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Development of SNARC and distance effects and their relation to mathematical and visuospatial abilities

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A B S T R A C T

The current experiment measured symbolic SNARC (Spatial–Numeric Association of Response Codes) and distance effects in school-aged children and investigated the relation between these measures and visuospatial skills and mathematics ability. In the experiment, 6-, 7-, and 8-year-olds performed a magnitude-relevant SNARC task, in which they indicated whether a target number was less or greater than 5, as well as standardized tests of visuospatial skills (Developmental Test of Visual Perception–Second Edition, DTVP-2) and mathematics ability (Test of Early Mathematics Ability–Third Edition, TEMA-3). Consistent with previous research using numerical SNARC tasks with Western children, all age groups exhibited robust distance effects, and SNARC effects were observed only in 7- and 8-year-olds. Distance effects, but not SNARC effects, were moderately but significantly correlated with a subtest of the DTVP-2 measuring the ability to mentally manipulate objects in space but no other subtest. These data suggest that mental orientation abilities, but perhaps not visuospatial skills involved in visual perception and visuomotor coordination, are related to some aspects of mental number line development. Nevertheless, no relation was observed between SNARC or distance effects and mathematics ability. This result is consistent with previous developmental studies investigating the association between SNARC and math skill. However, these data are inconsistent with most experiments assessing the relationship between distance effect strength and math—a difference that can likely be attributed to the fact that a magnitude-relevant SNARC task was employed as opposed to a traditional SNARC parity task.

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Introduction

Adults appear to automatically map number onto space in a consistent directional manner. For example, when Western adults indicate the parity (i.e., odd or even) of an Arabic number with left or right key presses, they respond faster to smaller numbers (i.e., 1–4) with a left-sided response and to larger numbers (i.e., 6–9) with a right-sided response (the Spatial–Numeric Association of Response Codes [SNARC] effect; Dehaene, Bossini, & Giraux, 1993). A similar effect is observed when Western adults indicate whether an Arabic digit is less or greater than a target digit; left-sided key presses are faster when indicating a "less than" response, and right-sided key presses are faster when indicating a "greater than" response (e.g., Dehaene, Dupoux, & Mehler, 1990). This association is so robust that it influences visual attention, such that smaller numbers cue attention to the left visual field and larger numbers cue attention to the right visual field (Fischer, Castel, Dodd, & Pratt, 2003). SNARC-like effects are typically interpreted as behavioral manifestations of a horizontal mental number line oriented from left to right, resulting in faster manual responses when the response side and the position of the number on the mental number line are congruent (Fias, 1996; Fischer et al., 2003; Nuerk, Bauer, Krummenacher, Heller, & Willmes, 2005).

Further evidence of an association between numbers and space comes from the numerical distance effect: faster responses to indicate the larger of two distant digits (e.g., 1 and 9) than two digits closer in magnitude (e.g., 1 and 2) (Moyer & Landauer, 1967). This phenomenon is consistent with a linear organization of neural populations in which each population optimally responds to a specific numerosity while to some degree also responding to close-by numerosities represented by adjacent populations, impairing the discrimination of adjacent (but not distant) numbers (Dehaene et al., 1990; Nieder, 2005).

Children's mental number line

Characteristics of the directional mental number line reported in adults are also observed in children. In the first investigation into the development of the SNARC effect, Western children performed the traditional SNARC parity task, and a left-to-right SNARC effect was observed in 9-year-olds but not in 7-year-olds (Berch, Foley, Hill, & Ryan, 1999). Berch and colleagues (1999) noted that these findings did not negate the possibility of a directional mental number line in even younger children given that their youngest group of participants exhibited relatively slow and highly variable reaction times, which may have obscured any number–space mappings.

Indeed, subsequent studies with modified methods have revealed traditional SNARC or SNARC-like effects in even younger children. One group of researchers increased the power of Berch and colleagues' (1999) design by presenting more trials per digit and providing feedback to groups of 6-, 7.5-, and 8.5-year-olds (White, Szücs, & Soltész, 2012). SNARC effects were evident in reaction times for both the 7.5- and 8.5-year-olds but not for the 6-year-olds, and they were evident in accuracy data (i.e., greater accuracy for congruent trials than for incongruent trials) for only the 8.5-year-olds. These data suggest that spatial information is automatically activated by magnitude in children as young at 7.5 years and that their number sequences run from left to right. However, they leave uncertainty about younger children because of the inherent difficulty of a parity task for children younger than approximately 8 years. To address this limitation, two SNARC-like paradigms previously used with adults were adapted for use with 7-, 8-, and 9-year-old children (van Galen & Reitsma, 2008). First, the children performed a magnitude-irrelevant task based on the attentional SNARC effect (Fischer et al., 2003). Like adults, 9-year-olds, but not 7- or 8-year-olds, exhibited an attentional left-to-right SNARC effect; after viewing small numbers (i.e., 1–4) they detected leftward targets faster, whereas after viewing large numbers (i.e., 6–9) they were faster to detect targets in the rightward box. In a second magnitude-relevant task, the same three groups indicated whether an Arabic digit was greater or less than 5 with a left- or right-handed response. Unlike the magnitude-irrelevant task, all three age groups exhibited a SNARC effect on this second task. Together, these data suggest that by 7 years of age Western children automatically map numbers onto space in a left-to-right manner; nevertheless, merely seeing a digit does not automatically cue its magnitude and spatial location until 9 years of age.

Unlike the results for Western children, a SNARC effect using the traditional SNARC parity task has been observed in Chinese children as young as 5 years (Yang et al., 2014). This earlier automatic processing of number magnitude, and an earlier understanding of the concept of parity, is likely a result of earlier training and acquisition of mathematical principles in Chinese children (Zhou et al., 2007).

The absence of SNARC-like effects in Western children under 7 years of age is perplexing, particularly given evidence that even (Western) preschoolers exhibit a left-to-right bias when counting and ordering objects or sequence items (Opfer & Thompson, 2006; Opfer, Thompson, & Furlong, 2010). Predicting that task difficulty was responsible for a lack of SNARC effect under 7 years, three recent studies employed SNARC-like paradigms adapted for testing young children. In the first, a magnitude-irrelevant SNARC task was used in which children were presented with black Arabic digits that turned red or green after 200 ms; participants (5-year-olds) indicated whether the number had turned red or green with a left- or right-sided response (Hoffmann, Hornung, Martin, & Schiltz, 2013). The 5-year-olds exhibited a SNARC effect, responding faster to smaller numbers with the left hand and to larger numbers with the right hand. In a second study, 4-year-olds were presented with two arrays of objects on a touch screen and asked to indicate by touching the screen which array had more objects (Patro & Haman, 2012). Children responded faster to large numerosities on the right side of the screen and to small numerosities on the left side of the screen than the opposite mapping, suggesting that children as young as 4 years have automatic access to a left-to-right mental number line. A study with a similar methodology, in which children indicated with a left or right key press which of two adjacent dot arrays had more items, revealed a SNARC-like effect in 6-year-olds (Ebersbach, Luwel, & Verschaffel, 2014).

Despite the mixed results for the SNARC effect in 4- to 8-year-olds, children of the same age consistently exhibit a robust distance effect; when asked to judge which of two Arabic digits is larger, children as young as 6 years respond faster to distant numbers (e.g., 1 and 9) than to numbers close in magnitude (e.g., 5 and 6) (Sekuler & Mierkiewicz, 1977). The strength of the distance effect decreases with age, with younger children (e.g., 6-year-olds) exhibiting larger distance effects than older children (e.g., 13-year-olds) (Duncan & McFarland, 1980; Holloway & Ansari, 2008; Sekuler & Mierkiewicz, 1977). These data support the hypothesis that even young children possess an internal, directionally oriented mental number line.

Relation between mental number line and children's visuospatial skills

The mental number line is hypothesized to be a spatial representation of numerosity. Hence, it is possible that visuospatial abilities modulate the development of, and reliance on, the mental number line and, in turn, influence mathematics ability—or vice versa. There is some evidence suggesting that measures of visuospatial skills and mathematics skills are correlated with one another. For example, in a sample of high school students, mental rotation skills and visuospatial working memory (both visuospatial skills) correlated with a measure of mathematics ability (Reuhkala, 2001). These results converge with evidence that children with visuospatial disabilities exhibit difficulties with written mathematics, particularly with problems that require borrowing and carrying (Venneri, Cornoldi, & Garuti, 2003). One experiment revealed that, in contrast to a control group, 7- to 12-year-olds with visuospatial deficits did not exhibit a SNARC effect at the group level (Bachot, Gevers, Fias, & Roeyers, 2005); however, these children had comorbid dyscalculia, so it is unclear whether a lack of SNARC effect was related to underlying visuospatial or numerical deficits. One recent study in adults reports a negative correlation between two-dimensional mental rotation abilities and the SNARC effect, such that individuals with weaker SNARC effects exhibited superior mental rotation performance (Viarouge, Hubbard, & McCandliss, 2014). Nevertheless, to our knowledge no study to date has investigated the link between measures of visuospatial skills and the SNARC effect in typically developing children.

Relation between mental number line and children's mathematics ability

The mental number line has been hypothesized to be the core of the "number sense"; that is, it is believed to be represented by a fundamental neural architecture on which complex mathematical abilities are built (e.g., Dehaene, 1997). This hypothesis is supported by evidence that, unlike age-matched controls, children with dyscalculia as a group do not exhibit the SNARC effect and exhibit a smaller distance effect than age-matched controls (Bachot et al., 2005; Rousselle & Noël, 2007). These data suggest that typical development of the mental number line may be critical for normal mathematics processing. However, studies that have investigated this relationship directly report either a paradoxically negative relationship—with superior mathematics ability associated with weaker SNARC or distance effects in adults (e.g., Dehaene et al., 1993; Fischer & Rottmann, 2005; Hoffmann, Mussolin, Martin, & Schiltz, 2014)—or no relationship at all (Cipora & Nuerk, 2013). These data suggest either that adults proficient in mathematics have a lesser degree of left-to-right number line directionality or that the directionality is less salient to number processing than in those with comparatively poorer math skills. Both of these possibilities run contrary to the hypothesis that the mental number line is at the core of number processing.

In children, only two studies have investigated the relationship between the SNARC effect and math ability. In the first, boys' mathematics ability at 5.5 years of age, but not their math ability at 8 years, was correlated *negatively* with the degree of left-to-right directionality of their SNARC effects at 8 years (as measured by a parity task); however, for girls, as well as collapsed across sex, there was no systematic relationship between these variables (Schweiter, Weinhold Zulauf, & von Aster, 2005). In the second study, 11-year-olds' performance on the traditional SNARC parity task (i.e., from Dehaene et al., 1993) did not correlate with their mathematics grades or with their performance in interpreting graphs (Schneider, Grabner, & Paetsch, 2009). However, there are problems with the measure of the SNARC effect used in both of these studies. In the first, reaction times of only right-handed responses were analyzed, which is unprecedented and an odd choice considering that the SNARC effect is, by definition, differential responding biases between the left and right hands. In the second study, the measure of the SNARC effect calculated, the beta coefficient of the regression slope of each participant's right-hand reaction time (RT) minus left-hand RT (difference in reaction time, dRT) regressed onto target magnitude, is commonly used in the literature (e.g., Fias, Brysbaert, Geypens, & d'Ydewalle, 1996). In this procedure, for each number, the mean (or median) RT of each participant's left hand is subtracted from the mean (or median) RT of the participant's right hand, yielding the difference in reaction time between the two hands; dRT is subsequently regressed onto number magnitude. Using this method, a left-to-right SNARC effect is characterized by a regression slope that is significantly more negative than zero. It is problematic, however, that despite the SNARC effect being described as a categorical difference in responses between low and high numbers, the dRT regression slope (particularly in a magnitude-relevant task) takes into account the different magnitudes of the target numbers—and, therefore, is necessarily confounded by participants' distance effects. To accurately assess the relationship between the SNARC effect and math ability, an alternative more categorical measure of the SNARC effect needs to be employed. One purpose of the current experiment was to investigate the SNARC effect in children using this new measure.

In most developmental studies to date, the size of the non-symbolic distance effect does not correlate with measures of mathematics achievement (e.g., 6- to 8-year-olds: Holloway & Ansari, 2009; 5-, 6-, 7-, and 11-year-olds: Sasanguie, De Smedt, Defever, & Reynvoet, 2012; 5- to 7-year-olds: Sasanguie, Van den Bussche, & Reynvoet, 2012; but see Lonnemann, Linkersdörfer, Hasselhorn, & Lindberg, 2011, for a positive correlation between a subtraction task and distance effects in 8- to 10-year-olds). The size of the symbolic distance effect, however, has been shown to have a robust *negative* relationship to mathematics ability in many (e.g., Holloway & Ansari, 2009; Sasanguie, Göbel, Moll, Smets, & Reynvoet, 2013; Sasanguie et al., 2012; Vanbinst, Ghesquière, & De Smedt, 2012), but not all (Ferreira et al., 2012; Lonnemann et al., 2011), developmental studies. The negative correlation between distance effects and math abilities is consistent with the above SNARC investigations; together, the two lines of evidence suggest that mathematical competency is characterized by less reliance on, and/or a less cognitively salient, mental number line. It is possible, however, that the mental number line (i.e., as measured by SNARC and distance effects) is fundamental to math and numerical processing at an early age when math concepts and numerical understanding are just beginning to develop—particularly because the strength of both effects decreases with age (Holloway & Ansari, 2008; van Galen & Reitsma, 2008). The more sophisticated mathematics ability in adults, on the other hand, may be characterized by more advanced computational strategies and, therefore, less reliance on the mental number line.

The current study

The current study investigated the relation among mental number line strength (as measured by SNARC and distance effects), visuospatial abilities, and math skills in typically developing children. In the study, 6-, 7-, and 8-year-olds performed a magnitude-relevant SNARC task. In congruent blocks, children indicated whether a number on-screen was less than 5 with a left-handed key press or greater than 5 with a right-handed key press; incongruent blocks had the opposite mapping. The order of blocks (congruent or incongruent) was counterbalanced, and they were performed on separate days. This task allowed us to calculate independent SNARC and distance effect measures for each child. Children were also administered standardized tests that measured math and visuospatial skills. Unlike previous studies, this design allowed us to assess the symbolic SNARC and distance effects with separable measures and to evaluate their relationship to developing visuospatial and mathematical skills.

Method

Participants

Participants were recruited from a database of parents who volunteered their children for future experimental testing during hospital visits shortly after their children's births. The final sample consisted of 20 6-year-olds (±3 months, M = 6.04 years, SD = 0.10, 13 boys), 20 7-year-olds (±3 months, M = 6.99 years, SD = 0.11, 7 boys), and 20 8-year-olds (±3 months, M = 8.02 years, SD = 0.10, 13 boys). Data of an additional 12 participants were excluded from the final sample because the children did not return for the obligatory second laboratory visit (2 6-year-olds and 2 7-year-olds), because they had an error rate above 25% (2 6-year-olds, 1 7-year-old, and 2 8-year-olds), or because they did not follow task instructions (3 6-year-olds). The parents accompanying the children gave informed consent. Participants were rewarded for their participation with their choice of a toy.

Apparatus

The SNARC task was programmed using SuperLab 4.0 running on a Macintosh Mini computer. A Dell Trinitron P1130 50-cm monitor with a resolution of 1152 × 870 and refresh rate of 75 Hz displayed the stimuli. Participants were seated on a raised chair 60 cm from the screen so that the screen was at roughly eye level. They made manual responses using the "x" key with the left hand and the "." key with the right hand on a Macintosh keyboard placed directly in front of them. As a visual aid, each response key was marked with a colored sticker. In addition, as in the setup used by van Galen and Reitsma (2008), two small white cards were taped above the response keys; one card displayed a small black circle and indicated the response key for numbers less than 5, and the other card displayed a large black circle and indicated the response key for numbers greater than 5. On the day with congruent mapping, the card with the small black circle was placed over the more leftward "x" key and the card with the large black circle was placed over the more rightward "." key; on the day with incongruent mapping, the cards were reversed.

The experimental stimuli consisted of Arabic digits 1 through 9 (excluding 5). Each target number appeared in black Times New Roman 110-point font centered on a white screen and subtended a visual angle of 2.24 degrees. The digits appeared in the center of a white, black-bordered box with sides 100 pixels in length and a stroke width of 2 pixels.

To evaluate children's mathematical skills, we administered the Test of Early Mathematics Ability–Third Edition (TEMA-3; Ginsburg & Baroody, 2003). The TEMA-3 is a comprehensive standardized measure of mathematics ability, testing both formal math skills typically gained with explicit instruction and those informal number skills that children acquire without direct instruction. Standard scores (Math Ability Scores) on the TEMA-3 are age-referenced and based on a mean of 100 with a standard deviation of 15, and the measure is normed for use with children aged 3 years 0 months to 8 years 11 months.

To evaluate children's visuospatial abilities, we administered three subtests of the Developmental Test of Visual Perception–Second Edition (DTVP-2; Hammill, Pearson, & Voress, 1993). The three subtests were used to assess spatial orientation abilities: (a) the Position in Space subtest, which assesses spatial orientation ability by having children match two figures, one of which has been rotated and/or reversed; (b) the Spatial Relations subtest, which tests the ability to reproduce dot patterns that form increasingly complex shapes; and (c) the Figure–Ground subtest, which measures the ability to distinguish shapes embedded in complex designs. Scaled stores on the DTVP-2 are age-referenced with a mean of 10 and a standard deviation of 3, and the measure is normed for children aged 4 through 9 years of age.

Procedure

Children performed each response mapping (i.e., congruent and incongruent) in a magnitude-relevant SNARC task. Each response mapping was tested in an independent session on a separate day in order to minimize fatigue and prevent confusion over the switch in response mapping from the first SNARC task to the second one. Block and test order were counterbalanced across participants.

The SNARC task commenced with a brief explanation of the task by the experimenter, after which the experimenter performed 12 demonstration trials to familiarize participants with the task. Each participant subsequently performed 16 practice trials. Each experimental trial began with a black-bordered square presented on the screen. After 1000 ms, the target number appeared in the center of the box and remained on the screen until the participant responded or 5000 ms had elapsed. Following each trial, there was a blank screen for 1000 ms before the beginning of the next trial.

On each visit to the lab, after the practice trials, participants performed 14 blocks of 8 trials, 1 trial for each number from 1 through 9, excluding 5, presented in randomized order. There was a brief break after 7 blocks. In the congruent trial blocks (presented during one session), participants were instructed to push the "x" key with their left hand if the target number was less than 5 and to push the "." key with their right hand if the target number was greater than 5. For the incongruent trial blocks (presented during the other of the two sessions), participants performed the opposite mapping. Participants were instructed to respond as quickly and accurately as possible.

Following completion of the SNARC task during the first session, participants were administered either the TEMA-3 or the DTVP-2 by the experimenter. The other standardized task was administered after the second session. The order of standardized tests was counterbalanced across children in each age group. Each session was approximately 30 to 40 min in duration.

Results

For each participant, we calculated the median RT on correct trials for each target number separately for the congruent and incongruent conditions. Error rates were generally low (6-year-olds: 7.54%; 7-year-olds: 6.08%; 8-year-olds: 5.45%), and data of 5 additional participants with error rates greater than 25% were excluded (see "Participants" section above). There was no evidence of a speed–accuracy trade-off at any age, as indicated by a lack of negative correlation between mean RT and error rates across all trials for 6-year-olds ($r = .119$, $p = .464$), 7-year-olds ($r = .159$, $p = .327$), or 8-year-olds ($r = .096$, $p = .567$). See Table 1 for the mean scores for each of the standardized tests for each age group.

In line with the goals of the current study, we wished to determine whether SNARC and numerical distance effects were present within each level of age. For that reason, and to be consistent with previous literature (e.g., van Galen & Reitsma, 2008), we calculated a 2 (Response Hand: left vs. right hand) $\times$ 2 (Target Magnitude: low [i.e., 1–4] vs. high [i.e., 6–9] digit) $\times$ 4 (Distance: distance of the target from the number 5) repeated measures analysis of variance (ANOVA) for each age group. With this type of analysis, a SNARC effect emerges as an interaction between response hand and target magnitude, with the left hand responding faster to low numbers and the right hand responding faster to high numbers. A distance effect emerges as a main effect of distance, with participants responding faster to numbers further from 5 (e.g., 1 and 9) than numbers closer to 5 (e.g., 4 and 6).

Table 1
Means (and standard deviations) for each age group for the three administered subtests of the DTVP-2 (Position in Space, Figure–Ground, and Spatial Relations) and the TEMA-3 Math Ability Score

Age (years)	Position in Space	Figure–Ground	Spatial Relations	TEMA-3 MAS
6	16.5 (4.51)	11.15 (3.17)	39.45 (3.59)	106.25 (10.59)
7	20.05 (2.89)	12.90 (2.85)	41.85 (1.66)	110.35 (12.24)
8	20.15 (2.78)	12.65 (2.72)	41.60 (2.37)	104.60 (14.05)

Note. MAS, Math Ability Score.

To quantify the magnitude of the SNARC effect for each individual, we took the difference in median RTs for congruent and incongruent blocks divided by their sum, $S = (C - I)/(C + I)$. This formula expresses the strength of the congruency (i.e., SNARC effect) as a proportion of each participant's average reaction time and, hence, adjusts for differences among participants in speed of responding. Using this formula, a left-to-right SNARC effect is expressed as a negative number. To calculate a measure of each individual's numerical distance effect, we used a method modeled after that reported by Holloway and Ansari (2009) in a manner that was consistent with our SNARC effect formula. Collapsed across congruent and incongruent trials, each participant's median RTs for far numbers (i.e., 1 and 9) was subtracted from the participant's median RTs for close numbers (i.e., 4 and 6); this difference was then divided by the sum of median RTs for close and far numbers, thereby expressing the distance effect as a proportion of each individual's RT. With this measure, a larger distance effect is revealed by a larger positive number.

SNARC and distance effects

6-year-olds

For 6-year-olds, there was a main effect of distance, $F(3, 37) = 15.289$, $p < .001$, $^2 = .446$, such that numbers close to 5 (i.e., 4 and 6) were responded to significantly more slowly than those far from 5 (i.e., 1 and 9), $t(19) = 4.917$, $p < .001$, $d = 1.10$. There was also a significant Target Magnitude × Distance interaction, $F(3, 57) = 4.251$, $p = .009$, $\eta^2 = .183$, such that at a distance of 4 (i.e., 1 and 9), but not any other distance, low numbers were responded to significantly faster than high numbers, $t(19) = -2.190$, $p = .041$, $d = 0.49$. Crucially, the Response Hand × Target Magnitude interaction did not near significance ($p = .569$, $\eta^2 = .017$; see Fig. 1A), providing no evidence of a SNARC effect. No other interactions were significant.

7-year-olds

For 7-year-olds, there was a main effect of target magnitude, $F(1, 19) = 4.494$, $p = .047$, $\eta^2 = .191$, with low numbers being responded to significantly faster than high numbers, $t(19) = -2.120$, $p = .047$, $d = 0.474$. There was also a main effect of distance, $F(3, 57) = 14.907$, $p < .001$, $\eta^2 = .440$, with numbers at a distance of 4 (i.e., 1 and 9) being responded to significantly faster than those at a distance of 1 (i.e., 4 and 6), $t(19) = -4.516$, $p < .001$, $d = 1.010$. The interaction between hand and target magnitude was marginally significant, $F(1, 19) = 4.108$, $p = .057$, $\eta^2 = .178$, with the left hand responding significantly faster to low versus high numbers, $t(19) = -2.503$, $p = .022$, $d = .560$ (see Fig. 1B).

8-year-olds

For 8-year-olds, there was a main effect of distance, $F(3, 17) = 17.858$, $p < .001$, $\eta^2 = .485$, with numbers at a distance of 1 (i.e., 4 and 6) being responded to significantly more slowly than those at a distance of 4 (i.e., 1 and 9), $t(19) = 4.693$, $p < .001$, $d = 1.049$. There was also a marginally significant main effect of hand, $F(1, 19) = 4.202$, $p = .054$, $\eta^2 = .181$, with right-handed responses being slightly faster, $t(19) = 2.05$, $p = .054$, $d = 0.458$. Crucially, there was a significant interaction between hand and target magnitude, $F(1, 19) = 6.70$, $p = .018$, $\eta^2 = .261$. Dissection of the interaction revealed that for the left hand participants responded significantly faster to low numbers, $t(19) = -2.464$, $p = .023$, $d = 0.551$, and for the right hand participants responded significantly faster to high numbers, $t(19) = -2.251$, $p = .036$, $d = 0.503$ (see Fig. 1C). There was also a significant three-way interaction among hand, target

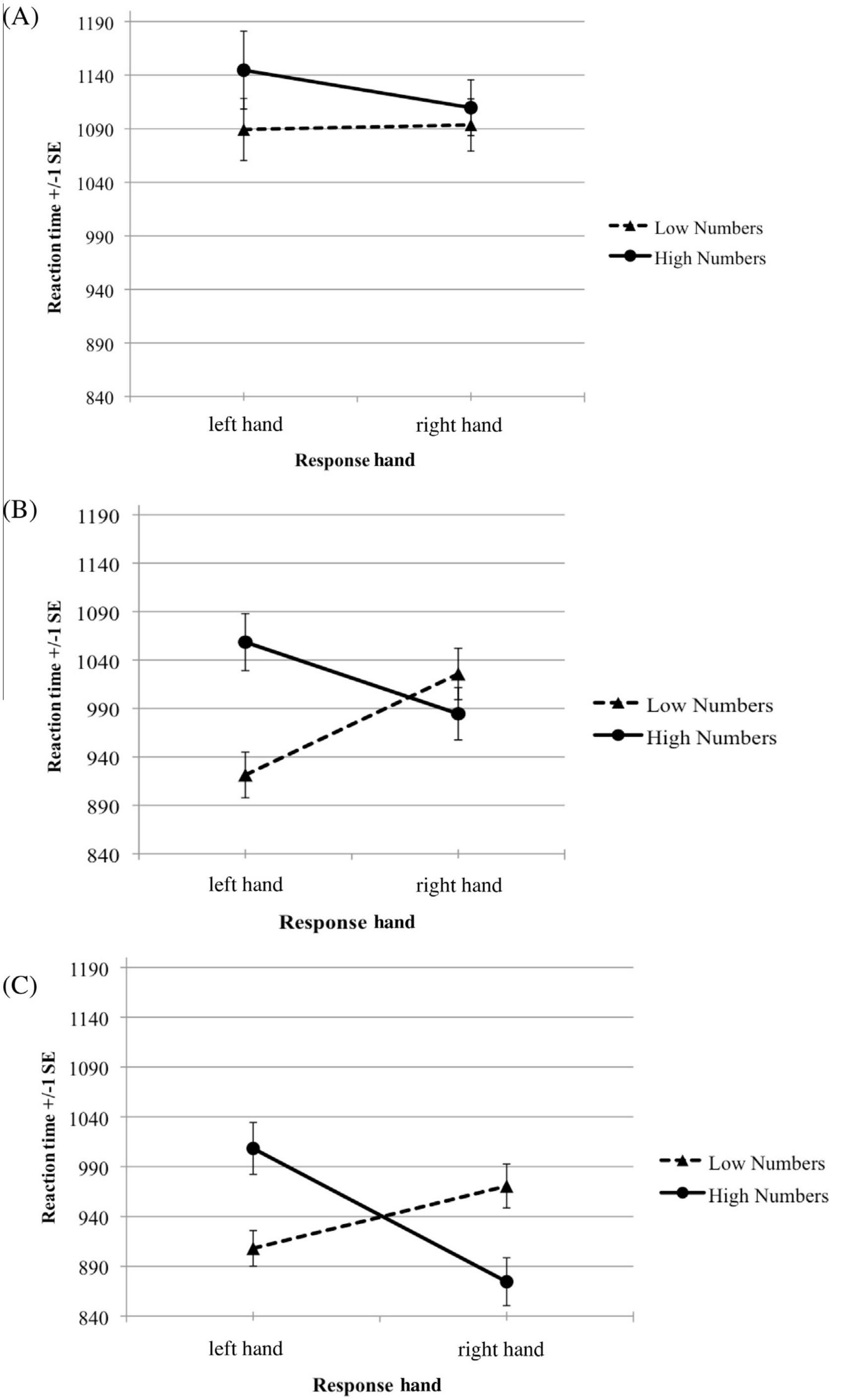

Fig. 1. Mean of the median RTs for each hand for low and high numbers for 6-year-olds (A), 7-year-olds (B), and 8-year-olds (C). Standard error bars were calculated using within-participants variability, as described by Cousineau (2005).

magnitude, and distance, $F(3, 17) = 4.681$, $p = .005$, $\eta^2 = .198$. To dissect this interaction, we looked at the relationship between response hand and target type at each level of distance. At a distance of 1 (i.e., 4 and 6), left-handed responses were significantly faster for low numbers, $t(19) = -2.374$, $p = .028$, $d = 0.531$, and right-handed responses were faster for high numbers, $t(19) = 2.936$, $p = .008$, $d = 0.657$; at a distance of 3 (i.e., 2 and 8), the left hand responded significantly faster to low numbers, $t(19) = -2.532$, $p = .020$, $d = 0.566$, and the right hand responded faster to high numbers, $t(19) = 2.941$, $p = .008$, $d = 0.658$; and at a distance of 4 (i.e., 1 and 9), the left hand responded significantly faster to low numbers, $t(29) = -2.621$, $p = .017$, $d = 0.586$. There was no significant difference in RTs between the left and right hands for high and low numbers at a distance of 2 ($ps > .40$).

Partial correlation analyses

Partial correlation analyses were performed to determine whether our measures of the mental number line (i.e., SNARC and distance effects) exhibited systematic relationships with mathematics ability and visuospatial skills across our entire sample while controlling for age. A similar analysis was also used to test whether children's SNARC and distance effects correlated with one another. Based on findings from adults and children with visuospatial disabilities, we expected visuospatial skills to correlate with both the SNARC and distance effects. Similarly, because the symbolic distance effect is typically related to measures of math skills in school-aged children (e.g., Holloway & Ansari, 2009; Sasanguie et al., 2012, 2013; Vanbinst et al., 2012), we predicted that children's distance effects would correlate with our standardized measure of mathematics ability. Lastly, although previous studies have not revealed an association between SNARC effect strength and math ability in children (Schneider et al., 2009; Schweiter et al., 2005), because of our revised methodology and analyses, we predicted that our SNARC effect measure would correlate with children's math ability. For these correlations, data points with values more than 3 standard deviations from the group mean were omitted.

SNARC correlations. Controlling for age and multiple comparisons, the correlation between participants' raw score on the Position in Space subtest of the DTVP-2 and the SNARC effect was not significant ($\alpha = .0125$), $r = -.195$, $p = .069$. Correlations between the SNARC effect and raw scores on the Figure–Ground and Spatial Relations subtests did not approach significance, $p = .427$ and $p = .169$, respectively; neither did the correlation between participants' SNARC effect and their TEMA-3 Math Ability Score, $p = .129$.

Distance effect correlations. Controlling for participant age and adjusting for multiple comparisons ($\alpha = .0125$), there was a significant correlation between participants' raw scores on the Position in Space subtest of the DTVP-2 and their distance effect, $r = .332$, $p = .005$ (see Fig. 2; the outlying score of 1 6-year-old was excluded from this analysis). Correlations between the distance effect and raw scores on the Figure–Ground and Spatial Relations subtests were not significant, $p = .264$ and $p = .113$, respectively; neither was the correlation between the distance effect and TEMA-3 Math Ability Score, $p = .495$.

SNARC and distance effects. When controlling for age, there was not a significant correlation between participants' SNARC and distance effects, $r = -.06$, $p = .325$.

Discussion

The current experiment investigated the relationship between the development of the mental number line and children's visuospatial and mathematics abilities. The 6-, 7-, and 8-year-olds performed a magnitude-relevant SNARC task, allowing calculation of individual SNARC and distance effects—both of which are hypothesized to be measures of the strength of individual mental number lines. Participants also completed two standardized tests: the DTVP-2 (Hammill et al., 1993) and the TEMA-3 (Ginsburg & Baroody, 2003).

Consistent with previous literature, 7- and 8-year-olds (van Galen & Reitsma, 2008), but not 6-year-olds (White et al., 2012), exhibited magnitude-relevant SNARC effects at the group level. In

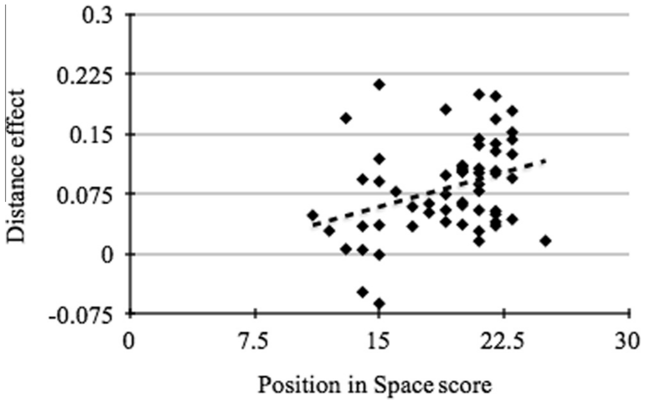

Fig. 2. Correlation between individual distance effect measures and scores on the Position in Space subtest of the DTVP-2. The dotted line shows the best-fitting linear regression line ($R^2 = .11$).

addition, similar to previous reports (e.g., Sekuler & Mierkiewicz, 1977), robust distance effects were observed for each age group, with participants responding faster to numbers further from 5 (e.g., 1 and 9) than those closer to 5 (e.g., 4 and 6).

The first goal of the current experiment was to assess the relationship between individual measures of mental number line strength and visuospatial abilities. Participants' performance on the Position in Space subtest of the DTVP-2, which measures spatial orientation ability, was moderately correlated with individual distance effects. These data suggest that, at least in 6- to 8-year-old children, mental visual orientation and mental rotation ability are related to the strength of their mental number line representation. Nevertheless, no correlation was observed between mental number line measures and two other DTVP-2 subtests that measured participants' ability to separate figure from ground in increasingly complex designs (i.e., Figure–Ground subtest) and to reproduce dot patterns that increase in complexity (i.e., Spatial Relations subtest). Therefore, it is possible that mental number line representation is related only to visuospatial abilities that involve the mental manipulation of form and space (e.g., mental rotation) but not those involved in visual perception or visuomotor skills. In the future, more comprehensive tests of mental rotation ability, in both children and adults, would be useful to further investigate this relationship. In addition, future investigations into whether the third commonly used measure of the mental number line (i.e., number line estimation tasks) correlates with certain visuospatial skills would be informative.

The second goal of the current study was to assess the relationship between the mental number line and mathematics ability using both the SNARC and distance effects as measures of the former. Contrary to our predictions, there was no relationship between individual measures of the SNARC and distance effects and TEMA-3 scores in our 6- to 8-year-old participants. Despite the use of different measures of mathematics ability, the lack of correlation between children's SNARC effect and math ability in our data is consistent with previous findings in fifth- and sixth-grade children (Schneider et al., 2009). Thus, it is possible that the specific directionality of children's mental number line has little or no bearing on their ability to manipulate numerosities in a mathematical context. Perplexingly, these findings stand in contrast to the adult literature, which has reported *negative* correlations between the degree of left-to-right directionality of the mental number line and math competency (Dehaene et al., 1993; Fischer & Rottmann, 2005; Hoffmann et al., 2014; but see Cipora & Nuerk, 2013)—a relationship typically interpreted as evidence that mathematically inclined adults rely more on advanced, abstract numerical operational strategies and less on mental number line constructs. Perhaps this discrepancy can be explained by mathematics exposure: school-aged children, by default, and adult undergraduates in math-based programs (e.g., accounting and engineering majors), but not liberal arts programs, are regularly exposed to, and engaged in, mathematics operations. Although the difficulty and complexity of these operations differ significantly between children and mathematically inclined adult undergraduates, it is possible that regular exposure to arithmetic, and not simply expertise in it, encourages the adoption of more advanced abstract strategies above and beyond reliance on a directional number line. Conversely, relatively less exposure to arithmetic (e.g., in liberal arts undergraduates) may cause individuals to rely more heavily on the directional number line.

Given the (relatively) consistent finding of a negative relationship between distance effect strength and math ability (e.g., Holloway & Ansari, 2009; Sasanguie et al., 2012, 2013; Vanbinst et al., 2012), the lack of correlation between these two measures in our data is surprising but not unprecedented (e.g., Ferreira et al., 2012; Lonnemann et al., 2011). The discrepancy between our data and those of others can likely be attributed to differences in stimulus parameters, paradigms, and methods for calculating the distance effect (see De Smedt, Noël, Gilmore, & Ansari, 2013, for a discussion). Notably, to calculate both SNARC and distance effects for each participant, the current study necessarily employed a magnitude-relevant SNARC task, whereas other studies have used a number comparison task (e.g., Holloway & Ansari, 2009). Our task asked children to indicate whether the target number is less or greater than 5 rather than indicating which of two target digits was larger. In our task, the largest comparison distance is 4 (i.e., between 1 and 5 and between 9 and 5), whereas in the digit comparison task using digits 1 through 9, distance between digits can go up to 8 (although most studies limit digit distance to 6, e.g., Holloway & Ansari, 2009; Lonnemann et al., 2011). Because the distance effect is defined by significant differences in response time between digits close together versus those further apart, distance effects will be larger when the possible comparisons span a larger range. Indeed, when one study parsed its digit comparison pairs into small (i.e., 1–3) and large (i.e., 4–6) distances, only the distance effects yielded by large distances, and not all distances overall, were significantly correlated with 8- to 10-year-olds' mathematics ability (Lonnemann et al., 2011). Therefore, it is conceivable that our stimuli did not yield distance effects strong enough to reveal true correlations with mathematics skill.

Lastly, our experimental paradigm enabled us to assess whether two highly cited measures of the mental number line, the SNARC and distance effects, are correlated with one another in 6- to 8-year-old children. One previous developmental study reported conflicting findings in older children, with SNARC and distance effects moderately correlated in one experiment, but not in a second experiment, with fifth- and sixth-graders (Schneider et al., 2009). In our sample of school-aged children, SNARC and distance effects were not correlated with one another—a result contrary to what one would expect if these two measures are manifestations of the same cognitive construct. Nevertheless, in theory the SNARC and distance effects represent wholly independent aspects of the mental number line construct—its directionality and the degree of representational overlap between adjacent numerosities. Therefore, it is possible (and perhaps likely, as suggested by the current data and those of Schneider et al., 2009) that these measures exhibit different independent developmental trajectories, eventually becoming correlated during adulthood.

In conclusion, this is the first study to report a relationship between a mental number line measure (i.e., the distance effect) and visuospatial abilities in children. This is also the first study to test how mathematics ability is related to individual SNARC and distance effects, as measured by a magnitude-relevant SNARC task, in 6- to 8-year-old children. The finding of no relationship between math scores and either of these mental number line variables, especially in an age range characterized by stronger SNARC and distance effects than in older children (e.g., van Galen & Reitsma, 2008), suggests that the mental number line construct (i.e., at least as measured by the SNARC and distance effects) might not be as integral in the development of numerical and mathematical competencies as previously thought. Further longitudinal research with larger samples of children in this age range—and perhaps with more age groups—is necessary to understand if, and when, these variables are related. Lastly, to our knowledge, this study is the first to investigate the correlation between SNARC and distance effect measures in 6- to 8-year-old children. The lack of correlation suggests that these two measures cannot be used interchangeably in children as equivalent measures of the mental number line construct and that different aspects of that construct might have different developmental trajectories.

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