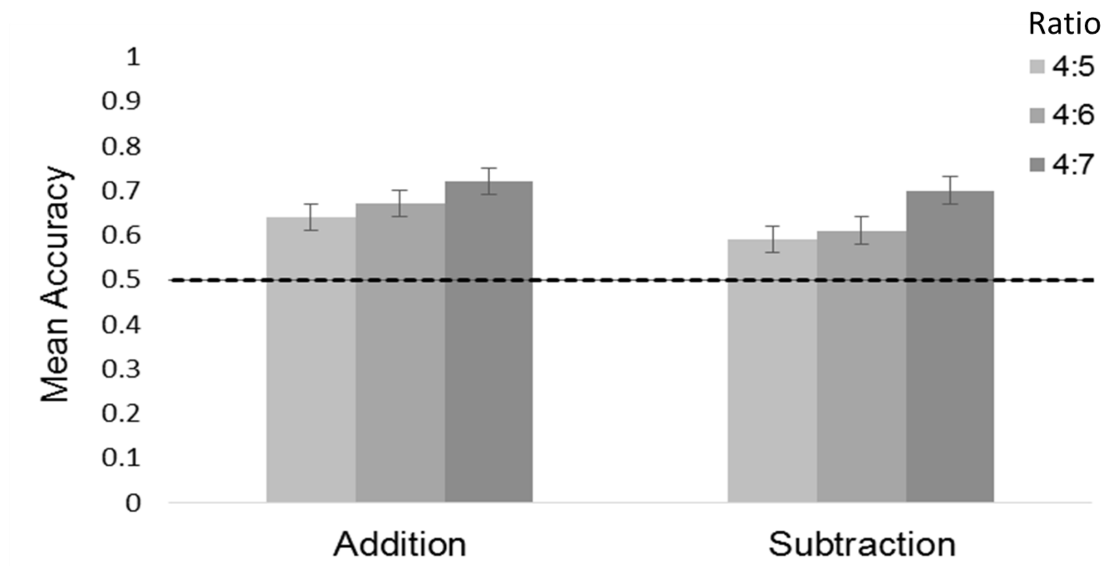

Figure 4. Mean accuracy (i.e., proportion correct) on the cross-modal arithmetic task as a function of operation (addition and subtraction) and ratio (4:5, 4:6, and 4:7). Error bars represent +/- 1 SEM. Black dashed line denotes chance performance.

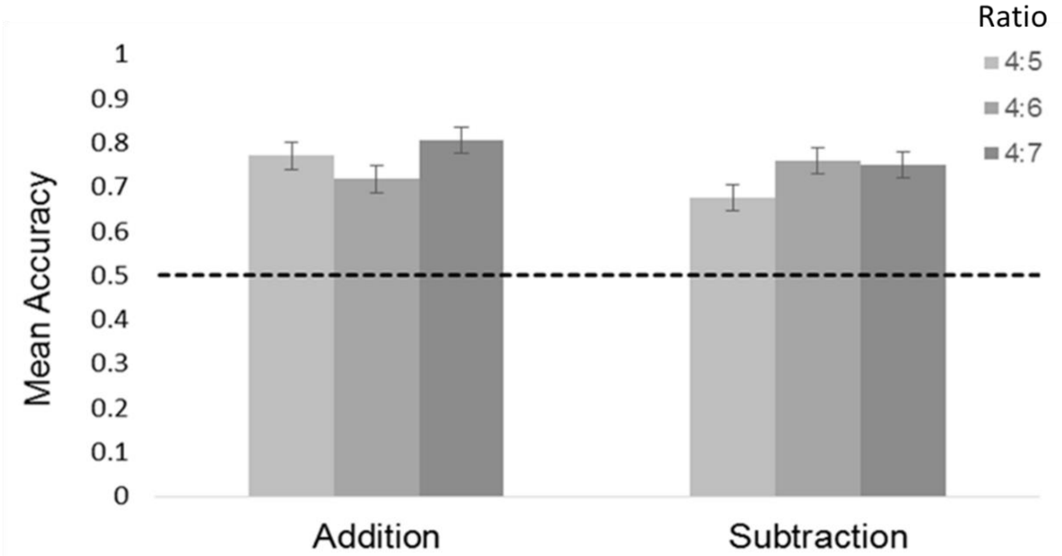

Figure 5. Mean accuracy (i.e., proportion correct) on approximate symbolic arithmetic as a function of operation (addition and subtraction) and ratio (4:5, 4:6, and 4:7). Error bars represent +/- 1 SEM. Black dashed line denotes chance performance.