THE MENTAL SEQUENCE LINE: ITS DEVELOPMENT AND STABILITY

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General Abstract

The mental sequence line is a cognitive construct by which sequences are perceived as beginning on the left and extending rightwards. Its developmental origins are unknown. In the first experiment, 4- and 5-year-old children placed items in order from four ordinal sequences, two of which they may have seen in print (i.e., letters and numbers) and two they would not have (i.e., times of day and meals). Four-year-olds systematically ordered letters from left to right; by age 5, numbers and times of day, but not meals, were ordered this way as well. These data suggest experience that cultural text direction, rather than inherent cortical organization, is responsible for development of the mental sequence line. The second experiment measured the mental sequence line in 6-, 7-, and 8-year-old children, and assessed its relation to visuospatial skills and mathematics ability. Mental sequence lines were measured by Spatial-Numerical Association of Response Codes (SNARC) and distance effects. Children's mental rotation ability was moderately correlated (r=.303) with the distance effect but neither it nor the SNARC effect correlated with mathematic ability. These data suggest the mental sequence line is not at the core of children's number sense, as previously hypothesized. The final experiment assessed consistency across time of SNARC and distance effects in adults for numbers, weekdays, and months. Despite often being described as trait variables, SNARC and distance effects were only moderately consistent for numbers, with even more variable results for months and weekdays, results suggesting mental sequence lines are not byproducts of stable, inflexible neural architectures. Combined, my data show sequence-space associations first emerge for letters, and subsequent development supports an enculturation hypothesis. By middle childhood, individual differences are evident in these effects that, as in adults, correlate with measures of spatial cognition. By adulthood, those individual differences have become modestly stable.

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List of Abbreviations and Symbols

ANOVA: Analysis of Variance—a statistical model used to assess the influence of one or more independent variables on a dependent variable.

ANS: Approximate number system—hypothesized to be cognitive construct by which humans and animals can estimate the number of items in an array or grouping of stimuli.

C: median congruent RTs—utilized to calculate individual measures of the SNARC effect.

cm: centimetre—a unit of length. 1 cm is 1/100 of a metre.

DTVP-2: Developmental Test of Visual Perception-2—a standardized measure of visuospatial abilities normed for use in children aged 4 through 9 years of age.

dRT: difference in reaction time—represents the mean RT of the right hand minus the mean RT of the left for a given stimulus; typically regressed onto magnitude to evaluate individual SNARC effects.

EEG: electroencephalography—an experimental procedure in which electrical activity (i.e., voltage) is measured across regions of the scalp.

ERP: event-related potential—a measure of the brain activity time-locked to a specific stimulus presentation. ERPs are measured in EEG experiments.

F: the statistic for an *F*-test—an *F*-test is used to assess the influence of one or more independent variables on the dependent variable.

fMRI: functional magnetic resonance imaging—a neuroimaging procedure that measures neural activation by detecting changes in cerebral blood flow.

I: median incongruent RTs—utilized to calculate individual measures of the SNARC effect.

M: Arithmatic mean—the average of a given set of values.

ms: millisecond—a unit of time. 1 ms is 1/1000 of a second.

n: in statistical testing, the number of individuals within a given sample.

p: *p*-value—in statistical testing, the *p*-value indicates the probability of obtaining the collected data given that the null hypothesis is true.

r: the Pearson correlation coefficient—measures the degree of linear correlation between two variables. *r* values range from -1 to +1, with more extreme values indicative of more linear relationship.

RT: reaction time—a measure of elapsed time between the presentation of a stimulus and participant response.

rTMS: repetitive transcranial magnetic stimulation—a procedure in which repetitive magnetic stimulation is applied to the scalp to depolarize (and thus temporarily disrupt normal processing of) underlying neurons.

s: second—a unit of time. 1 s is 1/60 of a minute.

S: a measure of the SNARC effect—calculated by taking the difference in median RTs for congruent and incongruent blocks and dividing this by their sum

SD: Standard deviation—an estimate of the amount of variation from the mean within a given sample.

SE: Standard error of the mean—based on the sample size and standard deviation of the sample, *SE* is an estimate of how from the mean of the sample is from the actual population mean. A small *SE* indicates that the sample mean is a good estimate of the population mean.

SNARC: Spatial-Numeric Association of Response Codes—the name of a behavioural effect in which Western individuals respond faster to lower numbers with a left-sided response, and higher numbers with a right-sided response.

t: the statistic for a *t*-test, which tests whether two means differ significantly.

TEMA-3: Test of Early Mathematics Ability-3—a standardized measure of mathematics ability normed for use in children aged 3 through 9 years of age.

WRAT-3: Wide-Range Achievement Test-3—a standardized measure of reading and mathematics ability, normed for use in individuals 5 through 74 years of age.

Declaration of Academic Achievement

For the study described in Chapter 2, the experiment was conceived of, and designed by, myself and my supervisor, Daphne Maurer. The data were collected by myself with the help of other lab members, including Sally Stafford (lab research assistant), Molly McGrath and Elizabeth Lee (undergraduate students supervised by me), Renata Samigullina (volunteer/summer NSERC student), Holly Lockhart and Katelyn Gramsch (summer volunteers), all of whom I supervised. The analyses, interpretation, and write-up were carried out by myself. For the study described in Chapter 3, the experiment was conceived of, and designed by, myself and Daphne Maurer. The data were collected by myself, with the assistance of Versailles Nair, an undergraduate thesis student supervised by me, and Holly Lockhart and Katelyn Gramsch (summer volunteers), all of whom I supervised. The analyses, interpretation, and write-up were completed by me. Lastly, the study described in Chapter 4 was conceived by myself and Daphne Maurer, and the data were collected primarily by me, with some assistance from Sally Stafford. The analyses, interpretation, and write-up were carried out by myself.

Chapter 1: Introduction

The ability to accurately represent and manipulate discrete numerosities is necessary for success in modern society. Indeed, a recent large-scale British survey indicates that adults with poor numeracy skills are more likely to be unemployed, depressed, and convicted of a crime, while simultaneously less likely to be homeowners and in good physical health compared to their peers with normal numeracy skills (Bynner & Parsons, 2005). While these data are only correlational, they highlight the importance of understanding the origins of numeracy, as well as the biological and environmental influences affecting its development.

With mathematical training, most adults are able to perform extensive, elaborate numerical manipulations; however, even infants exhibit precursors of basic numerical abilities. Infants appear to possess two distinct systems for representing numerosity: an imprecise, approximate number system (ANS) that represents large numerosities, as well as a precise 'object file' system that represents small numerosities. Using the ANS, infants [and many non-human animals, such as chimpanzees (Tomonaga, 2008), guppies (Piffer, Agrillo, & Hyde, 2012), and pigeons (Emmerton, 1998)], can represent the estimated number of items in large arrays of objects, and can discriminate between two large numerosities in accordance with Weber's law; that is, successful discrimination depends on the ratio between quantities, rather than the exact number of items or the absolute difference between item numbers. For 6-month-old infants, the ratio for the discrimination of large numerosities appears to be 1:2, as infants this age show evidence of discriminating between arrays of 8 and 16 and 16 and 32 discs, but not between arrays of 8 and 12 or 16 and 24 discs (Xu & Spelke, 2000; Xu, Spelke, & Goddard, 2005). With increasing age, this ratio is reduced: by 9 months, infants show evidence of discriminating numerosities with a ratio of 2:3 (i.e., 8 vs. 12, but not 8 vs. 10, discs; Libertus & Brannon, 2010; Xu et al., 2005; Xu & Arriaga, 2007), and 3-, 4-, 5-, and 6-year-old children and adults tested under conditions that discourage counting successfully discriminate object arrays with ratios of 2:3, 3:4, 4:5, 6:7, and 9:10, respectively (Halberda & Feigenson, 2008). Evidence that Weber ratios governing discrimination abilities are not merely limits of visual processing comes from reports of equivalent discrimination ratios in other modalities (e.g., discriminations among number of sounds; Lipton & Spelke, 2003).

Infants appear to possess a second, object file system that represents small numerosities. In contrast to the ANS, this system represents each item within a small number range with a single object file; thus, the system provides a precise, one-to-one representation of small numbers. Unlike the approximate number system, discrimination performance utilizing the object file system does not follow Weber ratios, but is instead limited by the absolute size of discriminated arrays themselves. To illustrate, infants can discriminate between displays of one and two (Feigenson, Carey, & Spelke, 2002), one and three (Ceulemans, Loeys, Warreyn, Hoppenbrouwers, Rousseau, & Desoete, 2012), and two and three (Clearfield & Mix, 1999) objects. However, as three seems to be the maximum number of object files infants can simultaneously represent (although this number may be smaller for newborn infants; Coubart, Izard, Spelke, Marie, & Streri, 2014), infants fail to show evidence of discriminating between low numbers (i.e., 1 to 3) and high numbers (i.e., 4 or greater) under most conditions (e.g., Xu, 2003; Feigenson, Carey, & Hauser, 2002; but see Cordes & Brannon, 2009). For example, even at a 1:2 Weber ratio, 7-month-old infants show no evidence of discriminating between two- and four-, or three- and six-, item arrays (Cordes & Brannon, 2009).

Strikingly, in addition to the ability to represent both small and large numerosities (precisely and imprecisely, respectively), young infants appear to possess an understanding of basic mathematical principles. In a seminal study, Wynn (1992) presented 5-month-old infants with a single doll; the researcher subsequently covered the doll with an occluder, and added a second doll behind the occluder as the infant watched. The occluder was then removed, revealing either two dolls (i.e., the expected outcome of the 1+1 addition operation) or one doll (i.e., the unexpected outcome). A similar procedure was used for subtraction: infants saw two dolls prior to occlusion, at which point one doll was removed from behind the occluder as the infant watched, and the occluder was then removed to reveal one (i.e., expected outcome) or two (i.e., unexpected outcome) dolls. In both cases, infants looked longer at the unexpected event, suggesting that they were surprised at the incorrect arithmetic outcome, and therefore capable of performing basic addition and subtraction. A subsequent study suggests that by 9 months, infants are capable of performing addition and subtraction with even larger numbers, exhibiting longer looking times when five plus five objects equals five (but not ten), and ten minus five objects equals ten (but not five) (McCrink & Wynn, 2004). There is, however, debate in the literature as to whether this behaviour is actually indicative of addition and subtraction, as opposed to a more general object tracking strategy (e.g., Simon, 1997; Uller, Carey, Huntley-Fenner, & Klatt, 1999) or looking times based on a familiarity preference (Cohen & Marks, 2002).

Data from several neuropsychological studies support the behavioural evidence of infant numerical and mathematical abilities. In one experiment, electroencephalography (EEG) was utilized to measure neural responses as 7-month-olds and adults viewed quickly-changing, steady-state displays that changed the number of elements in the display every 2400 ms (Libertus, Brannon, & Woldorff, 2011). Oscillatory entrainment patterns in both groups changed with numerosity when the numerosities differed by a 1:2 or 1:3 Weber ratio, with the change in response pattern proportionate to the ratio change between the numerosities. However, unlike adults, 7-month-olds did not exhibit oscillatory entrainment pattern changes when the numerosity switch was of a 2:3 ratio (also see Libertus, Pruitt, Woldorff, & Brannon, 2009 for similar results). These data are consistent with behavioural evidence suggesting infants of a similar age (i.e., 6-month-olds) can discriminate numerosity differences with a 1:2 but not those of 2:3 ratio (e.g., Lipton & Spelke, 2003, 2004; Xu & Spelke, 2000). Further, consistent with Wynn's (1992) behavioural data, in an event-related potential (ERP) experiment, 6- to 9-month-old infants exhibited significantly more negative polarity (associated with error or conflict detection) over the mediofrontal area when they observed an impossible solution, as opposed to a possible solution, to a simple addition or subtraction problem (Berger, Tzur, & Posner, 2006).

The above data provide compelling evidence that even at a very young age and prior to mathematics education, humans possess a degree of rudimentary number sense, or a basic intuition concerning numerosity (Dehaene, 1997). With development across early childhood, humans begin to acquire more advanced numerical and mathematical skills: by 11 months of age, infants can tell the difference between decreasing and increasing numbers of objects (Brannon, 2002); by 2 years of age, children start to learn how to count in sequence (Fuson, 1992); by 3 years of age, children can count small numbers of objects (Wynn, 1990); by 4, children use their fingers as counting aids (Fuson & Kwon, 1992); and, by age 5, children can count to 40 (Fuson, 1988) and perform addition operations by counting upwards from the larger number (Carpenter & Moser, 1982). However, while these aspects of numerical cognition have been studied extensively, the development of the mental sequence line (a hallmark of adult numerical cognition), and the factors affecting its emergence, has not been investigated thoroughly.

The Mental Sequence Line in Adults

It is widely hypothesized that the mental representation of magnitude is spatially organized. Results from various behavioural studies suggest that this representation takes the form of a horizontally-oriented line, such that small numerosities (e.g., 1-4) are represented on the left side of space, and larger numerosities (e.g., 6-10) on the right—a cognitive construct known as the mental sequence line. For example, in a seminal study investigating the cognitive representation of parity and magnitude, Dehaene, Bossini, & Giraux (1993) reported the first observation of the Spatial-Numeric Association of Response Codes (SNARC) effect: the finding that Western adults respond faster to small numbers (e.g., 1-4) with a left-sided response, and large numbers (e.g., 6-9) with a right-sided response. In the traditional SNARC paradigm utilized by Dehaene et al., the

SNARC effect was elicited when participants were asked to indicate the parity (i.e., odd or even) of a target number with either a left- or right-sided key press. Subsequently, however, the SNARC effect has been elicited in adults utilizing a variety of experimental paradigms. For example, a robust SNARC effect is observed when participants perform a magnitude-relevant SNARC task, in which they indicate with a left- or right-sided key press whether a target number is greater or less than 5: "less than" responses are faster with a left-sided response, and "greater than" responses with a right-sided response (Dehaene, Dupoux, & Mehler, 1990). Similarly, an attentional SNARC effect is observed when participants are required to locate a target in one of two boxes horizontally flanking a number on a computer screen: individuals are faster to locate leftward targets when the number on the screen is less than 5, and faster to locate rightward targets when the number is greater than 5, even though participants know that number magnitude is non-predictive of target location (Fischer, Castel, Dodd, & Pratt, 2003). The SNARC effect and its variants are typically cited as evidence that Western adults possess a mental sequence line that is inherently spatial in nature and oriented horizontally from left to right, such that responses to digits are faster when response side and the number's position on the mental sequence line are congruent (Fischer et al., 2003; Fias, 1996; Nuerk, Bauer, Krummenacher, Heller, & Willmes, 2005).

Data from two other widely used behavioural tasks, as well as a growing amount of neuroimaging data, lend support to the hypothesis of a spatially-oriented mental sequence line. First, when participants are asked to indicate the larger of two Arabic numbers, response times for numbers close in magnitude (e.g., 4 and 6) are considerably longer than those for numbers that are further apart (e.g., 1 and 9) (Moyer & Landauer, 1967). Known as the numerical distance effect, this finding is consistent with a spatial, linear organization of neural populations, in which each population optimally responds to one numerosity, while to some degree activating adjacent neural populations that represent neighbouring numerosities. This pattern of neural populations would in essence impair the discrimination of close (but not distant) numbers (Dehaene et al., 1990; Neider, 2005).

Results from another class of behavioural tasks, known as number line estimation tasks, also lend support to the hypothesis of a spatially-oriented mental sequence line. In this type of task, participants are given an Arabic number, and asked to indicate its approximate position on an unmarked horizontal line anchored with 0 on the left and a larger number on the right (usually 100 or 1000). For adults performing this task, there is a robust, systematic one-to-one relationship between the magnitude of the number and its estimated position on the number line, indicating that adults map numbers onto space linearly, even across relatively large number ranges (Siegler & Opfer, 2003). The high consistency between adults' responses, in addition to the ease of the task, even for uneducated, illiterate adults (Dehaene, Izard, Spelke, & Pica, 2008), has been taken as evidence for a mental sequence line.

Recent evidence suggests that the left-to-right mapping observed in Western adults is a characteristic of ordinal sequences in general. A left-to-right SNARC effect has been observed for non-numerical sequences such as weekdays, months, letters of the alphabet, time, and even for words in a recently-learned ordered list (Gevers, Reynvoet,

& Fias, 2003, 2004; Santiago, Lupiáñez, Pérez, & Funes, 2007; Previtali, de Hevia, & Girelli, 2010; but see Dodd, Van de Stigchil, Leghari, Fung, & Kingstone, 2008 for no attentional SNARC effect with non-numeric ordinal sequences). These data suggest that the cortex develops and maintains connections linking sequences to space, likely in the parietal cortex (Hubbard, Piazza, Pinel, & Dehaene, 2005), and that ordinality generally, and not numerosity exclusively, may serve as the basis of these associations. As such, the term 'mental sequence line' may be a more accurate term for this cognitive representation than "mental number line".

Converging neuroimaging and neuropsychological data nicely complement the behavioural results from typical adults in support of a spatially-oriented mental sequence line. In a recent functional magnetic resonance imaging (fMRI) study, researchers investigated whether neural circuits recruited for spatial attentional processes are also utilized during mental arithmetic. First, a multivariate classifier algorithm was trained to use posterior parietal activation (an area known to be active during the processing of both number and space) to determine the direction (i.e., left or right) of participants' horizontal saccades. Subsequently, in the absence of further training, the classifier was able to determine from posterior parietal activation whether participants were performing mental addition or subtraction (Knops, Thirion, Hubbard, Michel, & Dehaene, 2009). These data support the prediction that mental arithmetic, and addition and subtraction specifically, are performed via respective rightward and leftward shifts along a spatially-oriented mental sequence line.

Evidence of a mental sequence line also comes from patients suffering from (left) hemispatial neglect. This type of neglect is often caused by right parietal lesions, and typically renders patients unable to direct attention to the left side of space. These patients systematically indicate the midpoint of an unmarked line well to the right of the actual midline (Halligan & Marshall, 1993); crucially, these patients also exhibit an analogous deficit when asked to bisect number intervals, as they estimate the midpoint of two numbers as closer to the larger of the two numbers (a "rightward" shift on the left-to-right mental sequence line; Zorzi, Priftis, & Umiltà, 2002). These data are complimented by evidence that healthy controls exhibit the same "rightward" shift in the bisection of numerical intervals when they are administered repetitive transcranial magnetic stimulation (rTMS), a magnetic stimulation of the scalp that depolarizes underlying neurons to disrupt normal processing, over the right posterior parietal cortex (Göbel, Calabria, Farnè, & Rossetti, 2006). Together, these data suggest that the cognitive representation of numerosity is analogous to that of a horizontal line.

Finally, evidence supporting the neural overlap between number and space comes from patients with parietal lobe lesions. These patients typically exhibit combined deficits in both space and number processing (Hubbard et al., 2005). For example, individuals with Gerstmann's syndrome, which is typically the result of a lower parietal/middle occipital lesion, display a characteristic combination of spatial deficits, such as left-right disorientation and finger agnosia, as well as dyscalculia (i.e., a profound deficit in mathematics and number processing) (Gerstmann, 1940).

The Mental Sequence Line in Children

Many characteristics of the spatially-oriented mental sequence line observed in adults have also been reported in children. Western children as young as 7.5 years of age (White, Szücs, & Soltész, 2012), and Chinese children as young as 5.8 years (Yang, Chen, Zhou, Zu, Dong, & Chen, 2014), exhibit significant left-to-right SNARC effects using the traditional SNARC parity task. However, this SNARC paradigm is difficult to administer to younger children, as parity is a relatively advanced mathematics concept. Utilizing the less conceptually challenging magnitude-relevant SNARC task (i.e., in which children indicate whether a target number is greater or less than 5), SNARC-like effects are observed in Western children by age 7, with the strongest SNARC effects (i.e., the largest difference in response times to low and high numbers between the two hands) observed in the youngest age group, and the effect attenuated with age (van Galen & Reitsma, 2008). Given the challenging nature of both the traditional SNARC parity task and the magnitude-relevant SNARC task for very young children, a recent study employed a more child-friendly version of the SNARC task. Similar in nature to the SNARC parity task, children were presented with black digits that turned either green or red after 200 ms, and their task was to indicate whether the number had turned green or red with a left- or right-sided response (Hoffmann, Hornung, Martin, & Schiltz, 2013). Five-year-olds exhibited a SNARC-like effect; that is, they responded faster to low numbers with the left hand, and high numbers with the right. In another recent child-friendly SNARC experiment, 4-year-old children were presented with two arrays of objects on a touch screen, and asked to touch the side of the screen with more or fewer objects (Patro & Haman, 2012). Exhibiting a SNARC-like effect, children responded faster to small arrays when they were positioned on the left side of the screen, and large arrays when they were positioned on the right. Taken together, these data can be interpreted as evidence that children as young as 4 exhibit left-to-right SNARC-like effects similar to their adult counterparts, a pattern suggesting that the neural architecture underlying the left-to-right mental sequence line may be established early in childhood.

Children as young as 5 exhibit a robust numerical distance effect similar to that observed in adults; that is, when they make speeded decisions about which of two numbers is larger, they responded faster when the numbers are distant (e.g., 1 and 9) rather than close (e.g., 4 and 5) in magnitude (Sekuler & Mierkiewicz, 1977). Converging data indicates that, similar to the SNARC effect, the strength of the distance effect attenuates with age, with younger children exhibiting larger distance effects than older children (e.g., 5- to 10-year-olds; Sekuler & Mieriewicz, 1977; 6- versus 7- and 8-year-olds; Holloway & Ansari, 2008). While these data do support the hypothesis that children possess a spatial representation of number, they suggest that the reliance on the mental sequence line may decrease with age—possibly because of the development of more automatic number processing with age and/or more advanced strategies.

Children, like adults, are consistent at any given age in how they perform number line estimation tasks. However, younger children's performance on this task differs from that of adults: 7- to 9-year-olds systematically place numbers on an unmarked line in a logarithmically-increasing manner, unlike adults, who place numbers linearly (Siegler & Opfer, 2003). These data suggest that children have an expanded representation of low numbers, paired with a more compressed representation of higher numbers, on their mental sequence lines. By age 11, children's placements of numbers on a line is linear and, thus, adult-like (Siegler & Opfer, 2003). Notably, the directionality of the unmarked line (i.e., whether the anchors such as 0 and 100 are on the left or the right side of the number line) in these tasks is important: 6-year-olds' performance on this task is worse when the number line is oriented from right to left as opposed to when it is oriented from left to right; a similar but attenuated effect is observed in 7-year-olds (Ebersbach, in press).

Even very young children (i.e., preschoolers) exhibit behaviours that suggest they possess a salient mental sequence line, and that it is directional in nature. For example, the majority of 2.5- to 5.5-year-old children will count a line of objects from left to right (Opfer & Thompson, 2006; Opfer, Thompson, & Furlong, 2010). By age 4, most children count objects beginning at one end of a line, and count adjacent items consecutively (Briars & Siegler, 1984). When 4- and 5-year-olds are asked to add or take away a poker chip from a line of poker chips, they add the chip to,, and subtract the chip from the right side of the line—suggesting they perceive the rightmost side of the line as representing "more" (Opfer & Thompson, 2006; Opfer et al., 2010).

Causal Origins of the Mental Sequence Line

The left-to-right bias observed in Western adults' sequence-space mappings may develop as a result of exposure to the reading and writing direction used in a particular culture. The main evidence supporting this hypothesis comes from research done in cultures in which individuals read and write from right to left (e.g., cultures in which Arabic is spoken). One of the first studies of this kind utilized an adapted, oral version of the SNARC task to assess mental sequence line direction in monoliterate English and Arabic speakers, in addition to biliterate and illiterate Arabic speakers (the latter of which were able to read and write numerals, but not Arabic text; Zebian, 2005). In this task, two numbers appeared on a computer screen, with one number located on the left side of the screen, and the other on the right; the numbers were arranged such that their order was either congruent with a left-to-right number line (e.g., 2 9) or a right-to-left number line (e.g., 9 2). The participants' task was to verbally indicate whether the two numbers were the same or not as quickly as possible. As predicted, the Arabic monolinguals exhibited a reversed, oral right-to-left SNARC effect (i.e., they responded faster to number pairs consistent with a right-to-left number line), and a weakened reverse oral SNARC effect in Arabic bilinguals, suggesting that knowing two languages with opposing reading/writing directions may weaken one's SNARC effect for their predominant language (see also Dehaene et al., 1993, Experiment 7). However, perhaps more telling is that illiterate participants did not exhibit a SNARC effect in either direction.

Zebian's (2005) results have since been replicated and extended using the traditional SNARC task. In a recent study, Canadians (who read text and numbers from left to right), Palestinians (who read text and numbers from right to left), and Hebrew-speaking Israelis (who read text from right to left but numbers from left to right) performed the traditional SNARC task using parity judgements (Shaki, Fischer, & Petrusic, 2009). As expected, the Canadians exhibited a typical, left-to-right SNARC effect, and the Palestinian participants exhibited a reversed, right-to-left SNARC effect. The Hebrew-speaking participants, however, displayed no consistent directional number-space associations—suggesting that the reading and writing directions for both text and numbers influence the directionality of the mental sequence line. Further, for individuals who use multiple number formats (e.g., Arabic numerals versus number words) with differing directionalities, there appear to be distinct mental sequence lines matching the directionality of the number format in use. For example, Taiwanese participants, who read and write Arabic digits from left to right, but Chinese characters representing number words from top to bottom, exhibit a left-to-right SNARC effect for Arabic numbers and a top-to-bottom SNARC effect for Chinese characters (Hung, Hung, Tzeng, & Wu, 2008).

Nevertheless, not all cross-cultural data lend support to the hypothesis that enculturation determines the directionality of the mental sequence line. For example, Japanese individuals exhibit a vertical, bottom-to-top SNARC effect, which is opposite to their direction of reading and writing (i.e., top to bottom) (Ito & Hatta, 2004). It is possible that this discrepancy comes from Japanese individuals encountering conflicting directional cues about number; for example, thermometers display low numbers on the bottom and high numbers on the top, and measurements of individuals' heights are represented in a similar fashion. Additionally, it is possible that during development, the neural architecture connecting sequences and space is more sensitive to texts that are horizontal (i.e., the direction most of the world's cultures), than texts that are vertical—especially if individuals have a 'natural bias' (e.g., reviewed in Maurer, Gibson, &

Spector, 2012) to map sequences vertically onto space in a bottom-to-top, as opposed to a top-to-bottom, manner.

Despite the reported influence of culture, it is possible that the cortical organization observed in humans predisposes individuals to connect sequences to space, especially in a left-to-right manner. Indeed, in two recent experiments, adult nutcrackers and newborn domestic chicks were trained to find food in the *n*th hole in a series of 16 holes that extended out sagitally in front of the bird (Rugani, Kelly, Szelest, Regolin, & Vallortigara, 2010; Rugani, Regolin, & Vallortigara, 2007). Once the subjects reliably visited the *n*th hole first, the testing arena was rotated 90 degrees, such that the birds encountered a line of 16 horizontal holes upon entering the arena. In both studies, birds visited the *n*th hole from the left more often than one would expect by chance—suggesting that the birds perceived the sequence of holes as beginning on the left, rather than the right, side of the arena. The authors suggest that the observed leftward bias may be a result of a right hemisphere dominance in visuospatial tasks, which causes most animals (and humans) to direct more attention towards the left side of space. This hemispheric dominance may facilitate the processing of sequences ordered from left to right as opposed as those ordered from right to left (or vertically), and thus predispose a left-to-right bias in the mapping of sequences onto space (de Hevia, Girelli, & Cassia, 2012), a bias that can either be strengthened or attenuated by cultural experience. Indeed, such a cortically-driven directional bias in ordering may explain why most of the world's languages evolved to be written and read from left to right.

To date, it remains unclear whether the robust sequence-space associations observed in adults and children develop solely as a result of cultural experience (i.e., literacy), or as a byproduct of cortical organization; nevertheless, the alternative accounts generate testable hypotheses. The enculturation hypothesis predicts (1) that a left-to-right sequence-space mapping will not be present until an individual begins to learn to read and write or, at the very least, until an individual is exposed to the cultural direction of reading and writing; and (2) that as some sequences are seen ordered in text prior to actual literacy (e.g., 1, 2, 3; A, B, C), these particular sequences will be the first to be systematically ordered from left to right for Western children (i.e., as opposed to other well-known sequences not seen in text, such as morning, afternoon, night). The biological hypothesis, however, predicts that Western children's left-to-right mapping is the result of an attentional bias, and therefore predicts (1) that children of all ages, at least once the parietal cortex matures, will exhibit left-to-right mappings; and (2) all sequences a child understands will be mapped from left to right, with no sequence exhibiting this mapping earlier than any other sequence.

In the research reported in Chapter 2, I tested the predictions generated by the enculturation and biological hypotheses concerning the development of the mental sequence line. I developed a novel, child-friendly paradigm in which preliterate 4- and 5-year-olds were asked to place the first, second, and third item of a sequence into the first, second, or third (respectively) of three boxes in a horizontal line. This paradigm allowed me to address my research question in two ways. First, I utilized four sequences that young children are familiar with: numbers (i.e., 1, 2, 3), letters of the alphabet (i.e., A, B, C), times of day (i.e., morning, afternoon, night), and meals (i.e., breakfast, lunch, dinner). By age 4, children are familiar with the ordinality of all four of these sequences; that is, they understand what comes first, second, and third. Importantly, these particular sequences were also chosen because two of them (i.e., 1, 2, 3 and A, B, C) are regularly seen ordered in print (e.g., on preschool walls, on educational toys) even before children learn how to read and write, while the remaining two sequences are rarely, if ever, encountered ordered in print by preliterate children. The enculturation hypothesis predicts that in preliterate children, a left-to-right mapping will emerge in those sequences seen left to right in print at an earlier age than those not seen in print. Alternatively, the biological hypothesis maintains that sequence type is irrelevant, and thus predicts that participants would order all four sequences from left to right. Second, I utilized two groups of pre-reading children, 4- and 5-year-olds. As the enculturation hypothesis states that a left-to-right mapping of sequences is a result of experience, it predicts that 5-year-olds would map more sequences from left to right than 4-year-olds. Alternatively, the biological hypothesis predicts that both age groups would be equally likely to map sequences from left to right.

Unlike previous studies, I assessed the level of literacy in the preschool participants were indeed preliterate. Past studies investigating number-space mappings in preschoolers report that their participants were preliterate, but did not test literacy in any way; therefore, it is possible that results of these studies were influenced by partially literate participants included in the analysis. My investigation is also the first to simultaneously test the predictions of both the enculturation and biological hypotheses.

Finally, while previous studies have investigated number-space mappings in (assumed) preliterate children, mine is the first to assess whether Western children exhibit the left to right mappings that are observed in adults for many non-numerical ordinal sequences (e.g., Gevers et al., 2003, 2004; Santiago et al., 2007).

Mental Sequence Line and Visuospatial and Mathematics Abilities

The SNARC effect is the finding that Western individuals automatically associate numbers with spatial locations, even when number magnitude is irrelevant to the task—leading researchers to suggests that Western individuals possess an inherent, left-to-right mental sequence line (e.g., Dehaene et al., 1993). As the mental sequence line is understood to be a spatial mapping of magnitude, visuospatial abilities likely play a key role in the development and use of this cognitive construct. This hypothesis is supported by one recent study in which school-aged children with visuospatial deficits did not exhibit a SNARC effect at the group level (Bachot, Gevers, Fias, & Roeyers, 2005). This hypothesis is further supported by evidence that visuospatial skills and math ability are related. For example, both mental rotation and visuospatial working memory (both visuospatial skills) correlated with a measure of math ability in Finnish high school students (Reuhkala, 2001); further, children with visuospatial deficits have difficulty with written mathematics (Venneri, Cornoldi, & Garuti, 2003). One recent study found that individual SNARC effects correlate with two-dimensional visuospatial abilities in adults (Viarouge, Hubbard, & McCandliss, 2014); nevertheless, to my knowledge no study has investigated the relation between visuospatial skills and markers of the mental sequence line in typically-developing children.

Additionally, the automaticity with which individuals make spatial associations when processing number (and sequences in general) suggests that number-space mappings are a fundamental base for number and mathematics skills, and numerical cognition in general. As such, many researchers have hypothesized that the mental sequence line is at the very core of an individual's number sense (e.g., Dehaene, 1997).

Early investigations into the relation between the mental sequence line and math skills suggested a link, albeit in a direction that is surprising: data from two studies indicated that undergraduates in math- and science-related disciplines have weaker SNARC effects than those of liberal arts students (Dehaene et al., 1993; Fischer & Rottmann, 2005). These initial investigations are substantiated at the individual level by recent data from a large-scale study in university students, in which those participants with more advanced math skills systematically exhibited weaker SNARC effects (Hoffmann, Mussolin, Martin, & Schiltz, 2014). Thus, it is possible that superior mathematics competency is characterized by advanced cognitive strategies beyond reliance on the mental sequence line, essentially resulting in an attenuation of the neural links between number and space. Alternatively, it is possible that inferior mathematics skills results in over-reliance on the mental sequence line, effectively strengthening number-space mappings. Either way, many subsequent experiments have investigated the relation between the strength of number-space mappings and various measures of mathematics ability, particularly as the two develop in school-aged children.

Most experiments testing the relation between the mental sequence line and math abilities utilize symbolic or non-symbolic comparison tasks as a behavioural measure of participants' mental sequence lines. In this type of task, participants indicate which of two numbers (i.e., symbolic) or object arrays (i.e., non-symbolic) on a computer screen is larger or has more objects, respectively. With these data, researchers can compute an individual's distance effect (i.e., slow reaction times when numerosities are close in magnitude), which is then correlated with some measure of participants' math ability. In the majority of developmental studies to date, a positive correlation has emerged between individuals' symbolic distance effect and math ability (e.g., 6- to 8-year-olds, Holloway & Ansari, 2009; 5-, 6-, 7-, and 11-year-olds, Sasanguie, De Smedt, Defever, & Reynvoet, 2012a; Vanbinst, Ghesquière, & De Smedt, 2012; 6- to 8-year-olds, Sasanguie, Göbel, Moll, Smets, & Reynvoet, 2013); however, this is not consistently the case (5- to 7-year-olds, Sasanguie, Van den Bussche, & Reynvoet, 2012b). Converging support for this positive correlation comes from evidence that children with dyscalculia, a developmental disorder characterized by pervasive number and math deficits, exhibit attenuated symbolic distance effects when compared to typically-developing children (Rousselle & Noël, 2007).

On the other hand, non-symbolic distance effects do not correlate with math ability in most studies (e.g., 6- to 8-year-olds, Holloway & Ansari, 2009; 5-, 6-, 7-, and 11-year-olds, Sasanguie et al., 2012a; 5- to 7-year-olds, Sasanguie et al., 2012b; but see Lonnemann, Linkersdörfer, Hasselhorn, & Lindberg, 2011 for a positive correlation between a subtraction task and distance effect in 8- to 10-year-olds). This finding is consistent with evidence that despite having severe math and number deficits, children with dyscalculia exhibit the same non-symbolic distance effects as their typically-developing peers (Rousselle & Noël, 2007). As the symbolic distance effect, but not the non-symbolic distance effect, is (typically) correlated with math ability, it is likely that the two distance effect measures are tapping into independent neural populations.

Performance on number line estimation tasks is also correlated with math skill: the ability of participants to accurately (i.e., linearly) estimate the position of numerosities on the number line positively correlates with measures of math ability (e.g., 5.8-, 6.8-, 7.9-, and 9.1-year-olds, Booth & Siegler, 2006; 7-year-olds, Booth & Siegler, 2008; Sasanguie et al., 2012a, 2012b; 6- to 8-year-olds, Sasanguie et al., 2013; 11-year-olds, Schneider, Grabner, & Paetsch, 2009). For example, in one study, 5.8- to 9.1-year-old children with more linear number line estimations on a 0 to 100 line had higher percentiles on the math section of a general achievement test; the same pattern of results was obtained with a separate 7.8- to 9.9-year-old sample on a 0 to 1000 number line (Booth & Siegler, 2006).

Only one previous study has investigated the correlation between performance on SNARC tasks, one of the most commonly cited behavioural measures of the mental sequence line, and math ability. In this experiment, 11-year-old German children's performance on the SNARC parity task was not correlated with their self-reported recent math grades or performance on a task requiring interpretation of a graph (Schneider et al., 2009). These findings are unexpected, as other measures of the mental sequence line (i.e., symbolic distance effect and number line estimation tasks) have (often) been predictive of math ability. However, the measure of math ability utilized in the above study is unusual—a standardized test of mathematics skill is the most commonly utilized measure in the literature. Further, the participants in this study were 11 years old, and the

SNARC effect has been demonstrated to weaken with age (van Galen & Reitsma, 2008). Therefore, it is possible that younger children, with more robust SNARC effects, will exhibit associations between SNARC strength and performance on a standardized measure of math ability.

Accordingly, for the third chapter in this thesis, I investigated the relationship between the mental sequence line and visuospatial and mathematics abilities in children. I employed a magnitude-relevant SNARC task to obtain an estimate of mental sequence line strength in 6-, 7-, and 8-year-old children, and correlated it with participants' performance on standardized measures of visuospatial and mathematics abilities. To my knowledge, this is the first experiment to assess the relationship between SNARC itself and math ability in children of these ages; importantly, it is the first study to assess this relationship using a standardized measure of mathematics ability. This study is also the first assessment of the relationship between a measure of the mental sequence line and visuospatial skills in typically-developing children.

Consistency of Sequence-Space Mappings in Adults

The SNARC effect is one of the most commonly cited behavioural measures of the mental sequence line, and perhaps for good reason: the effect in its traditional sense is extremely robust at the group level and across a variety of paradigms (e.g., Fischer et al., 2003; Dehaene et al., 1990, 1993). As such, individual results from SNARC tasks have been taken as a dependable marker of the strength of each participant's number line in a plethora of studies (e.g., Dehaene et al., 1993; Hoffmann et al., 2013), regardless of the fact that the stability and consistency of this mental construct has not been established.

Indeed, a growing amount of evidence suggests that the SNARC effect specifically, and the mental sequence line in general, is a malleable mental construct that is highly sensitive to context.

On the traditional parity task, approximately 65 to 75 percent of Western participants exhibit a significant left-to-right SNARC effect in any given test (Wood, Nuerk, & Willmes, 2006a, 2006b). This certainly suggests that under normal circumstances, Western individuals naturally map numbers onto space from left to right, likely as a result of reading and writing habits (e.g., Zebian, 2005). Nevertheless, mounting evidence suggests that the directionality of one's SNARC effect is fairly malleable, and can change with very brief exposure to alternate directionalities. For example, when monolingual Western participants are asked to visualize the digits 1 through 11 on a horizontally-aligned ruler, they exhibit a classic, left-to-right SNARC effect. When the same participants are asked to imagine the digits on a clock face, however, their SNARC effect is reversed (Bächtold, Baumüller, & Brugger, 1998). In another study, Scottish and Hebrew participants performed the SNARC parity task, and then spent approximately 20 minutes reading recipes that had a number at the beginning and end of each line before performing the parity task again. The numbers were arranged such that the order of the two numbers was congruent with a left-to-right number line (e.g., cook 2 potatoes for 9 minutes) or a right-to-left number line (e.g., cook 8 potatoes for 1 minute) (Fischer, Mills, & Shaki, 2010). While the Scottish participants all exhibited a left-to-right SNARC initially, those exposed to the right-to-left number arrangement did not exhibit any SNARC effect at all in the post-test. Similarly, while

Hebrew participants as a group did not display any SNARC effect at the pre-test (as is consistent with previous literature, Shaki et al., 2009), those exposed to the right-to-left recipes exhibited a reversed SNARC effect at the post-test. Lastly, another experiment had Russian-Hebrew bilinguals perform a SNARC parity task in which Arabic digits and number words were interspersed, and half of the number words were displayed in Russian (i.e., read from left to right) and the other half in Hebrew (i.e., read from right to left) (Fischer, Shaki, & Cruise, 2009). For those digits presented immediately after Russian number words, participants exhibited a left-to-right SNARC effect; however, for digits presented immediately after Hebrew number words, no systematic SNARC effect was observed.

The aforementioned studies provide compelling evidence that the SNARC effect, and therefore the mental sequence line, is not necessarily the byproduct of an entrenched, stable neural architecture linking numbers and space. Rather, these studies suggest that even brief exposure to a specific number-space mapping can alter an individual's predisposed SNARC directionality—at least temporarily. The ease with which these mappings can be perturbed also suggests that individuals' performance on mental sequence line measures may also not be entirely consistent across time. This hypothesis is supported by a recent study that reported only moderate (r=.372) consistency of the SNARC effect across visits in adults (Viarouge et al., 2014). Converging evidence comes from the fact that another marker of the mental sequence line—the numerical distance effect—is only weakly consistent within individuals across trial blocks within the same experiment (Maloney, Risko, Preston, Ansari, & Fugelsang, 2010). A similar degree of modest consistency in the distance effect was found in 11-year-old children tested on two independent visits (Schneider et al., 2009).

Thus, it is possible that the discrepancies in both the adult and child literatures concerning the relation between mathematics ability and the mental sequence line [e.g., see Hoffman et al., 2014 versus Cipora & Nuerk, 2013; Holloway & Ansari, 2009 versus Sasanguie et al., 2012; Gibson & Maurer, in preparation (b)] stem from the possibility that the SNARC and distance effect paradigms do not measure the mental sequence line precisely. Alternatively, it is possible that the mental sequence line is not a stable, consistent cognitive construct. Nevertheless, to my knowledge, this hypothesis has only previously been tested for numbers utilizing a parity task, and not for the distance effect across extended time in adults. Furthermore, the consistency of both SNARC and distance effects for other, non-numerical ordinal sequences has not been evaluated.

The fourth chapter of this thesis reports an investigation of the consistency of the SNARC and distance effects within participants across two independent visits to the laboratory. In addition to the numerical SNARC and distance effects, I also investigated the consistency of the SNARC effect for two other ordinal sequences that are known to be spatially organized: weekdays and months. Given the reported malleability of the SNARC effect, combined with only moderate consistency of the SNARC and distance effects within individuals across time, I predicted I would observe only modest consistency in SNARC and distance effects within individuals across time. My paradigm also allowed me to examine, for the first time, whether SNARC and distance effects for the three ordinal sequences tested are equally consistent across time, or if certain sequence-space mappings, such as numbers onto space, exhibit more stability. It is conceivable that more overly learned sequences, such as numbers in contrast to weekdays or months, may develop more entrenched, and thus more stable, neural architectures. My paradigm also allowed me to evaluate the degree to which the mental sequence lines for each ordinal sequence relate to one another, as well as the degree to which SNARC and distance effects are correlated within each sequence type.

To test my predictions, a large sample of right-handed, English-speaking participants performed a magnitude-relevant SNARC tasks for digits, weekdays, and months of the year. Participants repeated the same task one to three weeks later, allowing me to assess the consistency of their individual SNARC effects for each sequence type across time. Establishing the stability of the SNARC and distance effects for numbers and other ordinal sequences is a crucial step for the numerical cognition literature, as a lack of consistency would essentially render SNARC and distance effects as questionable measures of individuals' mental sequence lines.

The thesis ends with a general discussion summarizing the results of the three empirical chapters, discussing their contribution to the literature, and describing their limitations and future steps.

Pre-Chapter Introduction

In the work described in Chapter 2, the developmental origins of the directional (i.e., left-to-right) mental sequence line were assessed. Four- and 5-year-old pre-reading children performed a task in which they arranged items from four familiar ordinal sequences in order using a horizontal line of boxes. Two of the sequences utilized (i.e., 1, 2, 3 and A, B, C) were ones children frequently see ordered in print, even prior to learning to read; the other two sequences (i.e., morning, afternoon, night and breakfast, lunch, dinner) were ones children were very unlikely to have seen ordered in print. Four-year-olds ordered letters, but no other sequence, systematically from left to right; by age 5, numbers and times of day were also ordered this way. As children first ordered a sequence seen ordered in text (i.e., letters) from left to right, and extended this pattern to other sequences by age 5, these data support the hypothesis that experience drives the development of the directionality of the mental sequence line, rather than a cortical bias.

Sequence-Space Associations in Pre-Reading Children

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Chapter 2: Sequence-Space Associations in Pre-Reading Children

Abstract

In Western cultures, adults tend to represent numbers and other ordinal sequences on a mental sequence line that is oriented from left to right. Evidence for this mental construct comes from the Spatial Numeric Association of Response Codes (SNARC) effect, which is the finding that adults respond faster to items early in an ordinal sequence with their left hand, and later items with their right hand (Dehaene et al., 1993). The left-to-right directionality of the SNARC effect has been attributed to enculturation—that is, experience with the cultural direction of reading and writing. However, evidence that non-human animals also organize sequences from left to right raises the possibility that a left-to-right directionality is an inherent bias (that can be attenuated by cultural experience), likely the result of cortical organization. The present study evaluates these two hypotheses by investigating the directional biases of 4- and 5-year-old children (n=200) confirmed to be pre-readers. Each participant was asked to place the first three items of an ordinal sequence into the first, second, and third box, respectively, in a horizontal line of three boxes. Items were used from four ordinal sequences: numbers (i.e., 1, 2, 3) and letters (i.e., A, B, C), both familiar sequences that are frequently seen in text even prior to learning to read; and times of day (i.e., morning, afternoon, night) and meals (i.e., breakfast, lunch, dinner), familiar sequences unlikely to be seen sequentially in print (n=25/sequence/age). Four-year-olds ordered letters, but no other sequence, from left to right more often than expected by chance. At age 5, letters, numbers, and times of day (but not meals) were ordered from left to right at levels exceeding chance. This

pattern of results supports the enculturation hypothesis, as a sequence commonly encountered ordered in text prior to learning to read was the first to be organized directionally. Additionally, the increased left-to-right organization of sequences by 5-year-olds suggests that the left-to-right bias becomes more pronounced and generalized with additional exposure to the cultural direction of writing.

Chapter 2: Sequence-Space Associations in Pre-Reading Children

Introduction

Recent investigations suggest that most individuals represent number with an inherent spatial component. In adults, this number-space association manifests behaviourally in a number of ways. First, when Western adults are asked to indicate the parity (i.e., odd or even) of an Arabic digit, they respond faster to low numbers (e.g., 1-4) with a left-sided key press and high numbers (e.g., 6-9) with a right-sided key press than with the opposite mapping (the Spatial Numerical Association of Response Codes [SNARC] effect; Dehaene, Bossini, & Giraux, 1993). Similar effects occur when adults indicate whether a digit is greater or less than a target number with a left- or right-sided response (e.g., Dehaene, Dupoux, & Mehler, 1990). The inherent mapping of number onto space is so robust that it even influences visual attention, with small numbers cueing attention to the left side of space, and large numbers cueing attention to the right (the attentional SNARC effect; Fischer, Castel, Dodd & Pratt, 2003). The SNARC effect and its variants are typically interpreted as evidence of an internal, horizontally-oriented left-to-right mental number line, such that a manual response to a number is faster when the side of response is congruent with the position of the number on that mental number line (Fischer et al., 2003; Fias, 1996; Fischer, 2003; Nuerk, Bauer, Krummenacher, Heller, & Willmes, 2005).

Second, when individuals indicate the larger of two Arabic digits in a speeded task, response times increase as a function of the distance between the two digits: comparison of digits close in magnitude (e.g., 4 and 5) yields relatively slow reaction times, while increasing the magnitude between the digits (e.g., 1 and 9) results in decreased response times (the numerical distance effect; Moyer & Landauer, 1967). Consistent with the hypothesis of a spatially organized mental number line, the distance effect suggests that digits are represented neurally in a sequential fashion, such that activation of one numerosity activates the representation of adjacent and closeby numerosities, in effect impairing the discrimination of numbers close in magnitude (Dehaene et al., 1990; Neider, 2005).

Mental line estimation tasks further support the existence of a mental number line. In these tasks, participants indicate the approximate position of a given number on an unmarked horizontal line flanked by two numerical anchors (e.g., 0 on the left, and 100 on the right). Typically, adults exhibit a linearly-increasing number line, suggesting each numerosity is cognitively represented equidistant from adjacent numerosities (Siegler & Opfer, 2003). Children perform differently, systematically assigning more space on the number line to smaller numbers, and increasingly compressing the differences in magnitude between higher numbers (Siegler & Opfer, 2003). This logarithmic mapping of number is hypothesized to reflect the lessened precision and increased noise associated with an underdeveloped understanding of large numerosities in young children—a hypothesis consistent with the logarithmic mapping observed in adults in an Amazonian indigenous society with little to no mathematics education (Dehaene, Izard, Spelke, & Pica, 2008). Children's mappings gradually become linear with increased exposure to mathematics education: by sixth grade, children represent numbers 1 through 1000 on a linear scale (Siegler & Opfer, 2003). The systematic ways in which children and adults map number onto space does, in itself, provide evidence of a mental number line with consistent characteristics across individuals. However, perhaps what is the most compelling evidence from this task is how natural and simple this task is for individuals—even young children and uneducated, illiterate adults.

Having established a robust mapping of numbers onto space, researchers investigated whether an inherent association with space is characteristic of ordinal sequences in general. A left-to-right SNARC effect has since been found for non-numerical ordinal sequences, such as weekdays, months, letters of the alphabet, time, and even for words in a recently-learned ordered list (Gevers, Reynvoet, & Fias, 2003, 2004; Santiago, Lupiáñez, Pérez, & Funes, 2007; Previtali, de Hevia, & Girelli, 2010; but see Dodd, Stigchil, Leghari, Fung, & Kingstone, 2008 for no attentional SNARC effect with non-numeric ordinal sequences). Distance effects are also observed when participants perform speeded comparison tasks with these sequences[1]. These data suggest the cortex develops and maintains neural architectures linking specific sequence items to space, likely in parietal cortex (Hubbard, Piazza, Pinel, & Dehaene, 2005), and that ordinality generally, and not numerosity exclusively, may serve as the basis of these associations.

There is considerable evidence that the left-to-right bias observed in Western adults' sequence-space mappings reflects associations learned through reading text in a culturally-specific direction. Individuals raised in non-Western cultures that read and write language from right to left (e.g., Arabic) exhibit a reversed, right-to-left SNARC effect (Zebian, 2005; Dehaene et al., 1993; Shaki, Fischer, & Petrusic, 2009).

[1] With the exception of time in Santiago et al. (2008), in which participants indicated with a key press whether words were past or future words; as such, no distance element was inherent to the task.

Furthermore, in cultures with languages that have varying text directionalities for different sequences (e.g., Hebrew, in which letters are read from right to left, and numerals are read from left to right), the SNARC effect for each sequence matches the text direction for that sequence (Shaki et al., 2009; Hung, Hung, Tzeng, & Wu, 2008). Together, these data provide evidence that directional biases in sequence-space associations are contingent on how each specific sequence is experienced in text. However, not all cross-cultural data are consistent with the hypothesis that mental number line directionality is a result of reading and writing habits: for example, Japanese participants, who typically read vertically from top to bottom, exhibit a vertical numerical SNARC effect in the *opposite* direction (small numbers at the bottom, and large numbers at the top) (Ito & Hatta, 2004). It is possible that Japanese individuals encounter conflicting directional cues when it comes to number; for example, numbers on a thermometer run opposite to the direction they would experience in text; but it is also conceivable that the development of cortical links between sequence and space is more sensitive to texts that are horizontal (i.e., text in the majority of the world's cultures) than texts that are vertical.

Additionally, data from ordering experiments in birds suggest that reading experience may not be the only factor driving the predominant left-to-right bias in sequence-space associations. In one experimental paradigm, newborn domestic chicks and adult nutcrackers were trained to find food in the *n*th hole in a series of 16 holes extending outward sagitally in front of the bird. After extensive training, the 16 holes were rotated 90 degrees, such that the birds entered the arena and encountered a horizontal line of holes. The birds searched for food in the *n*th holes from the left significantly more often than chance and any other hole, including the *n*th hole from the right (Rugani, Kelly, Szelest, Regolin, & Vallortigara, 2010; Rugani, Regolin, & Vallortigara, 2007). The authors suggest the birds perceived the sequence as beginning on the left, perhaps as a result of a right hemisphere dominance in visuospatial tasks that causes most animals (and humans) to attend preferentially to the left side of space. Indeed, topminnows that have been specifically bred for a right hemispheric lateralization of attention exhibit a systematic leftward bias after they are trained to choose the central door in a 9-door display (Dadda, Zandona, Agrillo, & Bisazza, 2009). This hemispheric dominance may cause the cortex to more easily process ordered stimuli that are arranged from left to right, regardless of sequence type, resulting in a natural left-to-right bias in the mapping of ordinal sequences onto space (de Hevia, Girelli, & Cassia, 2012). This hypothesis predicts that all pre-reading humans would exhibit a left to right bias in sequence-space associations, and that this bias may either be reinforced or attenuated and ultimately reversed by subsequent reading and writing experience.

Pre-school children already exhibit patterns of behaviour consistent with a left-to-right representation of number. Most 2.5- to 5.5-year-olds count objects from left to right, a finding that suggests they perceive the beginning of the sequence to be on the left; 4- and 5-year-olds count beginning at one end of the line, and count adjacent items consecutively (Opfer & Thompson, 2006; Opfer, Thompson, & Furlong, 2010; Briars & Siegler, 1984). When asked to add a poker chip to, or take a poker chip away from, a line of chips, 4- and 5-year-olds add the chip to, and subtract the chip from, the right side of the line (Opfer & Thompson, 2006; Opfer et al., 2010). There is also evidence that preschoolers (*M*=4.0) exhibit a left-to-right SNARC-like effect by responding faster on a touch screen to larger numerosities on the right, and smaller numerosities on the left (Patro & Haman, 2012). Lastly, German kindergarteners (*M*=6.0) are less accurate in judging where a number belongs on a line when it is oriented from right to left than they are on a typical, left-to-right oriented number line (Ebersbach, 2013).

These data suggest that a left-to-right bias in sequence-space associations is present in Western preschool children prior to the onset of reading and writing abilities. Problematically, however, while past studies investigating number-space associations in preschoolers have assumed their participants were pre-readers, no study has verified whether this was indeed the case. As such, it is possible that literacy in a proportion of their participants may have driven these patterns of results. Further, as Patro and Haman (2012) acknowledge, even pre-reading children are regularly exposed to the cultural direction of reading and writing from a very early age. For example, young, pre-reading children often engage in finger counting, which tends to be done from left to right in Western cultures; their parents tend to trace text from left to right as they read to their children; and Western preschoolers see their parents writing out the alphabet from left to right, one of the first sequences they are taught. Thus, it is conceivable that left-to-right sequence-space associations observed in pre-reading children reflect this cultural experience, rather than an inherent, cortically-driven left-to-right bias.

The present study was designed to provide further insight into the nature of sequence-space mappings in children who are pre-readers. We examined the directionality of four sequences that are highly familiar to children (i.e., letters of the alphabet, numbers, times of day, and meals) in 4- and 5-year-olds who were confirmed as pre-readers. To our knowledge, the directionality of non-numerical sequence-space associations has not been tested previously in young children. Importantly, our results can speak to the debate about the origins of these associations. If a left-to-right bias is indeed a reflection of increased attention toward the left visual field, one would expect a systematic left-to-right bias for all four sequence types in both 4- and 5-year-olds. However, if left-to-right biases are driven by enculturation, one would expect left-to-right mappings for some sequences, such as those often seen ordered in text even prior to learning to read and write (e.g., A, B, C and 1, 2, 3), but not others. Furthermore, the enculturation hypothesis predicts more left-to-right mappings in 5-year-olds than 4-year-olds, as they have experienced more exposure to the cultural direction of reading and writing.

Children first performed a validity task, in which they were asked to indicate in which of three coloured boxes an object belonged, based on the colour of that object. This task was employed to ensure participants understood the concept that an object can be matched with specific locations based on a specified characteristic of that object (e.g., colour, order, etc.). Subsequently, participants were asked to place the first, second, and third item of a familiar sequence in the first, second, and third box (respectively) arranged horizontally in front of them. While exceedingly simple, this task is revealing in that it indicates which of the three boxes the child considers to the first, second, and third box, respectively. Lastly, to confirm that participants were pre-readers, children performed the reading subtest of the Wide-Range Achievement Task, in which they are asked to identify letters and words that become progressively more difficult.

Methods

Participants

Participants were recruited from a database of parents who volunteered their children for future experimental testing during hospital visits shortly after their child's birth. The final sample consisted of 200 English-speaking Canadian children from 2 age groups, with one quarter of participants per age group assigned to each of 4 sequence types: 100 4-year-olds, ±3 months (numbers: n=25; M=4.02, SD=.1; 10 males; letters: n=25; M=4.05; SD=.10; 14 males; times of day: n=25; M=3.94, SD=.12; 11 males; meals: n=25; M=3.99; SD=.1; 10 males) and 100 5-year-olds, ±3 months (numbers: n=25, M=5.07; SD = .08; 16 males; letters: n=25; M=4.95; SD=.09; 14 males; times of day: n=25; M=5.03; SD=.09; 9 males; meals: n=25; M=5.04; SD=.15; 13 males). An additional 12 children were tested but excluded from the analyses because they did not pass the validity task or were deemed literate by having a WRAT-3 standard score over 2 standard deviations above the mean performance for 5-year-olds. Among 4-year-old participants, 7 were replaced for failing validity (2 participants for each the alphabet, meals, and times of day groups; 1 from the numbers group) and 2 for high scores on the WRAT-3 (1 in each of the meals and numbers groups). Among 5-year-olds, 2 participants were replaced for failing the validity task (both in the meals group), and data from 1 participant were replaced for high scores on the WRAT-3 (in the times of day group). See Table 1 for group WRAT-3 raw score means and standard deviations, and

Figure 1 for a histogram illustrating the distribution of scores. The parent accompanying the child gave informed consent. Children were rewarded for their participation with their choice of toy.

Apparatus

Three small cardboard boxes with a length of 11.3 cm, width of 8.5 cm, and height of 6.3 cm were utilized for the validity task. Each box was painted a different colour (1 green, 1 red, and 1 yellow). The 3 boxes were placed 10 cm apart 110 cm in front of the seated participant. Validity stimuli consisted of three objects: one plastic green tree, and two clear plastic shapes depicting a heart and a banana.

Three larger brown boxes with a length and width of 22.4 cm and height of 13.5 cm were utilized for the sequence item placement task. These boxes were placed adjacent to one another, separated by a distance of 4 cm, at a distance of 80 cm in front of the seated participant.

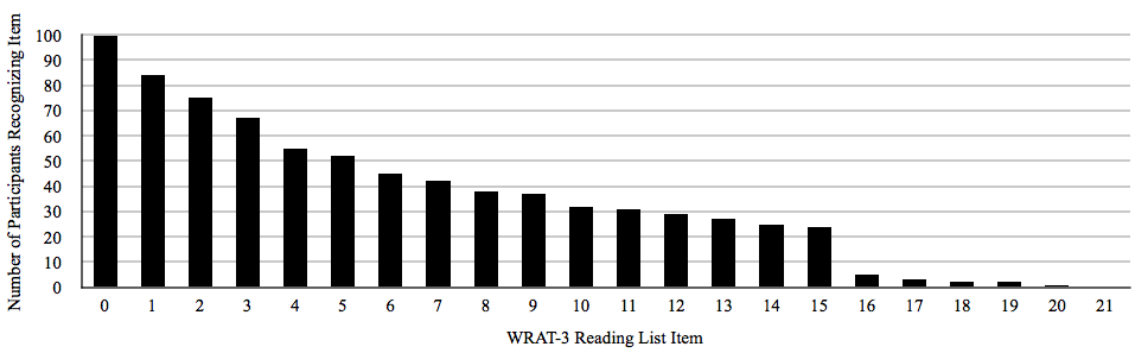
To verify pre-literacy in participants, we utilized the Word Reading card of the Wide Range Achievement Task-3 (WRAT-3), which is used to measure ability to recognize and identify letters and words. Participants go progressively through the list, starting with 15 letters (beginning with the most common), followed by words that get progressively more difficult as the child goes through the list. This task was terminated when children could not identify a letter or word. Raw scores are converted into standardized scores, which have a mean of 100 and standard deviation of 15; however, as the test's standardized scores are normed for ages 5.0 through 74.0 years, and thus could not be applied to our 4-year-old group, we utilized raw scores to evaluate literacy skills, as has been done previously in the literature (e.g., Levy, Gong, Hessels, Evans, & Jared, 2006; Anvari, Trainor, Woodside, & Levy, 2002).

Procedure

Participants entered the laboratory with a parent, and were brought inside the testing room while the parent was seated outside of the room. Once inside the room, participants were seated on a carpeted floor across from the experimenter.

Participants first performed a validity task to ensure an understanding of the experimental task—that is, we wanted to ensure the children grasped the concept that an object can be matched with specific locations based on a specified characteristic of that object (e.g.,

(a)



(b)

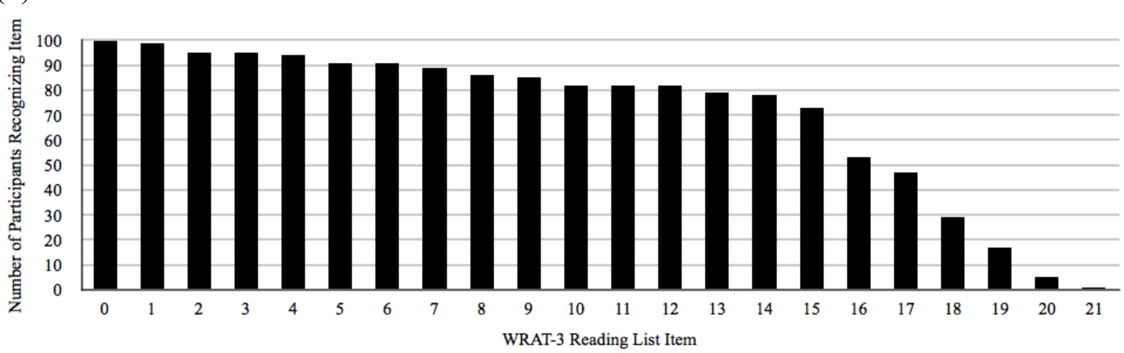


Figure 1. Histograms displaying the number of (a) 4-year-olds and (b) 5-year-olds that successfully recognized each WRAT-3 Reading List item.

colour, order, etc.). For this task, three small boxes, each a different colour (red, green, and yellow), were placed in front of the participant in a random order. One of three plastic objects (a tree, a banana, and a heart) was then presented to the participant, and the experimenter asked "Do you know what this is?". Following a correct response (e.g., "tree"), the experimenter asked "What colour are trees?". Following a correct response (e.g., "green"), the experimenter asked "So if trees are green, which of these three boxes do you think the tree belongs in?". This was subsequently repeated for the other two shapes. The expected placement of the shapes was tree/green box, banana/yellow box, and heart/red box. Two out of three correct placements was used as the criterion for data inclusion. Of the included participants, only 2 4-year-olds (1 in the times of day group, 1 in the meals group) and 1 5-year-old (in the alphabet group) scored 2 out of 3 on this task, with all other participants scoring 3 out of 3.

Following the validity task, the small boxes and shapes were removed and three larger boxes, all identical in size and colour, were placed in front of the participant. The experimenter sat facing the participant, with the large boxes equidistant between the experimenter and participant. The experimenter preceded to present the first, second, and third item of the utilized sequence, individually and in order. For each item presented, the experimenter said the following script: "[Number 1, letter A, morning, breakfast] is the *first* number/letter/time of day/meal, so it goes in the *first* box. Can you put it in the *first* box for me?". The experimenter then handed the item to the child across the middle of the central box. Once the child had placed the first sequence item in a box, it remained there, and the second and then third sequence items were presented, using the same script with the second and third items inserted at the beginning and the words *second* and *third* replacing *first,* respectively.

Following the completion of the sequence item placements, participants were presented with the WRAT-3 reading list card. The experimenter asked the participant to identify each of the letters across the top line of the card, followed by each of the progressively more difficult words on the lines below the letters. The task was terminated when the child could not identify a letter or word. To calculate raw scores, one point is assigned for each correctly read letter and/or word. For the purposes of the present study, literacy was defined as a standard score that was 2 standard deviations above the mean for 5-year-olds—a level of performance expected of 5-year-olds entering Grade 1[2]. At this level, children can identify letters as well as a few common, simple words (e.g., "cat", "in"), but fail when presented with words that are less common (e.g., "spell", "abuse").

Results

Given the 3 positions where an item could be placed, there are 6 possible item arrangements. Of primary interest was where the second sequence item was placed relative to the first item, as the participant necessarily had to place the third item in the only remaining box. Thus, there were 3 possible item arrangements that were classified as left-to-right orderings, and 3 classified as right-to-left orderings (see Figure 2).
The data of the two age groups (i.e., 4- and 5-year-olds) were analyzed separately. For each sequence, a binomial probability analysis was performed to determine whether the

[2] One 5-year-old included in the Times of Day group had a score roughly at the cut-off criterion of 2 standard deviations above the mean; however, with this participant's data removed, the results remained unchanged (75% left-to-right, p=.023).

Age Group	Letters	Numbers	Times of Day	Meals
4-year-olds	6.8 (5.78)	6.8 (6.82)	7.3 (5.73)	6.2 (5.95)
5-year-olds	13.2 (5.73)	13.8 (5.96)	15.9 (4.47)	15.44 (3.82)

Table 1. Means and standard deviations (in parentheses) of raw scores on the WRAT-3 for each group.

the proportion of participants exhibiting a left-to-right ordering pattern differed from the ordering proportions one would expect by chance (i.e., 50%). A significant proportion of 4-year-olds ordered letters A, B, C from left to right (72%; p=.043), but not numbers (52%; p=1), times of day (68%; p=.108), or meals (64%; p = .230). Five-year-olds systematically ordered letters (72%; p=.043), numbers (76%; p=.015), and times of day (76%; p=.015), but not meals (56%; p=.690), from left to right (see Figures 3 and 4).

We also examined whether the characteristics of participants' ordering of each sequence was consistent with typical counting behaviours previously identified in the literature (Briars & Siegler, 1984); namely, placing all consecutive items in sequence adjacently, and beginning a sequence on one end of a line. Once again, we utilized binomial probability analyses to examine whether the observed orderings differed from the patterns one would expect by chance (i.e., 2 of 6 [33.33%] possible orderings have all adjacent items, necessarily starting at one end of the line of boxes). 4-year-olds exhibited a systematic pattern of employing these two rules for all sequence types (letters: 64%; p=.002; numbers: 72%; p<.001; times of day: 72%; p<.001; meals: 60%; p=.006), as did

5-year-olds (letters: 100%; p<.001, numbers: 84%; p<.001; times of day: 96%, p<.001, meals: 84%, p<.001) (see Figure 3).

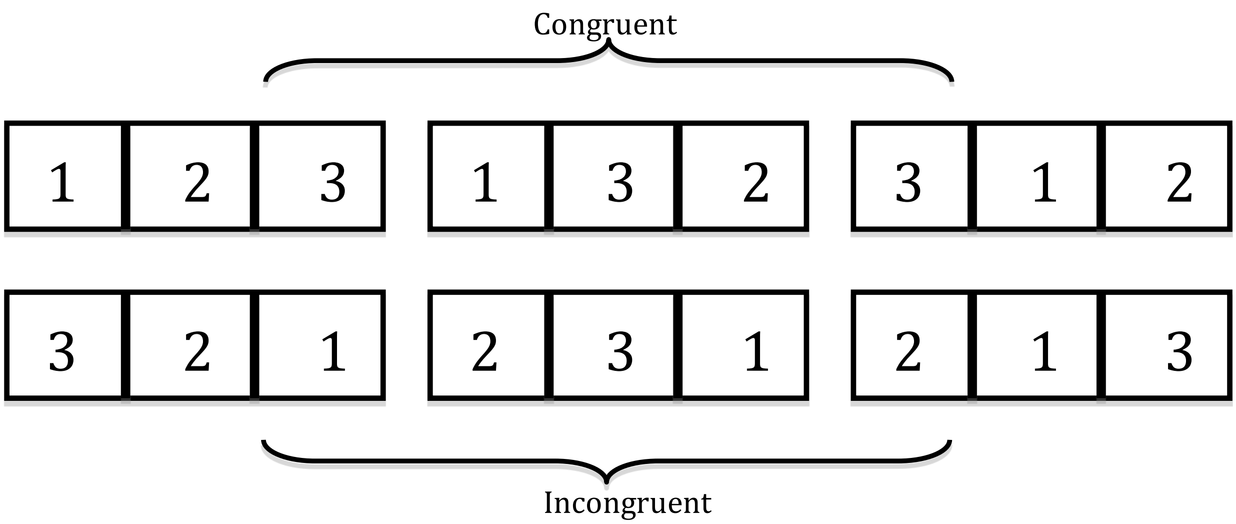


Figure 2. The six possible item arrangements. The top three represent congruent arrangements, with the second item placed to the right of the first; the bottom three are incongruent arrangements, with the second item placed left of the first. In this schematic, 1 represents the first sequence item (e.g., 1, A, morning, breakfast), 2 the second sequence item, and 3 the third.

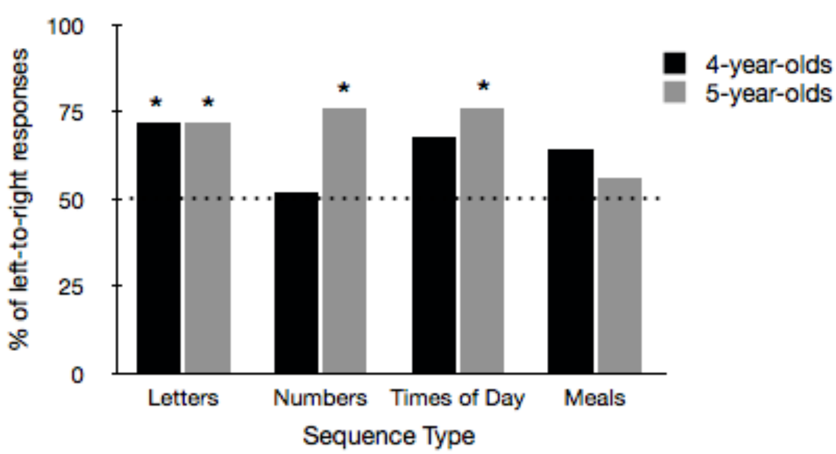
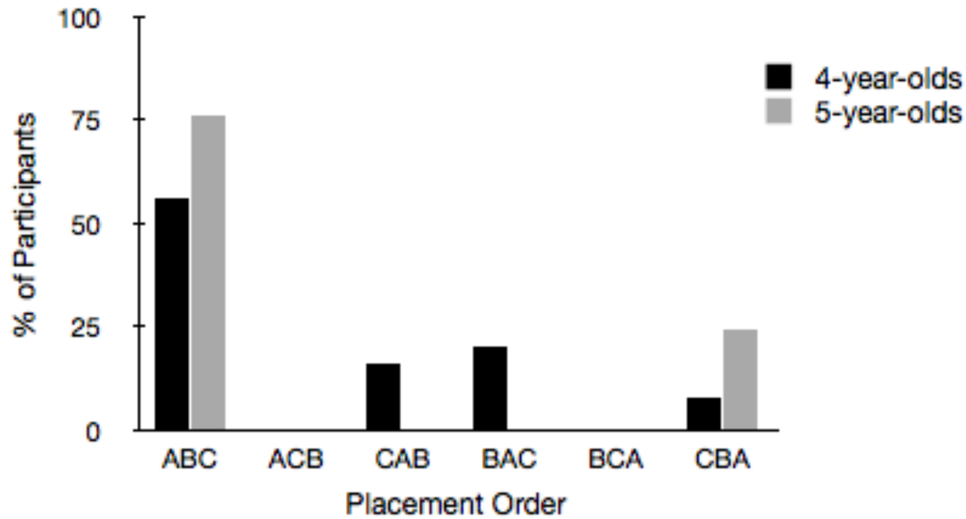
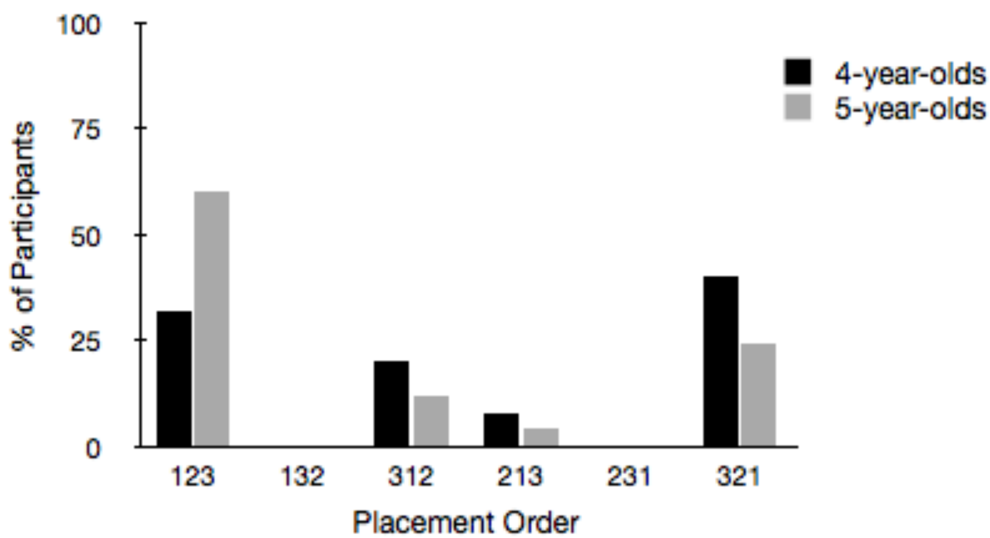


Figure 3. The percentage of 4- and 5-year-olds who exhibited a left-to-right ordering of each sequence type. The dotted line represents chance levels (i.e., 50%). Asterisks indicate alpha levels below .05.

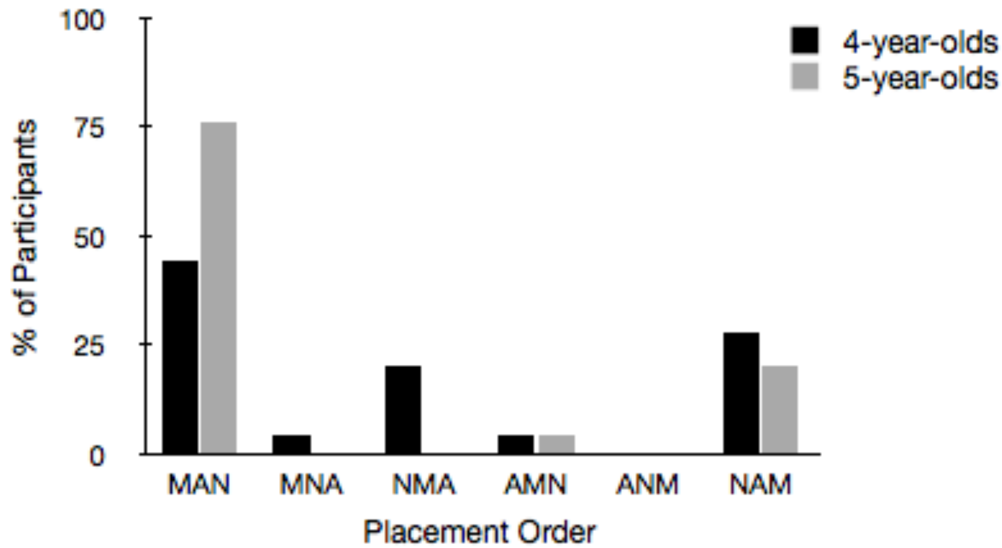
(a)


100
75
50
25
0
% of Participants
4-year-olds
5-year-olds
ABC
ACB
CAB
BAC
BCA
CBA
Placement Order

(b)


100
75
50
25
0
% of Participants
4-year-olds
5-year-olds
123
132
312
213
231
321
Placement Order

(c)



(d)

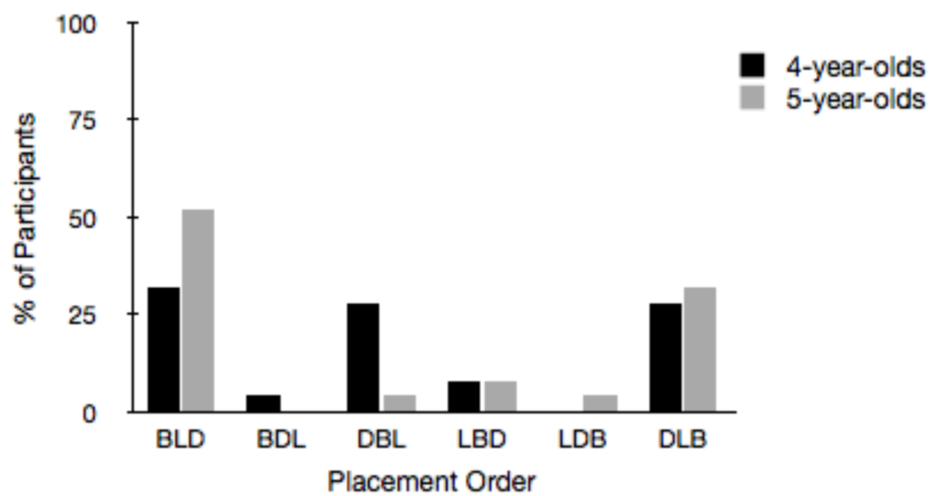


Figure 4. The percentage of 4- and 5-year-old participants who exhibited each of the 6 possible item arrangements for (a) letters, (b) numbers, (c) times of day, and (d) meals.

Discussion

The purpose of the present study was to investigate whether pre-reading 4- and 5-year-old children exhibit systematic biases in their ordering of items from four familiar ordinal sequences: letters, numbers, times of day, and meals. Previous research has revealed that preschoolers count, add and subtract, and perform number line estimations better from left to right; further, kindergarteners exhibit performance on a reaction time task consistent with a left-to-right SNARC-like effect (Opfer & Thompson, 2006; Opfer et al., 2010; Patro & Haman, 2012; Ebersbach, 2013). While these data do suggest young children exhibit a left-to-right mapping of number, this is the first study to investigate preschool children's mappings of other ordinal sequences, which are also mapped from left to right by Western adults (e.g., Gevers et al., 2003, 2004). To our knowledge, this is also the first study of its type to confirm that participants were indeed pre-readers. To do so, each participant was administered the Wide-Range Achievement Test—3 (WRAT-3), and the data of those participants whose standard scores were more than two standard deviations above the mean of performance expected from 5-year-olds entering Grade 1 were excluded. At this level, children can read letters as well as a few common, simple words (e.g., "cat", "in"), but fail when presented with words that are less common (e.g., "spell", "abuse"). Indeed, the majority of the included 4-year-old participants were only able to identify letters; this was the case for approximately half of the 5-year-olds, the remainder of whom could only identify very simple, common words. This step in the methodology differentiates our study from similar previous experiments, as we can conclude it is unlikely that our sample included children that are more advanced readers than the rest of their cohort, and whose literacy may have influenced the results.

In our sample, 4-year-olds systematically ordered letters, but not numbers, times of day, or meals, from left to right. By age 5, numbers and times of day were also ordered from left to right. These data indicate that the alphabet (i.e., A, B, C specifically) is the first sequence to be mapped onto the left-to-right mental sequence line, followed by numbers and times of day.

These data offer compelling support for the enculturation hypothesis of sequence ordering for various reasons. First, as the enculturation hypothesis posits that experience drives orientation of the mental sequence line, it predicts sequences seen left-to-right in print, even before the children can read them or understand what they mean, will be first to be consistently mapped from left to right. While it is likely that both the letters A, B, C and numbers 1, 2, 3 are often seen in print by preschoolers, these results suggest it is likely that the letter sequence is more commonly viewed (e.g., on fridge magnets, wooden play blocks). Regardless, the emergence of a left-to-right mapping for one sequence before others is inconsistent with the hemispheric specialization hypothesis, which predicts consistent left-to-right organization of all sequences, based on an attentional bias towards the left visual field (Rugani et al., 2010). Furthermore, the enculturation hypothesis predicts more left-to-right mappings in 5-year-olds than in younger preschoolers, who have had less exposure to the cultural direction of reading and writing. This prediction is also supported by our results: more 5-year-olds ordered letters from left to right than 4-year-olds (76% vs 56%, respectively), and we observed the same pattern for all three other sequences.

In addition to looking at the *direction* of sequence mappings, we also examined whether they reflected the object counting rules/expectations of 4- and 5-year-olds previously reported in the literature. Specifically, when judging the accuracy of another individual counting objects, children of both age groups tend to reject counts that do not start at one end of a line and do not count adjacent items consecutively (Briars & Siegler, 1984). Consistent with these observations, a high proportion of both the 4-year-olds (i.e., 64% letters, 72% numbers, 72% times, 60% meals) and the 5-year-olds (i.e., 100% letters, 84% numbers, 96% times, 84% meals) started their sequence at one end of the boxes, and then ordered consecutive items adjacently; these proportions were significantly different from what one would expect by chance (i.e., 33.3%). Our data suggest that early-learned counting principles are generalized to the physical ordering of sequence items of any type. It is possible that these ordering patterns are shaped by children learning to count using their fingers, which tends to emerge at about age 4 (Fuson & Kwon, 1992).

It is interesting to consider the fact that the 5-year-olds, even while still pre-readers, ordered a sequence they likely have never seen (or at least could not recognize) in print from left to right—that is, times of day. Thus, it is possible that once a neural architecture linking sequences to space is established for the first sequence, other overly-learned sequences may be bootstrapped onto this architecture, inheriting the directionality of the original sequence. Alternatively, it may be that by 5 years of age, children have better internalized the cultural text direction, and can spontaneously apply this knowledge to newly encountered sequences. This second possibility is unlikely, however, as meals were not consistently mapped from left to right by 5-year-olds.

It is not immediately clear why 5-year-olds consistently mapped three familiar ordinal sequences, but not meals, from left to right. One possibility is that the meal sequence is not as familiar to young children as letters, numbers, or times of day. This may be because children's eating regimes typically include various snacks throughout the day, some of which are unscheduled; therefore, children's representations of individual meals may not be assigned to fixed locations within an ordinal sequence. It is also possible that the stimuli utilized may have been misleading to some children. For the images on the meals stimuli we utilized what we deemed to be prototypical North American foods for each meal (i.e., cereal for breakfast, a sandwich for lunch, and spaghetti for dinner). However, these images may have been confusing to children who do not eat these specific items, or for those who eat the selected items at different meals than those assigned to them in our stimuli (e.g., some children might eat spaghetti for lunch, or eat a sandwich for dinner).

Our data establishes, for the first time, that confirmed pre-readers exhibit a systematic left-to-right bias in the ordering of various ordinal sequences. Although several other studies have reported number-space mappings in preschoolers (e.g., Opfer & Thompson, 2006; Opfer et al., 2010), these studies did not test the reading ability of participants. Therefore, it is possible that the proportions of pre-reading preschoolers exhibiting left-to-right number orderings in the literature are incorrect. As we were required to exclude three potential participants (i.e., two 4-year-olds and one 5-year-old) from the final sample for demonstrated literacy, it is possible that the samples utilized in these other studies included some literate children. One limitation of the present study, however, is that the cut-off utilized for literacy in this study was arbitrary; indeed, most of the children did recognize at least some letters. Nevertheless, this is the first study to document the level of literacy in participants.

The analysis utilized for the present study, i.e. non-parametric binomial tests, allowed us to assess whether participants ordered each sequence from left to right more often than one would expect by chance. The analysis did not, however, allow us to assess whether the proportions of left to right for each sequence type differed from one another; therefore, our conclusions about the differences between sequence types are indirect. While our conclusions concerning the directionality of numbers at age 4 are relatively straightforward (i.e., left to right ordering is at approximately 50%; see Figure 3), our conclusions about meals and times of day at age 4 are less clear, as the means are above 50%, but not significant. The conclusion of no systematic ordering for meals at age 4 is confirmed by the absence of left to right ordering at age 5, and a comparison at age 4 of strictly left to right with strictly right to left (about equal) (see Figure 4c). For times of day, however, the mean at age 4 is above 50% but not significant, and it is significant at age 5; additionally, at age 4, more children are ordering times from left to right than the opposite direction. Thus, the left to right mapping of times of day may be emerging at age 4, although our overall conclusions remain unchanged, as this proportion is smaller than the directional mapping of ABC at age 4.

Many questions regarding the development of sequence-space associations still remain. For example, these data do not establish the age at which left-to-right orderings of letters emerge; even younger children may exhibit this directional bias (i.e., at least for letters). Future studies could also investigate whether directional biases are exhibited for other ordinal sequences potentially familiar to preschoolers (e.g., seasons; other time sequences, such as yesterday, today, tomorrow, etc.), and the ages at which these directional biases become apparent. The role of visual experience in the development of these sequence-space associations could also be addressed. While our data suggest that seeing letters often in print may initiate a left-to-right mapping of that sequence and subsequently others, congenitally blind individuals do exhibit SNARC and distance effects for numbers (Castronovo & Seron, 2007; Szücs & Csépe, 2005). It is likely that the congenitally blind still glean their sequence-space associations from enculturation, such as learning to read Braille. However, acquiring these associations through tactile experience alone may result in a different developmental timeline. This is especially likely to be the case among children that are pre-readers, as seeing individuals have experience with the cultural direction of writing throughout their lives; blind children, on the other hand, may not be exposed to this direction until years later.

The results of this experiment also generate several testable hypotheses for future investigation. To begin, as these data lend compelling support to the enculturation hypothesis, they predict that individuals with little to no experience with a cultural direction of reading and writing will exhibit no systematic directional mapping in the ordering of ordinal sequences. Therefore, if a habituation or looking preference paradigm to test this hypothesis were employed, one would expect no directional bias in infants; similarly, one would expect no bias in isolated hunter-gatherer cultures with little to no access to formal education or any sort of text (e.g., the Hazda of Tanzania). Additionally, although the alphabet (i.e., A, B, C specifically, and in alphabetical order) may be first sequence learned for North American children, this may not be the case for children in other cultures. For example in the Czech Republic, children are taught letters in an order that is unrelated to actual alphabetical order; that is, groups of vowels and accented vowels are learned first, followed by groups of consonants (Watson, Akins, Chromy, Alderete, Hahn, & Enns, 2014). Therefore, one might expect Czech children to organize letters from left to right, but out of alphabetical order. Therefore, the first sequence, and the order of that sequence, to be consistently mapped onto space may vary by culture.

In conclusion, the current study presents the first evidence of a left-to-right bias in the mappings of number and other ordinal sequences in confirmed pre-readers. These data offer compelling support for the enculturation hypothesis on the development of sequence-space associations.

References

* References can be found at the end of the thesis.

Pre-Chapter Introduction

In the work described in Chapter 3, the association between the mental sequence line and visuospatial and mathematics skills was assessed in school-aged children. Six-, 7-, and 8-year-old children performed a magnitude-relevant SNARC task (i.e., is the number on the screen greater or less than 5?), which yielded measures of both the SNARC and distance effects for each child. Participants also completed two standardized tests measuring visuospatial and mathematics skills, respectively. As predicted, the strength of the mental sequence line (as measured by the distance effect, and less so by the SNARC effect) was correlated with the visuospatial ability of mental rotation. Mathematics ability, however, was not correlated with either the SNARC or distance effects. While visuospatial abilities are related to the SNARC effect in adults, these data are the first to suggest that they play a role in the development of the mental sequence line in children.

Development of SNARC and Distance Effects and their Relation to Mathematical and Visuospatial Abilities

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Chapter 3: Development of SNARC and Distance Effects and their Relation to Mathematical and Visuospatial Abilities

Abstract

The present experiment measured SNARC and distance effects in school-aged children, and investigated the relation between these measures and visuospatial skills and mathematics ability. Six-, 7-, and 8-year-old children 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 (DTVP-2) and mathematics ability (TEMA-3). Consistent with previous research, all age groups exhibited robust distance effects, and SNARC effects were only observed in 7- and 8-year-olds. Distance effects were moderately but significantly correlated (r=.303) with a subtest on the DTVP-2 measuring the ability to mentally manipulate objects in space, but no other subtest; a similar trend was observed for the SNARC effect (r=-.195; more negative values reflect stronger SNARC effects with our measure). These data suggest that mental orientation abilities, but perhaps not visuospatial skills involved in visual perception and visuo-motor coordination, are related to mental sequence line development. Nevertheless, no relation was observed between SNARC or distance effects and mathematics ability (both ps>.12). 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.

Chapter 3: Development of SNARC and Distance Effects and their Relation to Mathematical and Visuospatial Abilities

Introduction

In modern society, the ability to quickly and accurately process and manipulate numerosities is of utmost importance. As such, educators dedicate considerable time to the teaching of basic number principles, and the cognitive processes underlying these abilities have been the focus of a large amount of recent research. One such avenue of research has investigated the inherent association between numbers and space that is manifest in a mental number line, and how, in turn, that association is related to other skills, such as visuospatial and mathematics abilities. The present study measured these abilities in 6-, 7-, and 8-year-old children using two standardized tests measuring visuospatial and math skills, respectively, and assessed the relation between scores on these measures and the strength of individual mental number lines.

Adults' Mental Number Line

Performance on a number of behavioural tasks provides evidence that adults automatically map number onto space in a consistent, directional manner. For example, when Western adults are asked to indicate the parity (i.e., odd or even) of an Arabic number with left or right key presses, they respond faster to smaller numbers (e.g., 1-4) with a left-sided response and to larger numbers (e.g., 6-9) with a right-sided response (the SNARC effect; Dehaene, Bossini, & Gireaux, 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; Gibson & Maurer, in preparation). This association is so robust that it influences visual attentional processes, such that small numbers cue attention to the left visual field, and larger numbers to the right (Fischer, Castel, Dodd, & Pratt, 2003). SNARC-like effects are typically interpreted as behavioural manifestations of a horizontal mental number line that is oriented from left to right, resulting in faster manual responses when the side of response and the position of the number on the mental number line are congruent (Fischer et al., 2003; Fias, 1996; Nuerk, Bauer, Krummenacher, Heller, & Willmes, 2005).

Further evidence of a strong association between numbers and space comes from the numerical distance effect and from number line estimation tasks. The distance effect is the finding that individuals are faster to indicate the larger of two distant digits (e.g., 1 and 9) than of two digits closer in magnitude (e.g., 1 and 2) (Moyer & Landauer, 1967). This behaviour 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 closeby numerosities represented by adjacent populations, impairing the discrimination of adjacent (but not distant) numbers (Dehaene et al., 1990; Neider, 2005). For number line estimation tasks, participants are given an Arabic digit and asked to estimate its approximate position on an unmarked horizontal line that begins with 0 at the left and a larger number at the right (typically 100 or 1000). In this type of task, there is a robust linear relationship between number magnitude and location on the number line, suggesting adults systematically map number onto space in a linear manner, even across large spans of numbers (Siegler & Opfer, 2003). The consistency of responses across individuals on this task, coupled with how intuitive it is (so intuitive, in fact, that young children and even uneducated, illiterate adults perform it with relative ease; Siegler & Opfer, 2003; Dehaene, Izard, Spelke, & Pica, 2008) lends further support to the hypothesis of a mental number line.

In addition to behavioural evidence, data from patient and neuroimaging studies support a strong neural link between number and space. For example, one recent neuroimaging study tested whether the same neural circuits are recruited for spatial attention tasks and mental arithmetic. The researchers trained a multivariate classifier algorithm to utilize patterns of posterior parietal activation to determine the direction (i.e., left or right) of participants' eye movements (Knops, Thirion, Hubbard, Michel, & Dehaene, 2009). Subsequently, in the absence of further training, the same algorithm could accurately determine whether the participant was performing mental addition or subtraction. These data support the hypothesis that addition and subtraction are computed by performing rightward and leftward mental shifts across a mental number line, respectively. Another telling example of the neural overlap between number and space comes from patients with parietal lobe lesions, who often present with combined deficits in the processing of both number and space (Hubbard, Piazza, Pinel, & Dehaene, 2005). For example, patients with Gerstmann's syndrome exhibit a characteristic combination of dyscalculia and spatial deficits, such as left-right disorientation and finger agnosia (Gerstmann, 1940). Lastly while it is well-established that patients with (left) hemispatial neglect systematically estimate the midpoint of a line well to the right of the actual midline (e.g., Halligan & Marshall, 1993), recent evidence suggests this deficit extends to the bisection of numeric intervals, with patients incorrectly estimating the midpoint of two numbers as closer to the larger number (Zorzi, Priftis, & Umiltà, 2002). A similar "rightward" shift in the bisection of numerical intervals occurs in healthy controls when they spatial processing is disrupted by repetitive transcranial magnetic stimulation (rTMS) over the right posterior parietal cortex (Göbel, Calabria, Farnè, & Rossetti, 2006). Taken together, these neuropsychological and neuroimaging data suggest that numerosities are represented in space in a fashion quite analogous to a physical line.

The evidence summarized above suggests that number and space are intrinsically linked. Nevertheless, some evidence suggests that the specific directionality of the adult mental number line is influenced by cultural experience, that is, the directionality of reading and writing to which an individual is exposed. For example, individuals in Western cultures, who read and write from left to right, exhibit a typical, left to right SNARC effect (e.g., Dehaene et al., 1993), while those that read and write from right to left (e.g., in Arabic) exhibit a reversed SNARC effect (e.g., Zebian, 2005; Dehaene et al., 1993). It appears that the directionality of both text and number influence the direction of the number line, as Hebrew individuals, for whom text is read from right to left, but numbers from left to right, exhibit no SNARC effect—as though the opposite directionalities cancel each other out (Shaki et al., 2009). There is, however, evidence that newborn domestic chicks and adult nutcrackers process sequential information in a left-to-right manner (Rugani, Kelly, Szelest, Regolin, & Vallortigara, 2010). This raises the possibility that cortical organization—namely, a right hemispheric bias in visuospatial processing—may predispose individuals to process numbers in a left-to-right manner, but that this predisposition can be strengthened or attenuated and reversed with cultural experience.

Children's Mental Number Line

Many of the characteristics of the directional mental number line reported in adults are also observed in children. Akin to adults, children provide evidence of a mental number line through their performance on number line estimation tasks. When asked to indicate the position of specific numerosities on number lines from 0 to 100 and 0 to 1000, children do so in a systematic manner: 7- and 9-year-olds systematically order numbers in a logarithmically-increasing fashion, while by 11 years of age number placements resemble the linear pattern exhibited by adults (Siegler & Opfer, 2003). The directionality of this mental number line also resembles that of Western adults: kindergartners (M=6.0 years) perform less accurately on number line estimation tasks when the line is oriented from right to left as opposed to left to right (Ebersbach, 2013), with a similar but attenuated effect in second graders (M=7.75 years).

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 9.2-year-old, but not 7.8-year-old, participants (Berch, Foley, Hill, & Ryan, 1999). Berch et al. (1999) noted that these findings did not negate the possibility of a directional mental number line in even younger children, as their youngest group of participants exhibited relatively slow and highly variable reaction times, which may have obscured any number-space mappings.

Indeed, subsequent studies utilizing modified methods have revealed traditional SNARC or SNARC-like effects in even younger children. For example, one group of researchers increased the power of the design used by Berch et al. (1999) by presenting more experimental 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 the reaction time data for both the 7.5- and 8.5-, but not the 6-year-old, groups, and in accuracy data (i.e., greater accuracy for congruent than incongruent trials) for the 8.5-year-old group only. These data suggest that spatial information is automatically activated by magnitude in children as young at 7.5 years of age, 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 about 8. To address this limitation, two SNARC-like paradigms previously utilized with adults have been adapted for use with 7-, 8- and 9-year-old children (van Galen & Reitsma, 2008). First, in a magnitude-irrelevant task based on the attentional SNARC effect (Fischer et al., 2003), children were presented with an Arabic digit flanked horizontally by two empty boxes. Following a delay, a target appeared in one of the two boxes, and the task was to indicate the side of the target as soon as it was detected. The magnitude of the digit did not predict the location of the target. Like adults, 9-year-old children, but not 7- or 8-year-olds, exhibited an attentional left-to-right SNARC effect: after viewing small numbers (i.e., 1-4), they were faster to detect targets appearing in the leftward box, while 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 magnitude-relevant task. Together, these data suggest that by age 7 Western children are automatically mapping number onto space in a left-to-right manner, but merely seeing a digit does not automatically cue its magnitude and spatial location until age 9.

Unlike the results for Western children, a SNARC effect using the traditional SNARC parity task has been observed in Chinese children as young as 5.8 years of age (Yang, Chen, Zhou, Zu, Dong, & Chen, 2014). This earlier automatic processing of number magnitude, as well as the earlier understanding of the concept of parity, is likely a result of earlier training and acquisition of mathematical principles in Chinese children (Zhou, Chen, Chen, Jiang, Zhang, & Dong, 2007).

The absence of SNARC-like effects in Western children under the age of 7 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; Gibson & Maurer, in preparation). Predicting that task difficulty was responsible for a lack of SNARC effect under age 7, two recent studies employed SNARC-like paradigms adapted for testing of young children. In the first study, a magnitude-irrelevant SNARC task was utilized in which children were presented with black Arabic digits that turned red or green after 200 ms; 5-year-old children indicated whether the number had turned red or green with a left- or right-sided response (Hoffmann, Hornung, Martin, & Schiltz, 2013). Both younger (M=5.53) and older (M=5.84) 5-year-olds exhibited a SNARC effect, responding faster to smaller numbers with the left hand and larger numbers with the right. In a second recent study, 4-year-old Polish children 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). The participants responded faster to large numerosities on the right side of the screen and small numerosities on the left than the opposite mapping, thus suggesting that children as young as 4 have automatic access to a left-to-right mental number line.

Despite the mixed results for the SNARC effect in children 4 to 8 years old, 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 respond faster to distant numbers (e.g., 1 and 9) than 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 (13-, 11-, and 8-year-olds, respectively; Sekuler & Mierkiewicz, 1977; Duncan & McFarland, 1980; Holloway & Ansari, 2008). Combined with number line estimation and SNARC effect-like tasks in children, these data support the hypothesis that even young children possess an internal 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 an individual's development of, and reliance on, the mental number line and, in turn, influence mathematics ability—or vice versa. There is some evidence that does suggest that measures of visuospatial skills and mathematics skills are correlated with one another.

For example, in a sample of Finnish high school students, mental rotation skills and visuospatial working memory (both visuospatial skills) were found to correlate 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-old children 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 related to underlying visuospatial or numerical deficits. One recent study in adults, however, 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 one's "number sense"; that is, it is believed to be represented by a fundamental neural architecture upon which more complex mathematical abilities are built (e.g., Dehaene, 1997). This hypothesis appears to be supported by evidence that unlike age-matched controls, children with dyscalculia, a developmental disorder characterized by pervasive deficits in math and number processing, 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)—suggesting that 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 a weaker SNARC or distance effect in both adults and children – or no relationship at all.

For adults, several studies found that mathematics and science students have weaker SNARC effects than liberal arts students (Dehaene et al., 1993; Fischer & Rottmann, 2005; Hoffmann, Mussolin, Martin, & Schiltz, 2014; but see Cipora & Nuerk, 2013 for evidence of no correlation between SNARC effect and simple equation accuracy or completion RTs). These results suggest that adults proficient in mathematics either have a lesser degree of left-to-right directionality of the mental number line, or the directionality is less salient to (i.e., has less bearing on) 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.

For children, only two studies have investigated the relationship between the SNARC effect and math ability. In the first, 5.5-year-old boys' mathematics ability, but not their 8-year-old math ability, correlated *negatively* with the degree of left-to-right directionality of their SNARC effects at age 8 (as measured by a parity task); however, for females, as well as collapsed across sex, there was no systematic relationship between these variables (Schweiter, Weinhold Zulauf, & von Aster, 2005). In the second study, German 11-year-olds performed the traditional SNARC parity task (i.e., from Dehaene et al., 1993), and experimenters tested whether individual SNARC effects correlated with math ability, measured by both the participants' self-reported most recent mathematics grades and performance on a graph interpretation task (Schneider, Grabner, & Paetsch, 2009). There was no significant correlation between SNARC measures and graph test results or children's mathematics grades. However, there are problems with the measure of the SNARC effect utilized 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 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, i.e. the beta coefficient of the regression slope of each participant's right hand RT minus left hand RT (dRT) regressed onto target magnitude, is commonly used in the literature (e.g., Fias, Brysbaert, Geybens, & d'Ydewalle, 1996). Nevertheless, we propose that this is not a pure estimate of the SNARC effect. 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 their right hand, yielding the difference in reaction time (dRT) 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. Problematically, however, 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 is therefore 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 utilizing this new measure.

Investigations into the relationship between the distance effect (i.e., another hypothesized measure of the mental number line) and mathematics ability converge nicely with the above SNARC effect findings. In these paradigms, participants indicate which of two Arabic numbers (i.e., symbolic) or object arrays (i.e., non-symbolic) on a screen is larger or contains more items, respectively. From these tasks, researchers can calculate a numerical distance effect (i.e., slower RTs when the presented numbers are closer in magnitude), which is then correlated with a measure of mathematics ability. 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, 2012a; 5- to 7-year-olds, Sasanguie, Van den Bussche, & Reynvoet, 2012b; but see Lonnemann, Linkersdörfer, Hasselhorn, & Lindberg, 2011 for a positive correlation between a subtraction task and distance effect 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., 6- to 8-year-olds, Holloway & Ansari, 2009; 5-, 6-, 7-, and 11-year-olds, Sasanguie et al., 2012a; Vanbinst, Ghesquière, & De Smedt, 2012; 6- to 8-year-olds, Sasanguie, Göbel, Moll, Smets, & Reynvoet, 2013), but not all (5- to 7-year-olds, Lonneman et al, 2011; Ferreira, Wood, Pinheiro-Chagas, Lonnemann, Krinzinger, Willmes, & Haase, 2012) developmental studies. The fact that the symbolic, but (usually) not the non-symbolic distance effect, is associated with markers of mathematics ability suggests that the two measures are tapping into discrete neural architectures. More importantly, however, 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.

Lastly, a number of studies have investigated the association between number line estimation and math skill. The relationship between these two measures appears to be fairly robust, in that the ability of participants to accurately (i.e., linearly) estimate the location of numerosities on a number line correlates positively with math scores in a number of studies (e.g., 5.8-, 6.8-, 7.9-, and 9.1-year-olds, Booth & Siegler, 2006; 7-year-olds, Booth & Siegler, 2008; Sasanguie et al., 2012a, 2012b; 6- to 8-year-olds, Sasanguie et al., 2013; 11-year-olds, Schneider et al., 2009).

Taken together, these data suggest that perhaps the linearity, but not directionality and degree of neural overlap in the representation of neighbouring numerosities, on one's mental number line is a crucial foundation upon which mathematical concepts, and ultimately mathematics competency, is built. It is, however, possible that the mental number line (i.e., as measured by the SNARC and distance effects) is fundamental to mathematics and numerical processing at an early age, as mathematics concepts and numerical understanding are just beginning to develop—particularly because the strength of both effects decreases with age (van Galen & Reitsma, 2008; Holloway & Ansari, 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 Present Study

The present study was designed to investigate the relation between the strength of the mental number line (as measured by both the SNARC and distance effects), visuospatial abilities, and mathematics skills in typically-developing children. Six-, 7-, and 8-year-old children performed a magnitude-relevant SNARC task, allowing the calculation of independent measures of the SNARC and distance effects for each participant. The children were also administered two standardized tests designed to measure math and visuospatial skills, respectively.

Methods

Participants

Participants were recruited from a database of parents who volunteered their children for future experimental testing during hospital visits shortly after their child's birth. The final sample consisted of 20 6-year-olds (±3 months, M=6.04, SD=.104, 13 male), 20 7-year-olds (±3 months, M=6.99, SD=.106, 7 male), and 20 8-year-olds (±3 months, M=8.02, SD=0.10, 13 male). Data of an additional 12 participants were excluded from the final sample because they did not return for the obligatory second laboratory visit (2 6-year-olds, 2 7-year-olds), because they had an error rate above 25% (2 6-year-olds, 1 7-year-old, 2 8-year-olds), or because they did not follow task instructions (3 6-year-olds). The parent accompanying the child 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, 50cm monitor with a resolution of 1152 x 870 and a refresh rate of 75 Hz was used to display the stimuli. Participants were seated on a raised chair 60cm from the screen and 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 coloured sticker. Also, as in the setup utilized by van Galen & 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 five; the other card displayed a large black circle, indicating the response key for numbers greater than five.

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, subtending a visual angle of 2.24 degrees. The digits appeared in the centre 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; Ginburg & 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 independent of 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 it is normed for use with children aged 3.0 years 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 utilized to assess spatial orientation abilities: (1) 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; (2) the Spatial Relations subtest, which tests one's ability to reproduce dot patterns that form increasingly complex shapes, and (3) 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 in order to minimize fatigue and prevent confusion over the switch in response mapping from the first to the second SNARC task. On each visit, participants first performed one mapping of the magnitude-judgment SNARC task (i.e., 14 trial blocks that were either a congruent or incongruent mapping), followed by one of the two standardized tests. 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 themselves. 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 5 s had elapsed. Following each trial, there was a blank screen for 1000 ms before the beginning of the next trial.

Each trial block consisted of 8 trials, one for each number from 1 through 9, excluding 5, presented in randomized order. Participants performed 14 trial blocks on each visit, with 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 the “.” key with their right hand if the target number was greater than 5. For the incongruent trial blocks presented during the other session, participants performed the opposite mapping. Participants were instructed to respond as quickly and accurately as possible.

Following completion of the SNARC task, participants were administered either the TEMA-3 or the DTVP-2 by the experimenter. Each session was approximately 30 to 40 minutes in length.

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 participants with error rates of over 25 percent were excluded (n=5). There was no evidence of a speed-accuracy tradeoff 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).

In line with the goals of the present study, we wished to determine whether SNARC and numerical distance effects were present within each level of age. As such, a 2 (Response Hand: left vs. right hand) x 2 (Target Type: low [i.e., 1-4] vs. high [i.e., 6-9] digit) x 4 (Distance: distance of the target from the number 5) repeated measures analysis of variance (ANOVA) was performed for each age group in an effort to be consistent with previous literature (e.g., van Galen & Reitsma, 2008). With this type of analysis, a SNARC effect would emerge as an interaction between Response Hand and Target Type, with the left hand responding faster to low numbers, and the right hand responding faster to high numbers. A distance effect would emerge as a main effect of distance, with participants responding faster to numbers further from 5 (e.g., 1 and 9) than numbers close to 5 (e.g., 4 and 6).

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. Utilizing 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 utilized a method modeled after that reported in Holloway & 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 their median RTs for close numbers (i.e., 4 and 6); this difference was then divided by sum of median RTs for close and far numbers, thus 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, $F(3,17)=7.220$, $p=0.002$, such that numbers close to 5 (i.e., 4 and 6) were responded to significantly slower than those far from 5 (i.e., 1 and 9), $t(19)=4.917$, $p<.001$. There was also a significant Target Type x Distance interaction, $F(3,57)=3.119$, $p=0.033$, such that at Distance 4 (i.e., 1 and 9), but not any other distance, low numbers were responded to significantly faster than high numbers, $t(19)=-2.749$, $p=0.013$. Crucially, the Response Hand by Target Type interaction did not near significance ($p=.670$; see Figure 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 for Target Type, $F(1,19)=4.494$, $p=.047$, as low numbers were responded to significantly faster than high numbers, $t(19)=-2.120$, $p=.047$. There was also a main effect of Distance, $F(3,57)=14.907$, $p<.001$, as numbers at a Distance of 4 (i.e., 1 and 9) were responded to significantly faster than those at a distance of 1 (i.e., 4 and 6), $t(19)=15.280$, $p<.001$. The interaction between Hand and Target Type was marginally significant, $F(1,19)=4.108$, $p=0.057$, as the left hand responded significantly faster to low versus high numbers, $t(19)=-18.332$, $p<.001$, and the right hand responded faster to high versus low numbers, $t(19)=3.105$, $p=.006$ (see Figure 1b).

8-year-olds

For 8-year-olds, there was a main effect of distance, $F(3,17)=11.862$, $p<.001$, as numbers at a Distance of 1 from 5 (i.e., 4 and 6) were responded to significantly slower than those at a Distance of 4 (i.e., 1 and 9), $t(19)=4.693$, $p<.001$. There was also a marginally significant main effect of Hand, $F(1,19)=4.202$, $p=.054$, as right-handed responses were slightly faster, $t(19)=2.05$, $p=.054$. Crucially, there was a significant interaction between Hand and Target Type, $F(1,19)=6.70$, $p=.018$. Dissection of the interaction revealed that for the left hand, participants responded significantly faster to low numbers, $t(19)=-2.464$, $p=.023$, and for the right hand, participants responded significantly faster to high numbers, $t(19)=2.251$, $p=.036$ (see Figure 1c). There was also a significant three-way interaction between Hand, Target Type, and Distance, $F(3,17)=3.495$, $p=.039$. To dissect this interaction, we looked at the Response Hand by Target Type relationship at each level of Distance. At Distance 1 (i.e., 4 and 6), left handed responses were significantly faster for low numbers, $t(19)=-2.374$, $p=.028$, and right-handed responses were faster for high numbers, $t(19)=2.496$, $p=.022$; at Distance 3 (i.e., 2 and 8), the left hand responded significantly faster to low numbers, $t(19)=-2.532$, $p=.020$, and right handed responses were faster for high numbers, $t(19)=2.941$, $p=.008$; and at Distance 4 (i.e., 1 and 9), the left hand responded significantly faster to low numbers, $t(29)=-2.621$, $p=.017$. There was no significant difference in RTs between the left and right hand for high and low numbers at Distance 2 (ps>.4).

Partial Correlation Analyses

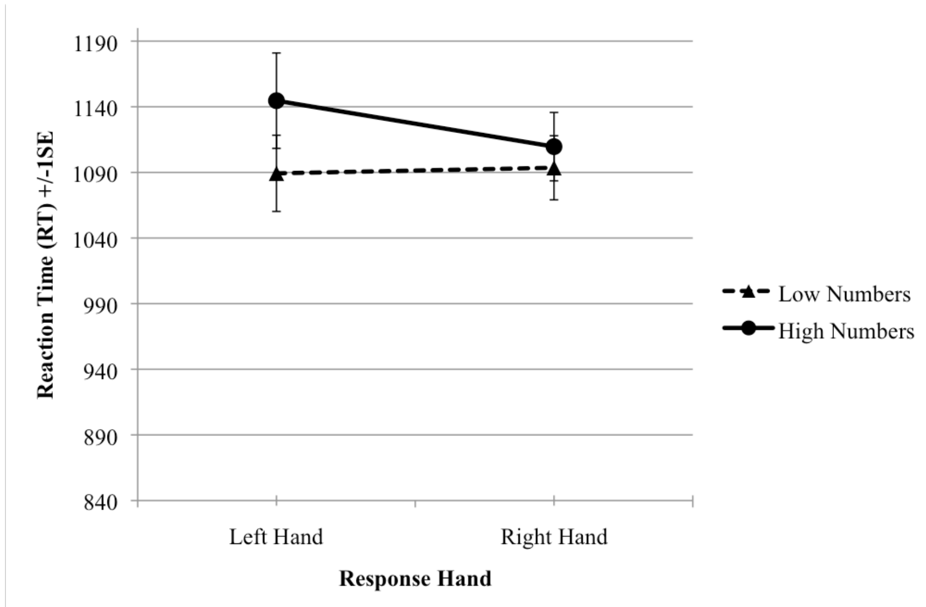
Partial correlation analyses were performed to determine whether our measures of the mental number line, namely, the SNARC and distance effects, exhibited systematic relationships with mathematics ability and visuospatial skills across our entire sample, while controlling for age. A similar analysis was also utilized to test whether children's SNARC and distance effects correlated with one another.

SNARC correlations. Controlling for age, the correlation between participants' raw score on the Position in Space subtest of the DTVP-2 and SNARC effect approached significance, r=-.195, p=.069 (see Figure 2). 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, r=.150, p=.129.

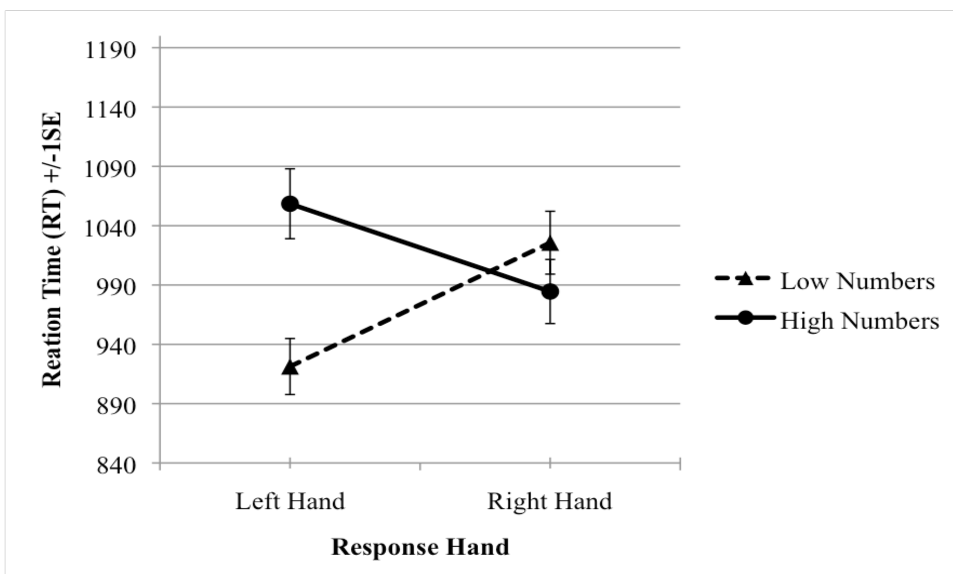
Distance effect correlations. Controlling for participant age, there was a significant correlation between participants' raw scores on the Position in Space subtest of the DTVP-2 and their distance effect, r=.303, p=.010 (see Figure 3). Correlations between the distance effect and raw scores on the Figure-Ground and Spatial Relations subtests of the DTVP were not significant, p=.264 and p=.113, respectively; neither did the correlation between the distance effect and TEMA-3 Math Ability Score, p=.495.

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

(a)


1190
1140
1090
1040
990
940
890
840
Reaction Time (RT) +/-1SE
Left Hand
Right Hand
Response Hand
Low Numbers
High Numbers

(b)


1190
1140
1090
1040
990
940
890
840
Reation Time (RT) +/-1SE
Left Hand
Right Hand
Response Hand
Low Numbers
High Numbers

(c)

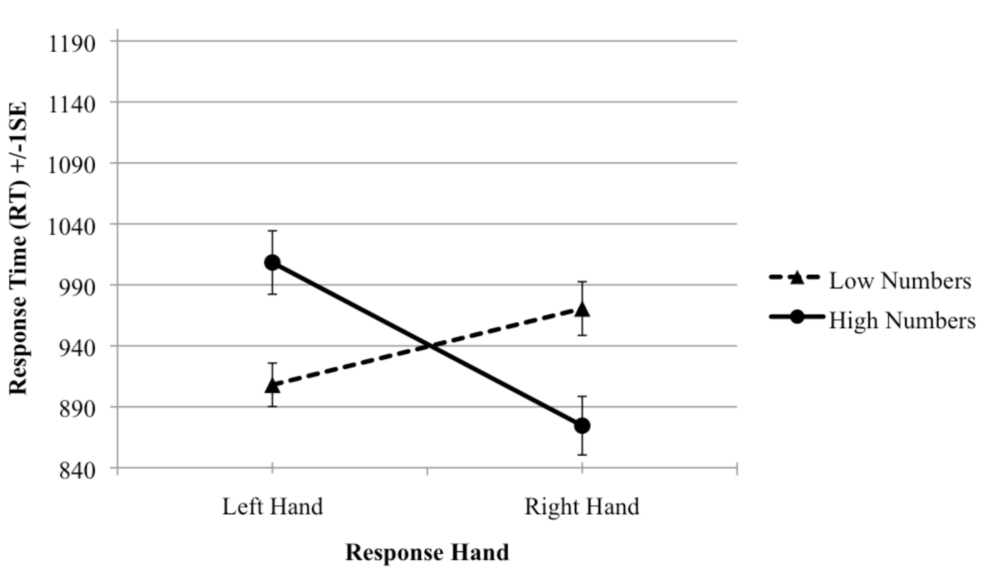


Figure 1. Mean of the median RTs for each hand for low and high numbers for (a) 6-year-olds, (b) 7-year-olds, and (c) 8-year-olds[3]. Standard error bars calculated using within-subjects variability, as described by Cousineau (2005).

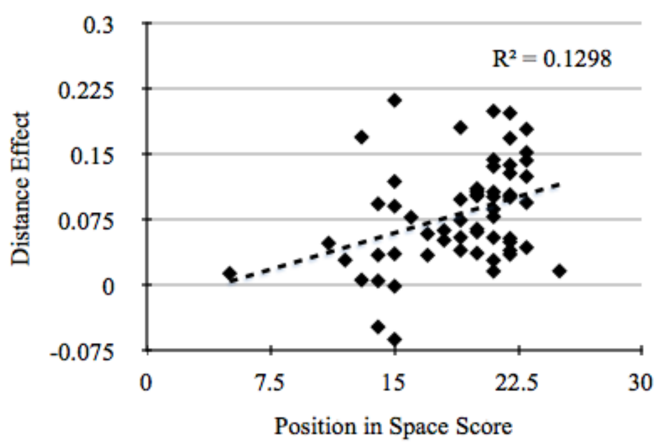


Figure 2. Correlation between individual distance effect measures and scores on the Position in Space subtest of the DTVP-2.

[3] For graphs displaying RTs for the left- and right-handed RTs for each individual early and late target item respectively, see Appendix 1.

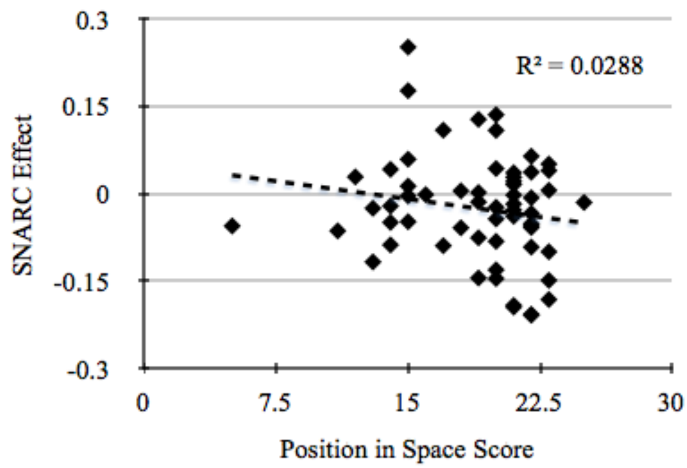


Figure 3. Correlation between individual SNARC effect measures and scores on the Position in Space subtest of the DTVP-2.

Discussion

The purpose of the present experiment was to investigate the relationship between the development of the mental sequence line and children's visuospatial and mathematics abilities. Six-, 7-, and 8-year-old children performed a magnitude-relevant SNARC task, allowing the calculation of individual SNARC and distance effects—both of which are hypothesized to be measures of the strength of individual mental sequence lines. Participants also completed two standardized tests: the Developmental Test of Visual Perception – Second Edition (DTVP-2), and the Test of Early Mathematics Ability – Third Edition (TEMA-3). While the relationship between visuospatial skills and mental sequence line measures has not been fully addressed in the literature, previous research has reported a significant, albeit negative, relationship between a variety of mental sequence line measures and mathematics ability in children. For example, in school-aged participants, good performance on math measures has been associated with weaker

SNARC and symbolic distance effects, as well as more linear number line estimations (e.g., Holloway & Ansari, 2009; Booth & Siegler, 2006, 2008). However, likely because of differences in stimulus parameters, tests of math ability, and calculations of mental sequence line measures, the results of these experiments have not been entirely consistent (e.g., see Sasanguie et al., 2012b, for no correlation between the symbolic distance effect and math ability). By administering a magnitude-relevant SNARC task, we were able, for the first time, to compare and contrast children's SNARC *and* distance effects, and investigate how both of these measures of the mental sequence line correlate with visuospatial and mathematics abilities.

Consistent with previous literature, 7- and 8-year-old (van Galen & Reitsma, 2008), but not 6-year-old (White et al., 2012), children exhibited magnitude-relevant SNARC effects at the group level. Additionally, 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 present experiment was to assess the relationship between individual measures of mental number line strength and visuospatial abilities. This relationship has not previously been tested directly in children; however, a lack of a SNARC effect has been reported in children with visuospatial disabilities, and visuospatial skills influence math ability in high school students (Bachot et al., 2005; Reuhkala, 2001). Additionally, a recent study shows a correlation between two-dimensional mental rotation tasks and SNARC effects in adults (Viarouge et al., 2014).

Combined, this evidence prompted us to hypothesize that we would observe a correlation between mental number line strength and visuospatial skills in our sample of typically-developing children. Consistent with this prediction, performance on the Position in Space subtest of the DTVP-2, which measures spatial orientation ability, was moderately correlated with individual distance effects, with a similar trend for SNARC effects. These data suggest that, at least in 6- to 8-year-old children, one's mental visual orientation and mental rotation ability is 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, which measured participants' ability to separate figure from ground in increasingly complex designs (i.e., Figure-Ground subtest), and reproduce patterns in relation to their own bodies (i.e., Spatial Relations subtest), respectively. Therefore, it is possible that mental number line representation is only affected by visuospatial abilities that involve the mental manipulation of form and space (e.g., mental rotation), but not those involved in visual perception or visual-motor skills. In the future, more comprehensive tests of mental rotation ability, in both children and adults, will be necessary to further investigate this relationship. Additionally, future investigations into whether the third commonly utilized 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 present study was to assess the relationship between the mental sequence line and mathematics ability, utilizing both the SNARC and distance effects as measures of the former. Two previous investigations have explored the relationship between the SNARC effect and math ability in children (Schweiter et al., 2005; Schneider et al., 2009). However, in both studies, the measurements of the SNARC effect utilized confound the snarc and distance effects; furthermore, in the second study, participants were considerably older (i.e., 11-year-olds) than the 6- to 8-year-olds tested in the present experiment, and a standardized measure of mathematics ability was not employed. As the SNARC effect has been reported to decrease with age (van Galen & Reitsma, 2008), we hypothesized that the relationship between mental number line measures and math ability might be stronger in younger children. Additionally, we predicted that a relationship would be would be more likely to be manifest using a more sensitive gauge of math ability (i.e., a standardized test). A relationship has been previously reported between the distance effect and math ability; however, this relationship has not always been replicated (e.g., Sasanguie et al., 2012b), and thus required further investigation.

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 seems reasonable to infer that the specific directionality of children's mental number line has little to no bearing on their ability to manipulate numerosities in a mathematical context. Perplexingly, these findings stand in contrast to 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 (e.g., accounting or engineering majors), but not liberal arts, programs are regularly exposed to and engaged in mathematics operations. While 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., 2012a; Vanbinst et al., 2012; Sasanguie et al., 2013), the lack of correlation between these two measures in our data is surprising, but not unprecedented (e.g., Lonneman et al., 2011; Ferriera et al., 2012). 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 discussion). Notably, in order to calculate both SNARC and distance effects for each participant, the present study necessarily employed a magnitude-relevant SNARC task, which is not the paradigm typically utilized in this type of investigation (i.e., a symbolic magnitude comparison task). For example, we employed a magnitude-relevant SNARC task to calculate distance effects, as opposed to the traditional number comparison task (e.g., Holloway & Ansari, 2009). Therefore, our task asked children to indicate if the target number is less than or greater than 5, rather than indicating which of two target digits was larger. One important distinction can be made between these two tasks, in that in the magnitude-relevant SNARC task, the largest comparison distance is 4 (i.e., between 1 and 5, and 9 and 5), while in the digit comparison task using digits 1 through 9, distance between digits can go up to 8 (although most studies limit digit distance at 6, e.g., Holloway & Ansari, 2009; Lonneman et al., 2011). As the distance effect is defined by significant differences in response time between digits close together versus those further apart, distance effects obtained using a digit comparison will be stronger than those obtained in a magnitude-relevant paradigm utilizing the digit span 1 through 9. Indeed, when one study parsed their 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 mathematics ability (Lonneman et al., 2011). Furthermore, another study employing the magnitude-relevant SNARC paradigm also found no predictive value of symbolic distance effects on math ability (Ferreira et al., 2012). 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. Unpublished data from our laboratory suggests that these two measures are moderately correlated in adults (r = -.327[4], p = .021; Gibson & Maurer, in preparation). However, one previous developmental study reported conflicting findings, with SNARC and distance effects moderately correlated in one, but not in a second, experiment in 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; that is, its directionality, and the degree of representational overlap between adjacent numerosities. Therefore, it is possible (and perhaps likely, as suggested by the present data and those of Schneider et al., 2009) that these measures exhibit different, independent developmental trajectories, eventually becoming correlated in adulthood.

In conclusion, this is the first study to report a relationship between a mental number line measure (i.e., the distance effect, and to a lesser extent, the SNARC 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

[4] This correlation is negative because our SNARC measure yields a negative number for a SNARC effect in the expected direction; i.e., left to right.

age range characterized by stronger SNARC and distance effects than older children (e.g., van Galen & Reitsma, 2008), is not consistent with the hypothesis that the mental number line construct (i.e., at least as measured by the SNARC and distance effects) is a core cognitive foundation upon which numerical and mathematical competencies are built. 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 school-aged children. The lack of correlation between these variables may help to inform future investigations involving the mental number line in children; particularly, our data suggests that these two measures cannot be utilized interchangeably in children as equivalent measures of the mental number line construct.

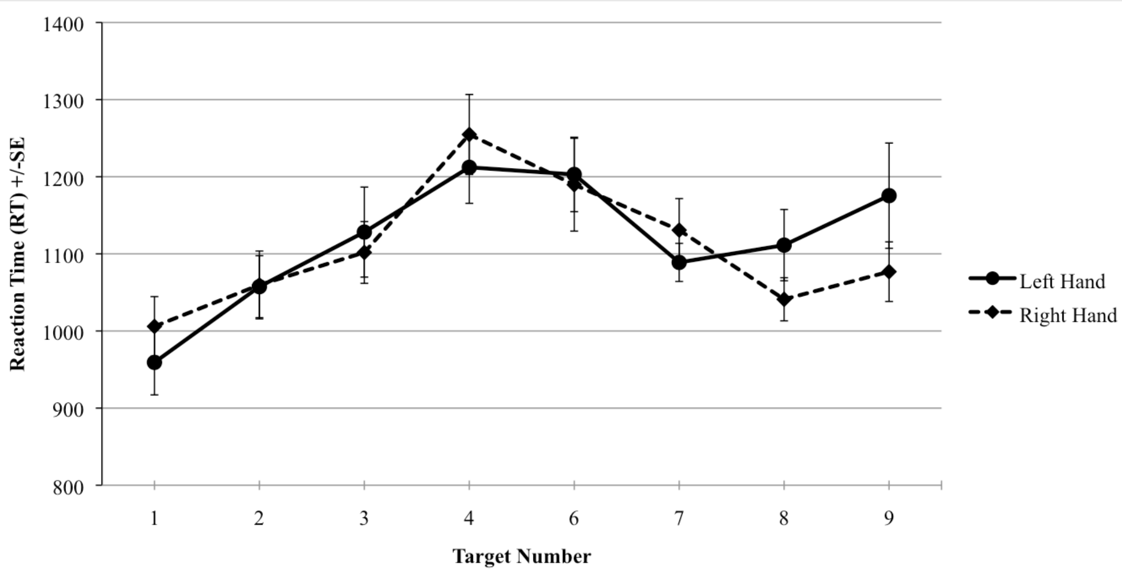
References

*References can be found at the end of the thesis.

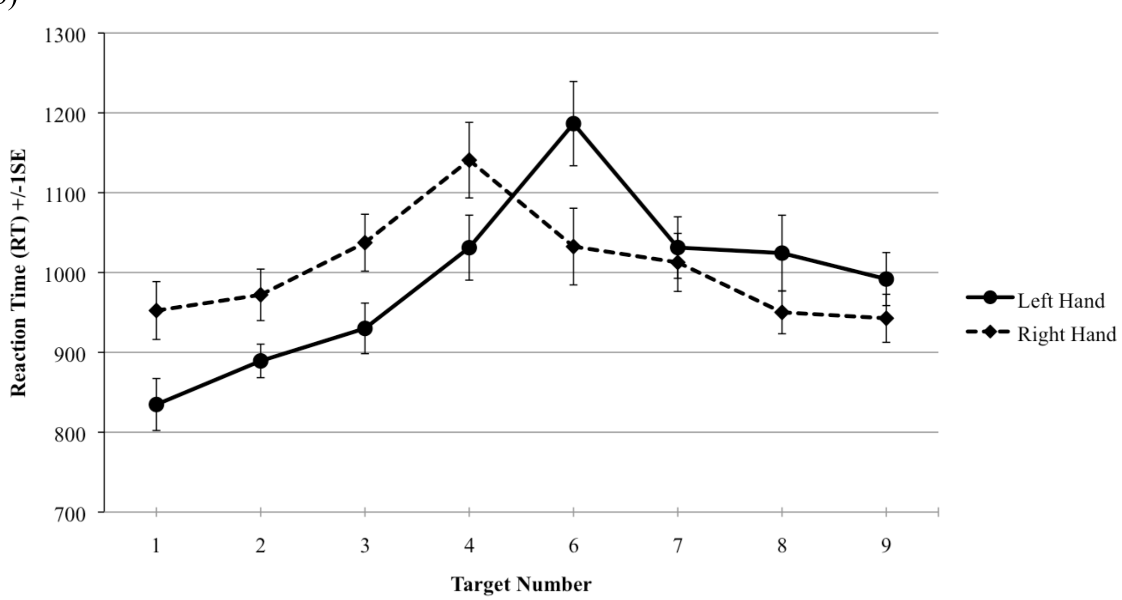
Appendix

Appendix 1.

(a)



(b)



(c)

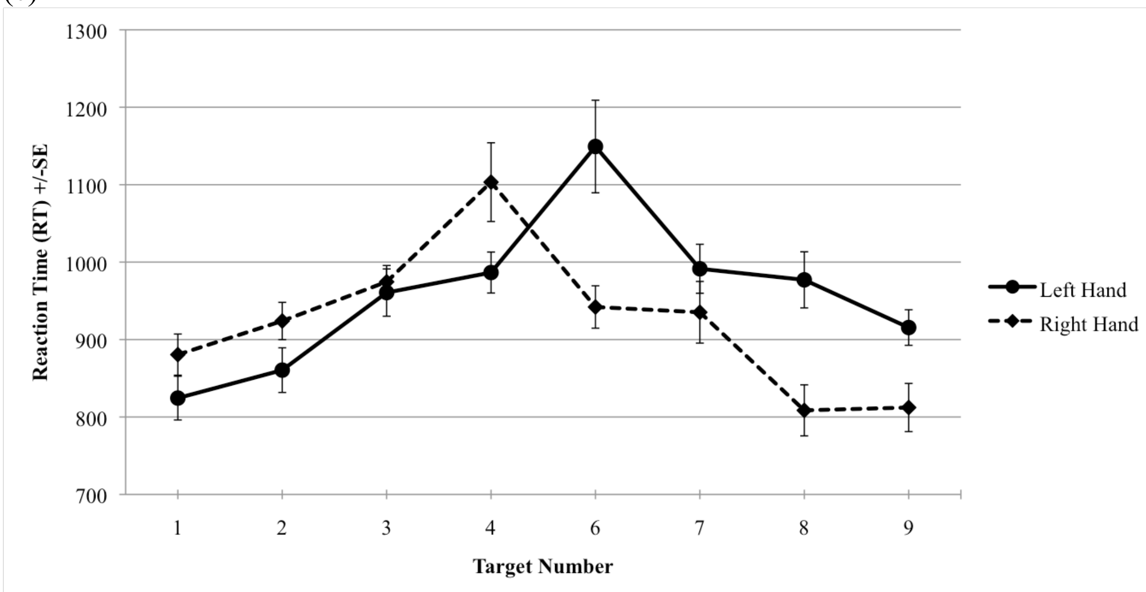


Figure 1. Means of median RTs for each hand for each target numbers for (a) 6-year-olds, (b) 7-year-olds, and (c) 8-year-olds. Standard error bars calculated using within-subjects variability, as described by Cousineau (2005).

Pre-Chapter Introduction

The work described in Chapter 4 assessed the stability of mental sequence lines for three well-known ordinal sequences, as measured by both the SNARC and distance effects. Fifty-six English-speaking adults performed magnitude-relevant SNARC tasks (i.e., does the item on the screen fall before or after Wednesday?) for numbers, weekdays, and months, and repeated this task at least one to three weeks later. There was a moderate correlation in the magnitude of SNARC and distance effects for numbers across sessions, and SNARC and distance effects were correlated with each other, suggesting both effects arise from the same underlying mental sequence line, which is moderately stable across time. A similar pattern was observed for weekdays, but not for months, although the SNARC effect for months was moderately consistent across time. Additionally, the strength of the SNARC effect was correlated for numbers and weekdays, with a similar trend for the distance effect. These data suggest that SNARC and distance effects for numbers and weekdays are behavioural manifestations of a moderately stable mental sequence line, while the spatial representation for months is more variable.

Individual "SNARC-iness": Consistency of Sequence-Space Associations across Time

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Chapter 4: Individual "SNARC-iness": Consistency of Sequence-Space Associations across Time

Abstract

Most western adults perceive numbers on a mental sequence line oriented from left to right, as evidenced by the Spatial-Numeric Association of Response Codes (SNARC) and numerical distance effects. However, the magnitude of these effects varies across individuals, with only modest consistency within (distance effect) or across sessions (SNARC effect) (Maloney et al., 2010; Viarouge et al., 2014; Schneider et al., 2009). Here we measured the stability of SNARC and distance effects for numbers, weekdays, and months by testing 56 participants twice on a SNARC paradigm and correlating performance across two visits separated by at least 2 weeks. For numbers there was a moderate correlation in the magnitude of SNARC and distance effects across sessions and the two effects were correlated with each other, patterns suggesting they arise from the same underlying mental sequence line, which is moderately stable across time. There was a similar pattern for weekdays, but not for months, despite moderate consistency across the two sessions for the SNARC effect for months. In addition, the size of the SNARC effect was correlated for numbers and weekdays, with a similar trend for the distance effect. These data suggest that the SNARC and distance effects for numbers and weekdays arise from a somewhat stable mental sequence line, while the organization for months is more variable.

Chapter 4: Individual "SNARC-iness": Consistency of Sequence-Space Mappings across Time

Introduction

The tendency to associate numbers with spatial locations is ubiquitous, and appears to occur involuntarily; the Spatial Numerical Association of Response Codes (SNARC) effect is commonly cited as evidence of this association (e.g., Gevers & Lammertyn, 2005; Neider, 2005). The SNARC effect is the finding that when judging parity, participants respond faster to lower numbers (e.g., 1-4) with a left-sided response, and higher numbers (e.g., 6-9) with a right-sided response (Dehaene, Bossini, & Giraux, 1993). Similar effects occur when participants must process the magnitude of the number by indicating whether a digit is greater or less than a central target number with a left- or right-sided response (i.e., a magnitude-relevant SNARC task; Dehaene, Dupoux, & Mehler, 1990). This left-to-right bias also influences visual attention, with small numbers cueing attention to the left side of space, and large numbers cueing attention to the right (the attentional SNARC effect: Fischer, Castel, Dodd & Pratt, 2003). The traditional SNARC effect and its variants are typically interpreted as evidence of an internal, horizontally-oriented left-to-right mental number line, with a manual response to a number being faster when the side of response is congruent with its position of the number on the mental number line (Fischer et al., 2003; Fias, 1996; Fischer, 2003; Nuerk, Bauer, Krummenacher, Heller, & Willmes, 2005).

This left-to-right bias is not exclusive to numbers, but also influences participants' responses to items of other ordinal sequences, such as weekdays, months, and letters.

Participants respond faster to items early in the sequence (e.g., Monday, January, A) with a left-sided response, and later items in the sequence (e.g., Friday, December, Z) with a right-sided response (Gevers, Reynvoet, & Fias, 2003, 2004). Thus, it seems that ordinality is key to evoking the unconscious perception of a mental sequence line that is oriented left-to-right, and that this sequence line influences responses on a host of SNARC-like tasks (e.g., Dodd, Van der Stigchel, Leghari, Fung, & Kingstone, 2008).

Further evidence of a mental number line comes from the numerical distance effect. When asked to indicate the larger of two Arabic digits, participants are faster to respond when the numerical distance between the numbers is large (e.g., 1 and 9) and slower to respond when the numerical difference is small (e.g., 3 and 4) (Moyer & Landauer, 1967). Consistent with the hypothesis of a spatially organized mental number line, in which numerals are represented sequentially in order of magnitude, this effect suggests that digits are represented neurally in a sequential fashion, such that activation of one numerosity activates the representation of other closeby numerosities, thus impairing discrimination of close numbers (Dehaene et al., 1990; Neider, 2005).

Both SNARC effects and distance effects are robust at the group level in Western cultures. For example, approximately 65% to 75% of participants exhibit left-to-right SNARC effects for numbers when performing the traditional SNARC parity task (Wood, Nuerk, & Willmes, 2006a). Similarly, in magnitude-relevant SNARC tasks in which the distance of the target sequence item to the comparison item is a factor in the analysis of variance (ANOVA), distance is consistently a highly significant factor (e.g., Gevers et al., 2003, 2004). Nevertheless, recent data suggest that context can modify the SNARC effect, raising questions as to the stability of the mental number line. For example, when Western, monolingual participants are asked to imagine the numbers 1 through 11 or months of the year on a horizontally-aligned ruler, they demonstrate the classic left-to-right SNARC effect. However, when asked to imagine the same numbers on a clock face, participants demonstrate a reversed, right-to-left SNARC effect (Bächtold, Baumüller, & Brugger, 1998). Similarly, reading cooking instructions with a number at the beginning and end of each line can eliminate the SNARC effect if the order of the numbers is incongruent (i.e., 9 at the beginning and 1 at the end) rather than congruent (i.e., 1 at the beginning and 9 at the end) with a left-to-right mental number line (Fischer, Mills, & Shaki, 2010). Further evidence of malleability comes from a recent experiment in which bilingual Russian-Hebrew participants performed a SNARC parity task in which the text of the target number word varied randomly between Cyrillic (which is written from left to right) and Hebrew (which is written from right to left) (Fischer, Shaki, & Cruise, 2009). A SNARC effect was observed on trials with Cyrillic, but not Hebrew text, a pattern suggesting that sequence-space associations are highly flexible within individuals and greatly influenced by context. Longer term exposure to a different mapping, such as being raised in a culture in which language is read and written from right to left, is associated with a reversed SNARC effect (Zebian, 2005; Shaki, Fischer, & Petrusic, 2009).

Because it is relatively easy to alter a group's mapping of sequences onto space, it has been suggested that these associations reflect fleeting mental constructs with high variability across time and situations (e.g., Fischer et al., 2010). Thus, it seems possible that although adults demonstrate a strong tendency to map sequences onto space that is highly consistent at the group level across experiments using the same context, it is likely that these sequence-space associations are not byproducts of a stable, robust neural architecture in each individual that links sequences and space in precisely the same manner every time. The one study that has evaluated the stability of the distance effect in adults found evidence of no (Maloney, Risko, Preston, Ansari, & Fugelsang, 2010, Experiment 2), or only moderate stability (Experiment 1, r=.38; Maloney et al, 2010), although the stability may be higher in 11-year-old children (r=.501; Schneider, Grabner, & Paetsch, 2009). Similarly, one recent study found only a moderate correlation in the size of the SNARC effect of adults across two sessions two weeks apart *(*r=.372) when measured by a parity task (Viarouge, Hubbard, & McCandliss, 2014). Taken together, these data suggest that the mental sequence line—at least its precision (i.e., the distance effect) and its directionality (i.e., the SNARC effect)—is not especially consistent at the individual level. However, the stability of the SNARC effect on tasks that require the processing of numerical magnitude (e.g., is this digit greater or less than 5) has not been evaluated. Nor has the stability of sequence-space associations for other ordinal sequences.

The purpose of the present experiment was to evaluate the stability of sequence-space associations in adults with a magnitude-relevant SNARC task and three ordinal sequences. A large sample of right-handed, English-reading participants performed magnitude-relevant SNARC tasks for digits, weekdays, and months, and repeated this testing two to three weeks later. This paradigm allowed us to examine, for the first time, the consistency of sequence-space associations, as measured by both the SNARC and distance effects, across visits for three ordinal sequences. Our paradigm also allowed us to assess whether SNARC and distance effects are correlated with each other within each sequence type. While previous studies using numbers have reported a moderate correlation between these two measures in adults (Viarouge et al., 2014) and children (Schneider et al., 2009), this relationship has not yet been assessed for non-numerical ordinal sequences. A final goal was to investigate whether the mental sequence lines for different ordinal sequences have similar degrees of left-to-right directionality and precision; that is, the correlation in the size of the SNARC effect and of the distance effect across sequence types.

Participants with suspected synaesthesia were excluded from analysis, as their number forms can be more visually salient and complex than those of non-synaesthetes, and are likely more consistent across time (Sagiv, Simner, Collins, Butterworth & Ward, 2006).

Methods

Participants

The final sample consisted of 56 right-handed English-speaking students between the ages of 18 and 36 (*M*=20.6; 38 female). Participants received course credit or financial compensation for participation. Data of an additional 30 participants were excluded because of failure to return for the second session (*n*=8), suspected synaesthesia (*n*=17), or equipment failure (*n*=5). Additionally, for blocks in which participants had high error rates (greater than or equal to 15%), that participant's data for that sequence type was not used (*n*=2 for each sequence type).

Apparatus

The task was programmed in SuperLab 4.0 running on a Macintosh Mini computer. Stimuli were displayed on a Dell Trinitron P1130, 50cm monitor with a resolution of 1152 x 870 and refresh rate of 75 Hz.

A six-item synaesthesia questionnaire based on that of Eagleman, Kagan, Nelson, Sagaram, & Sarma (2007) was given prior to testing, and utilized to determine whether participants experience synaesthesia[5]. The first four items asked about specific types of cross-modal associations present in synaesthetes (specifically: numbers-space, weekdays- and months-space, letter-colour, and sound-colour). The last two items described synaesthesia, and asked if the participant experienced it. If participants answered "yes" to any question about experiencing synaesthesia, their data were excluded.

Participants also completed a 10-item handedness questionnaire, in which they identified the hand they utilize for everyday tasks (e.g., threading a needle) as usually or exclusively right or left, with right choices given a score of 5 (exclusively) or 4 (usually). To be considered right-handed, participants needed to score 30 out of 50, and to indicate that they usually used the right hand for writing and drawing. The mean handedness score in the final sample was 47.7 (range: 37-50). Although evidence suggests that handedness does not play a role in the SNARC effect (Dehaene et al., 1993; Experiment 5), we did not want handedness to introduce a possible source of variability.

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[5] See Appendix 2 to view the synaesthesia questionnaire.

Procedure

This experiment received ethics clearance from the McMaster University Research Ethics Board. Each participant gave informed consent prior to participation. Responses to both the synaesthesia and handedness questionnaires were not viewed by the experimenter until testing was completed.

Participants sat 60 cm from the screen and responded on the "x" key with the left hand and the "," key with the right hand on a Macintosh keyboard. The space bar was utilized to proceed through trial instructions and to begin the first test trial. Subsequent trials began 2500 ms after the beginning of the previous trial.

Each block began with specific instructions on the screen and a set of 16 practice trials. All trials commenced with the 300 ms presentation of a black fixation cross on a white screen. The fixation cross was followed by the presentation of a target stimulus, which remained on the screen for 2500 ms, regardless of participant response. Subsequently, the target disappeared and the next trials commenced. Each target stimulus was presented 10 times within each trial block, for a total of 80 number, 40 weekday, and 40 months trials per respective trial blocks. Participants were given the option of a short break after each block.

Three sequence types were used: numbers, weekdays, and months of the year, such that each trial block contained only one stimulus type. For number blocks, the numbers 1 through 9, excluding the number 5, were presented. For weekday blocks, the days Monday, Tuesday, Thursday, and Friday were presented. For months of the year blocks, the months January, February, November, and December were presented (so as to include only words of approximately equal length). Each individual stimulus appeared in black 24-point font centered on a white screen.

Each participant performed six trial blocks, which included one congruent and one incongruent block for each sequence type (i.e., numbers, weekdays, and months). Block order was counterbalanced across participants, with the caveats that the order of blocks always alternated between congruent and incongruent, and sequence type changed between blocks such that it was never the same on two consecutive blocks.

For each sequence, an intermediate reference item within the sequence was selected: 5 for numbers, Wednesday for weekdays, and July for months. Participants were instructed to decide whether the sequence item presented on screen falls before or after this intermediate item in the relevant ordinal sequence. Prior to congruent blocks, participants were instructed to respond to stimuli falling before the intermediate item with a left-handed key press, and stimuli falling after the intermediate item with a right-handed key press. Conversely, prior to incongruent blocks, participants were instructed to respond to earlier stimuli with a right-handed key press, and later stimuli with a left-handed key press.

Reaction times (RTs) for all responses were measured. Participants completed the task in approximately forty minutes. Participants returned one to three weeks later and repeated the task. Practice and trial blocks were presented in the same order on both occasions for each participant.

Results

Error rates were generally low (M=4.61%), and there was no evidence of a speed-accuracy tradeoff, as indicated by the lack of negative correlation between each participants' overall mean RT and their respective error rates (r=.033, ns).

SNARC Effects

For each participant, we calculated the median RT on correct trials for each combination of target, hand, and visit for each sequence type. RTs were analyzed in a 2 (Response Hand: left vs. right) x 2 (Target Type: early (i.e., 1-4; Monday-Tuesday; January-February) vs. late (i.e., 6-9; Thursday-Friday; November-December) sequence item) x 2 (Time: visit 1 vs. visit 2) x 4 (Distance: distance from number 5) repeated measures analysis of variance (ANOVA).

For numbers, there was a main effect of Hand, $F(1,53)=14.865$, $p<.001$, reflecting faster responding with the right hand $t(53)=3.855$, $p<.001$, as expected given the right-handedness of the participants. There was also a main effect of Distance, $F(3,51)=53.175$, $p<.001$, such that stimuli further from 5 (e.g., 1 and 9) were responded to faster than stimuli closer to 5 (e.g., 4 and 6), $t(53)=9.946$, $p<.001$ (see Figure 1). There were no significant main effects of Target Type or Time. Crucially, there was an interaction of Response Hand and Target Type, $F(1,53)=16.849$, $p<.001$, with smaller digits responded to faster than larger digits with the left hand, $t(53)=-3.948$, $p<.001$, and larger digits responded to faster than smaller digits with the right hand, $t(53)=3.584$, $p=.001$ (see Figure 1). There was also an interaction of Target Type and Distance,

$F(3,53)=5.180$, $p=.002$, as participants responded faster to 3 than to 7 (both a distance of two from 5), $t(53)=-2.595$, $p=.012$. No other interactions were significant.

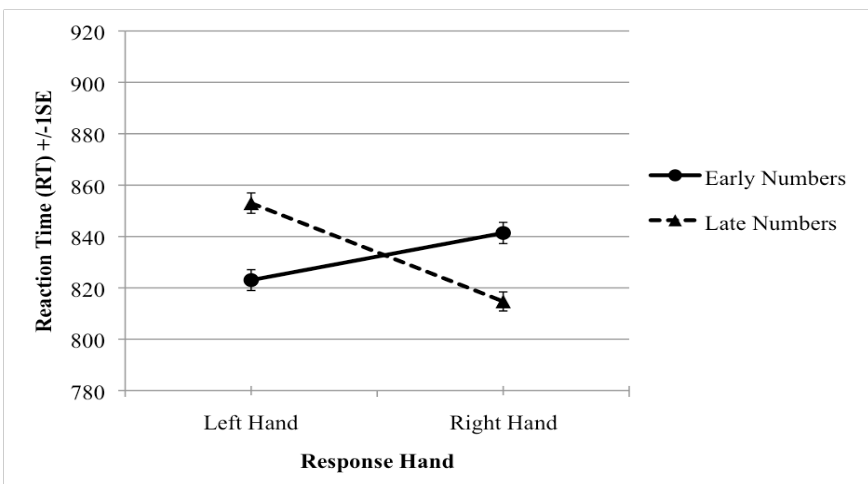
For weekdays, there was a main effect of Distance, $F(1,54)=120.350$, $p<0.001$, as weekdays further from Wednesday (e.g., Monday and Friday) were responded to faster than weekdays closer to Wednesday (e.g., Tuesday and Thursday), $t(54)=10.970$, $p<.001$, providing evidence of a distance effect (see Figure 1b). There were no significant main effects of Response Hand or Target Type, and no interactions involving Time. Crucially, there was a significant interaction of Response Hand and Target Type, $F(1,54)=12.631$, $p=0.001$, as early digits were responded to significantly faster than late digits by the left hand, $t(54)=-3.960$, $p<0.001$, and late digits significantly faster than early digits by the right hand, $t(54)=2.054$, $p=0.046$ (see Figure 1b). There was also a significant interaction of Response Hand and Distance, $F(1,54)=5.558$, $p=0.022$, with participants responding to weekdays at a distance of 2 from Wednesday (e.g. Monday and Friday) significantly faster with their right hand than their left hand, $t(54)=-2.979$, $p=0.004$, reflecting their right-handedness. Lastly, there was a significant Response Hand x Target Type x Distance interaction, $F(1,54)=4.487$, $p=0.039$. To dissect this interaction, we performed a 2 (Target Type) x 2 (Distance) repeated measures ANOVA for each hand separately. For the left hand, we found significant main effects of Target Type, $F(1,54)=12.813$, $p=0.001$, as early targets were responded to faster than late targets. There was also a main effect of Distance, $F(1,54)=49.319$, $p<0.001$, as targets further from Wednesday (e.g. Monday and Friday) were responded to faster than targets close to Wednesday (e.g. Tuesday and Thursday). There were no significant interaction effects. For the right hand, we again found a significant main effect of Target Type, $F(1,54)=4.184$, $p=0.046$, as late targets were responded to faster than early targets. There was also a significant main effect of Distance, $F(1,54)=112.388$, $p<0.001$, as targets further from Wednesday (e.g. Monday and Friday) were responded to faster than targets closer to Wednesday (e.g. Tuesday and Thursday). We also found a significant interaction of Target Type and Distance, $F(1,54)=4.116$, $p=0.047$, as the target Monday was responded to significantly faster than Friday, $t(54)=-71.657$, $p<0.001$. Thus, although the data for both hands revealed a SNARC effect (the left hand faster for early days and the right hand faster for late days), the exception was the comparison of Monday and Friday for the right hand, perhaps because of an overall advantage for Monday as the beginning (or near the beginning) of the sequence.

For months, there was a significant main effect of Distance, $F(1,54)=21.619$, $p<0.001$, such that months further from July (e.g. January and December) were responded to faster than months closer to July (e.g. April and September), $t(54)=4.650$, $p<.001$, providing evidence of a distance effect (see Figure 1c). There was also a main effect of Time, $F(1,54)=10.738$, $p=0.002$, with faster responses at Time 2, $t(54)=3.277$, $p=.002$, presumably representing a practice effect. Crucially, there was a significant interaction of Hand and Target Type, $F(1,54)=5.307$, $p=0.025$, such that participants responded significantly faster to early rather than late digits with their left hand, $t(54)=-2.179$, $p=0.034$, and significantly faster to late rather than early digits with their right hands, $t(54)=2.091$, $p=0.041$ (see Figure 1c). There were no other significant interactions.

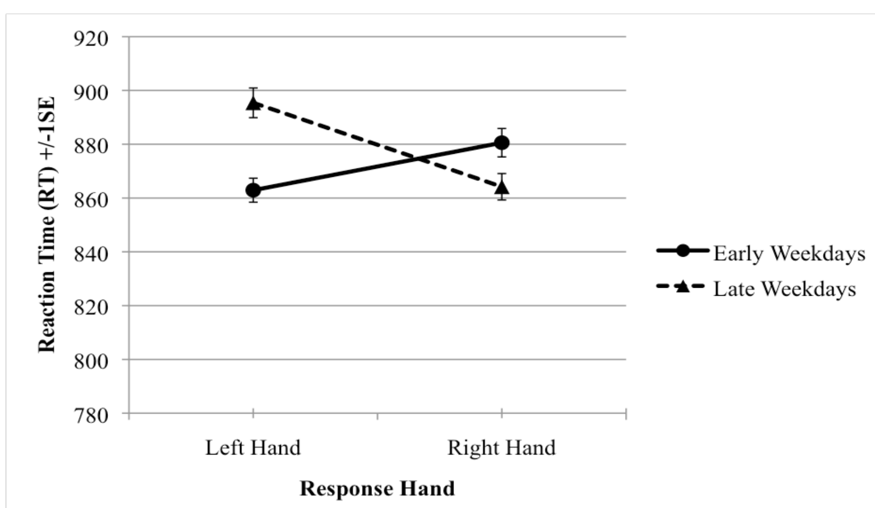
Consistency of SNARC effects

Typically, the degree of SNARC effect is calculated by subtracting, for each digit, the mean RT for left-handed responses from the mean RT for right-handed responses, yielding a difference in reaction time (dRT) between the two hands for each target number. This dRT is subsequently regressed onto target magnitude, such that a SNARC effect is manifest as a negative regression slope (e.g., Fias, Brysbaert, Geybens, &

(a)



(b)



(c)

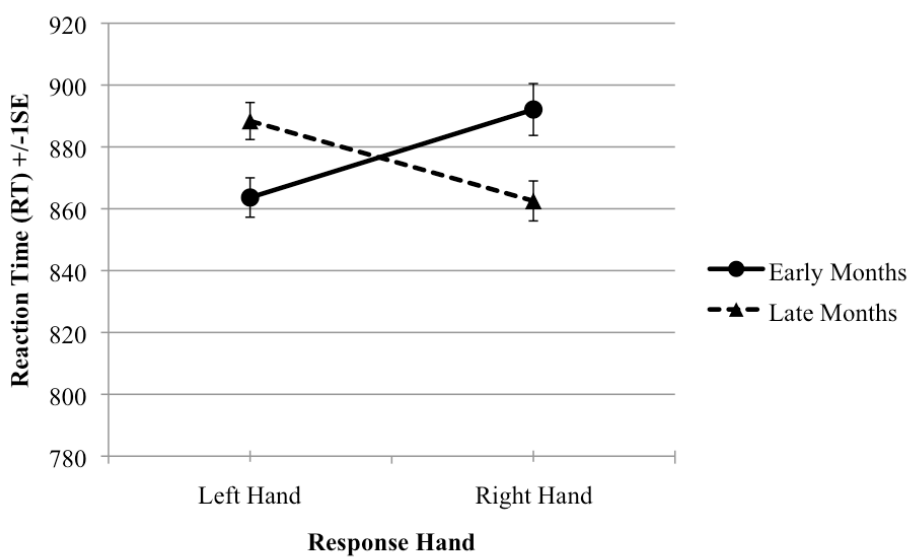


Figure 1. Means of median participant RTs for the left and right hands for early and late (a) numbers, (b) weekdays, and (c) months[6]. Standard error bars calculated using within-subjects variability, as described by Cousineau (2005).

d'Ydewalle, 1996). However, we contend that this method does not yield a pure estimate of the SNARC effect. Namely, 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 is therefore necessarily confounded by participants' distance effects. To quantify the magnitude of a more categorical 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

[6] For graphs displaying RTs for the left- and right-handed RTs for each individual early and late target item respectively, see Appendix 3.

average reaction time, and hence adjusts for differences among participants in speed of responding. For each participant, S was calculated at Time1 and Time2 for each sequence type.

Pearson *r* correlations[7] were performed to investigate the degree to which SNARC performance was consistent across time within each sequence type. Correlations were moderate but significant for numbers, $r = 0.372$, $p = 0.003$ [see Figure 2(a)], and months, $r=.312$, $p=.010$ [see Figure 2(c)], with a similar trend for weekdays, $r = 0.186$, $p = 0.093$ [see Figure 2(b)].

To examine whether the degree of SNARC effect was consistent across sequence type, we correlated each participants' degree of SNARC for each sequence type overall (i.e., collapsed across Time 1 and Time 2) with each other sequence. Overall SNARC effect measures were correlated for numbers and weeks, $r=.471$, $p<.001$ (see Figure 3), but SNARC effects were not correlated between numbers and months ($p=.314$) or weeks and months ($p=.256$). *T*-tests were also performed to investigate there was a systematic change in SNARC effects across time for each sequence. Although this test indicated significantly weaker SNARC effects for numbers at Time 2, $t(53)=-2.140$, $p=.037$, *t*-tests of performance across time were not significant for weekdays or months (both *p*s>.091).

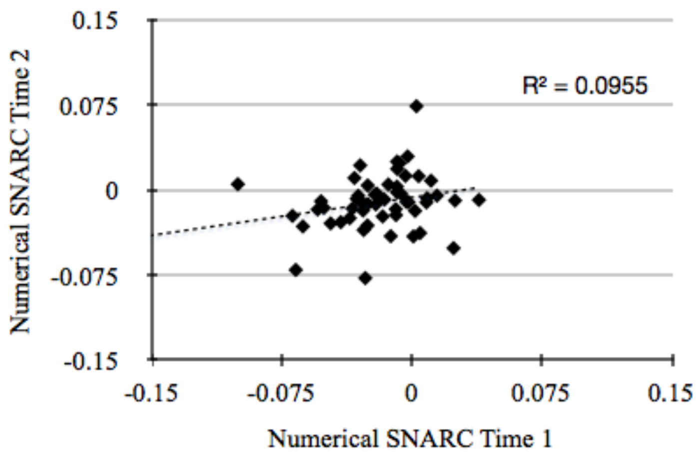
Consistency of Distance Effects

To determine each individual's distance effect, we utilized a method modeled after that reported in Holloway & Ansari (2009), and consistent with our SNARC effect formula. Collapsed across congruent and incongruent trials, each participant's median

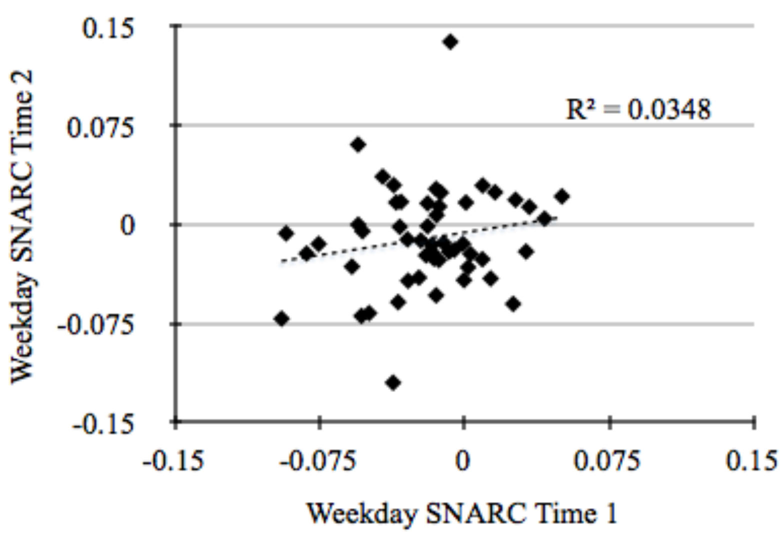
[7] As our correlation predictions are directional, all *p*s are 1-tailed.

RTs for far numbers (i.e., 1 and 9) was subtracted from 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, thus expressing the distance effect as a proportion of each individual's RT.

(a)



(b)



(c)

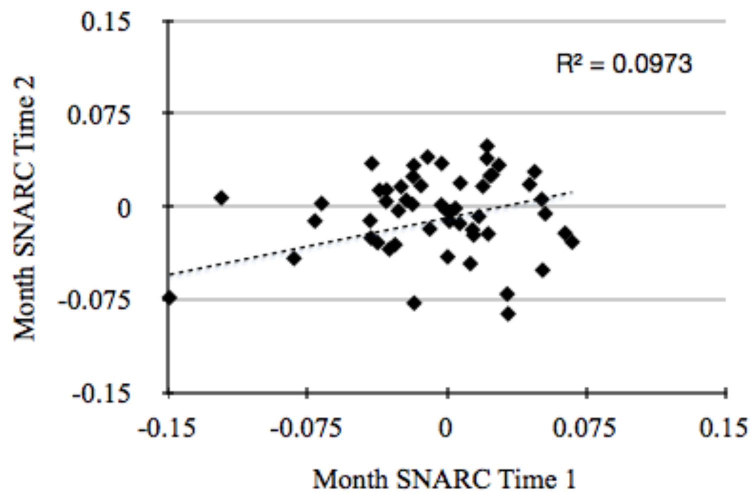


Figure 2. Scatterplots displaying the correlation between individual measures of the SNARC effect for (a) numbers, (b) weekdays, and (c) months between Time 1 and Time 2.

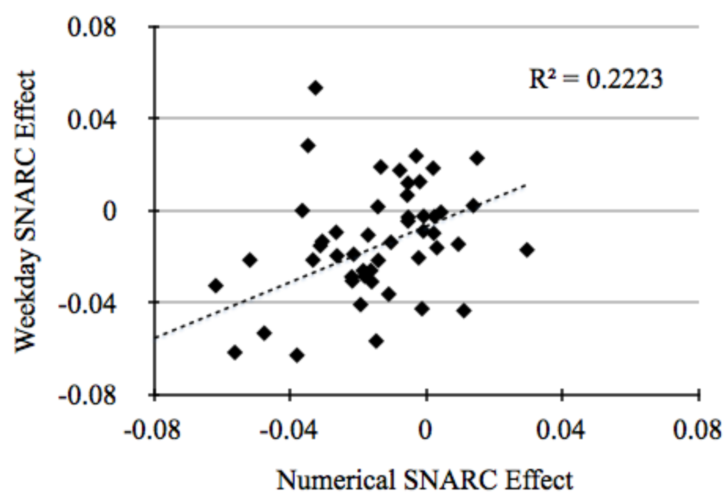
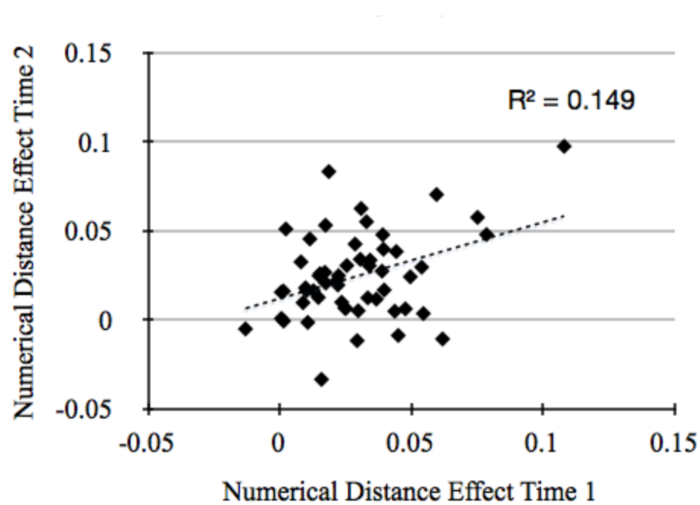


Figure 3. Scatterplot displaying the correlation between overall individual measures of the SNARC effect for numbers and weekdays.

Pearson *r* correlations were performed to investigate the degree of correlation between individual distance effect estimates across time for each sequence type. There was a significant correlation between participants' distance effects across time for numbers, r=.386, p<.001 [see Figure 4(a)], and weekdays, r=.378, p=.002 [see Figure 4(b)]; however, the correlation for months was not significant (p=.174).

To examine whether the degree of distance effect was consistent across sequence type, we correlated each participants' distance effect for each sequence type overall (i.e., collapsed across Time 1 and Time 2) with each other sequence. The correlation between distance effects for numbers and weekdays approached significance, r=.223, p=.056 (see Figure 5); however, there was no correlation between distance effects for weekdays and months (p=.279) or numbers and months (p=.096). Paired t-tests were also performed to investigate changes in distance effects across time for each sequence. These tests indicated there was not a significant difference between measures of distance effects for any of the sequence types (all ps>.101).

(a)



(b)

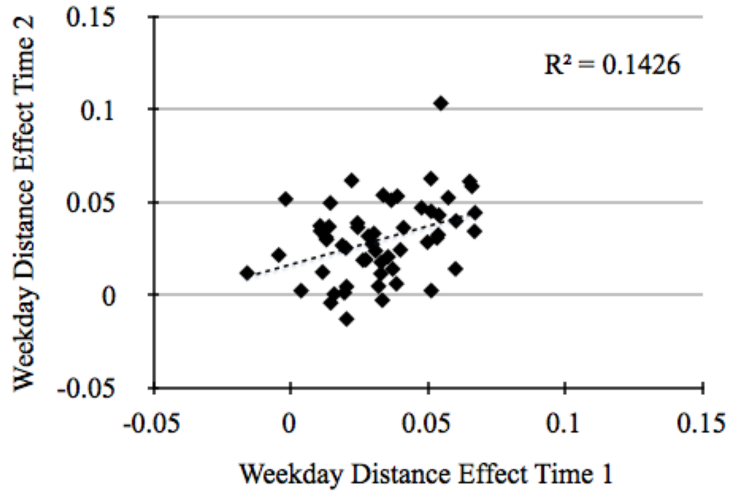


Figure 4. Scatterplots displaying the correlation between individual measures of distance effect for (a) numbers and (b) weekdays between Time 1 and Time 2.

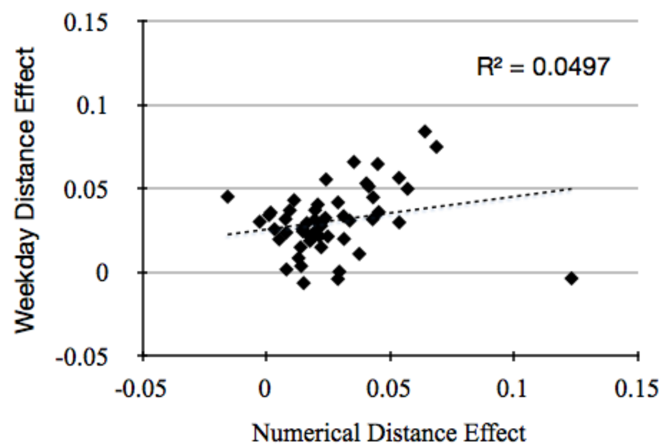
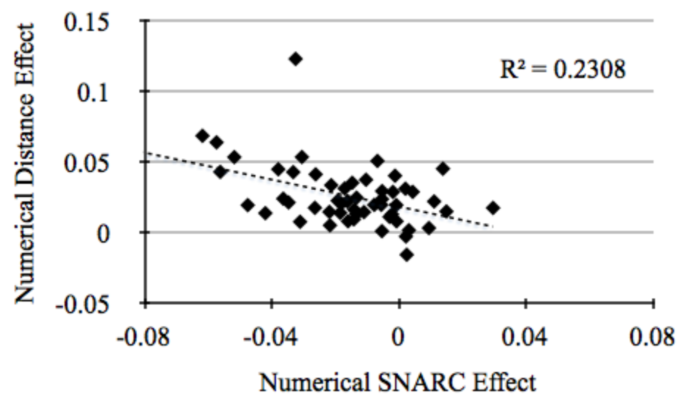


Figure 5. Scatterplot displaying the correlation between overall individual measures of the distance effect for numbers and weekdays.

SNARC and Distance Effect Correlations

Lastly, we tested whether individual participants' SNARC and distance effects for each sequence type, collapsed across time, were correlated with one another. SNARC and distance effects were significantly correlated for numbers, *r*=-.480, *p*>.001 [see Figure 6(a)], and weekdays, *r*=-.422, *p*<.001 [see Figure 6(b)], but not for months, *r*=-.160, *p*=.121 (these correlations are negative because with our SNARC measure, a stronger left-to-right SNARC effect is reflected by a more negative value).

(a)



(b)

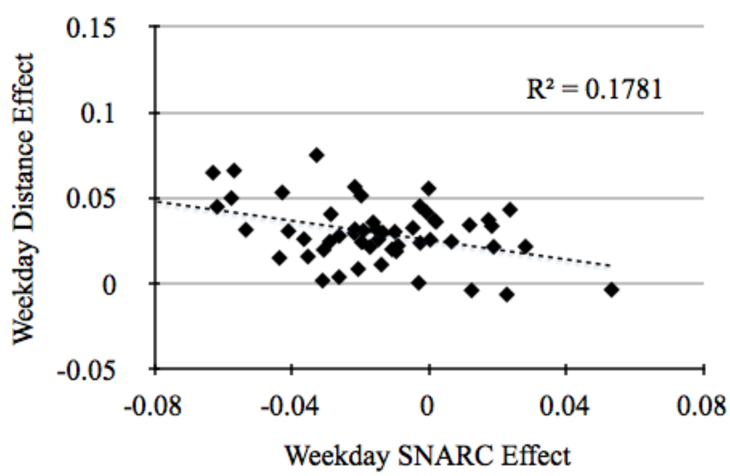


Figure 6. Scatterplot displaying the correlation between overall individual measures of the distance effect and the overall measures of SNARC effect for (a) numbers, and (b) weekdays.

Discussion

The present study examined the consistency of individual SNARC and distance effects, as measured by a magnitude-relevant SNARC task, for three ordinal sequences: numbers, weekdays, and months. On two occasions, participants saw early (e.g., 1, Monday, January) and late (e.g., 9, Friday, December) items from the sequence and their task was to indicate, with a left- or right-handed response, whether the target fell before or after an item intermediate in the sequence (i.e., 5, Wednesday, or July). Replicating previous literature (e.g., Dehaene et al., 1993; Gevers et al., 2003, 2004), group results revealed a SNARC effect for each sequence type; that is, participants responded faster to items early in the sequence with the left hand, and items later in the sequence with the right hand. Although there some evidence that the SNARC effect for numbers was weaker on the second visit, the expected interaction of hand and target type was significant at both visits (and did not interact with time in the overall ANOVA). Similarly, robust distance effects were observed for each sequence type, such that participants responded faster to targets further from the reference item (i.e., 1/9, Monday/Friday, January/December) than targets close to the reference item (i.e., 4/6, Tuesday/Thursday, February/November) (e.g., Gevers et al., 2003, 2004).

In line with our predictions, participants' SNARC effects were moderately correlated across time for numbers. This level of consistency is similar to that found in a recent study reporting only moderate (but significant with three potentially influential data points removed) consistency in the SNARC effect across time as measured by a parity task (Viarouge et al., 2014). The modest size of the correlation, however, is also in line with evidence that the SNARC effect is malleable based on context (e.g., Bächtold et al., 1999; Fischer et al., 2009; Fischer et al., 2010). Additionally, the current study is the first to show that, similar to numbers, the SNARC effect for months (and to some degree weekdays) is modestly consistent to a similar degree as the numerical SNARC within individuals across time.

This study is also the first to investigate the consistency of the distance effect across visits in adults. Our data revealed moderate consistency in distance effects for numbers and weekdays (but not months) across separate sessions. The only previous study addressing this in adults investigated the stability of the distance effect across trial blocks within the same experimental session, and found only modest consistency in performance (Maloney et al., 2010).

Combined, our data on the SNARC and distance effects indicate that individuals do exhibit some degree of consistency in the direction and/or precision of their mental sequence lines for numbers, weekdays, and months, even when tested in sessions one to three weeks apart, given that the experimental context remains unchanged. Nonetheless, the fact that participants' performance at times 1 and 2 was not highly correlated for either effect for any sequence suggests that sequence-space associations may not be the result of stable, highly specific neural connections between representations of individual sequence items and spatial locations in the parietal cortex. It is possible that the cortex applies a general, slightly more abstract rule of "left-to-right-ness" (depending on cultural experience; see Zebian, 2005) when processing ordinal stimuli, which would result in a standard left-to-right SNARC effect on most occasions in a given individual, with the actual strength of the effect varying across time. Therefore, our data suggest that researchers should exercise caution in interpreting the magnitude of either the SNARC or distance effect as an accurate measure of an individual's mental sequence line.

A second goal of the current study was to assess whether, for each sequence, participants' SNARC and distance effects correlated with one another. Replicating previous results (e.g., Viarouge et al., 2014; Schneider et al., 2009), we observed a significant correlation (r=-.480) between these two measures for number stimuli. Additionally, we show for the first time a similar degree of correlation between SNARC and distance effects for weekdays (r=-.422); as with numbers, participants with stronger SNARC effects also tended to have larger distance effects for this sequence. These data support the hypothesis that SNARC and distance effects are behavioural manifestations of the same mental construct (i.e., the mental sequence line), albeit measures of different characteristics of that construct (i.e., directionality and precision, respectively)—and that this is the case for at least one non-numerical ordinal sequence (i.e., weekdays). Nevertheless, as SNARC and distance effects were not correlated for months, it may be that the relation between directionality and precision is not the same for all sequence lines. Rather, the relationship may vary based on specific sequence characteristics, such as familiarity or sequence span.

A third goal of the present study was to investigate whether directionality and precision of individual participants' mental sequence lines is consistent across sequence types. The degree of SNARC effect overall was correlated between numbers and weekdays, with a similar, weaker correlational trend between numbers and weekdays for distance effects. While these data suggest individuals' mental lines for numbers and weekdays are similar, it remains unclear if all ordinal sequences form connections of varying degrees to a single neural template/architecture representing sequence-space mappings, or whether independent sequence lines are developed and maintained for each sequence type.

Although there was some correlation between the behavioural manifestationsof the mental sequence lines for numbers and weekdays share many characteristics, this appears not to be the case for months. Participants did exhibit a degree of consistency across the two tests of their month SNARC effects similar to that of numbers (and to a lesser extent, weekdays). Unlike the case for numbers and weekdays, however, month distance effect measures did not correlate across time; month SNARC and distance effects were not correlated; and month sequence line direction and precision did not correlate with the direction or precision of either of the two other ordinal sequences, respectively. It is possible that the mental sequence line of months is less linear in nature; indeed, some of our participants suggested that months may be spatially represented in a circular manner (a representation common for months in sequence-space synaesthetes; e.g., Smilek, Callejas, Dixon, & Merikle, 2007). It is also worth noting that many students (i.e., the population from which we selected our sample) may base their perception of the beginning and end of the year on the academic school year—that is, the first month of the year being September, and the last August. Nevertheless, it is unlikely that these two possibilities explain the discrepencies in our month data compared to that of numbers and weekdays, because at the group level, our participants did exhibit a left-to-right SNARC for months.

It is possible that differences in stimulus characteristics of the months sequence, relative to those of numbers and weeks, may account for this pattern of results. For example, the target stimuli for numbers and weekdays included stimuli that were only a one-step distance in magnitude from the comparison item (i.e., 4 and 6 for numbers, Tuesday and Thursday for weekdays). This was not the case for our month stimuli, for which the target stimuli classified as "close" to the comparison item (i.e., February and November) where actually relatively far from it in magnitude. Utilizing only extreme sequence items as probes would likely not impact our categorical measure of the SNARC effect and hence not impact the observed consistency of the month SNARC effect. However, responses to these extreme probes may not yield an accurate estimation of the distance effect for months, potentially resulting in less consistency across time, and ultimately a pattern of data inconsistent with that for numbers and weekdays. If this account is correct, one might expect to see a similar pattern of results when utilizing our paradigm with other ordinal sequences with similar sequence parameters. For example, one could use the paradigm described by Dodd et al. (2008) for letters with only extreme beginnings and ends of the alphabet (e.g., a, b, and y, z) as early and late sequence items—and hence only targets that are a fair distance from the comparison item (i.e., m).

Taken together, these data suggest that the SNARC and distance effect both represent behavioural manifestations of the same mental construct, and that both effects tend to exhibit modest consistency across time, even for non-numerical ordinal sequences. Nevertheless, the fact that the test-retest reliability of these effects was not higher suggests that neither effect is a trait variable. The only modest consistency of these effects within individuals over time is consistent with the hypothesis that the mental sequence line is not a highly stable, entrenched mental construct; indeed, this lack of consistency could explain the malleability of the SNARC effect in different contexts.

Future investigations could assess whether the degrees of consistency reported here are similar for other ordinal sequences known to be spatially organized, such as musical notes (Rusconi, Kwan, Giordano, Umiltà, & Butterworth, 2005) or letters (e.g., Gevers et al., 2003). Additionally, it has been suggested that humans may have an inherent left-to-right mapping of sequences as a result of a right hemispheric dominance in visuospatial tasks (Rugani, Kelly, Szelest, Regolin, & Vallortigara, 2010), but that such a bias can be attenuated or reversed with cultural experience. If this is the case, one might expect more tenuous, and thus less stable, mental sequence lines in individuals from cultures that read and write from right to left. Lastly, given that Western individuals have a natural inclination, at least in a neutral context, to exhibit a left-to-right SNARC effect, it is possible that this mapping might show higher degrees of consistency than the reversed-SNARC effects that have been observed under differing contexts. For example, future research could investigate whether individuals exhibit degrees of consistency similar to our numerical SNARC consistency when performing the clock-face SNARC task administered by Bächtold et al. (1998). If the degree of test-retest consistency of the SNARC effect is indeed mediated by the familiarity of the sequence-space directionality, one might expect markedly less (or no) consistency in these manipulated contexts.

References

* References can be found at the end of the thesis.

Appendices

Appendix 1.

Synaesthesia Questionnaire

Do you consistently experience or visualize numbers as having a specific spatial location?

□ Yes, each number has a specific location in space. Please describe the locations on the back of this paper.

□ No, I have never experienced this.

Do you consistently experience or visualize days of the week and/or months of the year as having a specific spatial location?

□ Yes, these sequences have specific locations in space. Please describe the locations on the back of this paper.

□ No, days of the week and months of the year are not spatially located to me.

Does looking at letters or numbers ever elicit the perception of colour for you?

□ Yes, letters and/or numbers always elicit colour.

□ No, I have never experienced this.

Do specific sounds (e.g. the note C # on a piano) elicit the perception of colour for you?

□ Yes, certain sounds reliably elicit colour.

□ No, I have never experienced this.

Synaesthesia is a neurological phenomenon in which normal input into one sensory modality, such as hearing, reliably and automatically triggers an additional perception in another sensory modality, such as vision, or along another dimension, such as colour. Have you ever heard of synaesthesia?

□ Yes.

□ No.

There are many types of synaesthesia that have not been mentioned above. Do you think you may have synaesthesia, or any type of atypical blending of the senses?

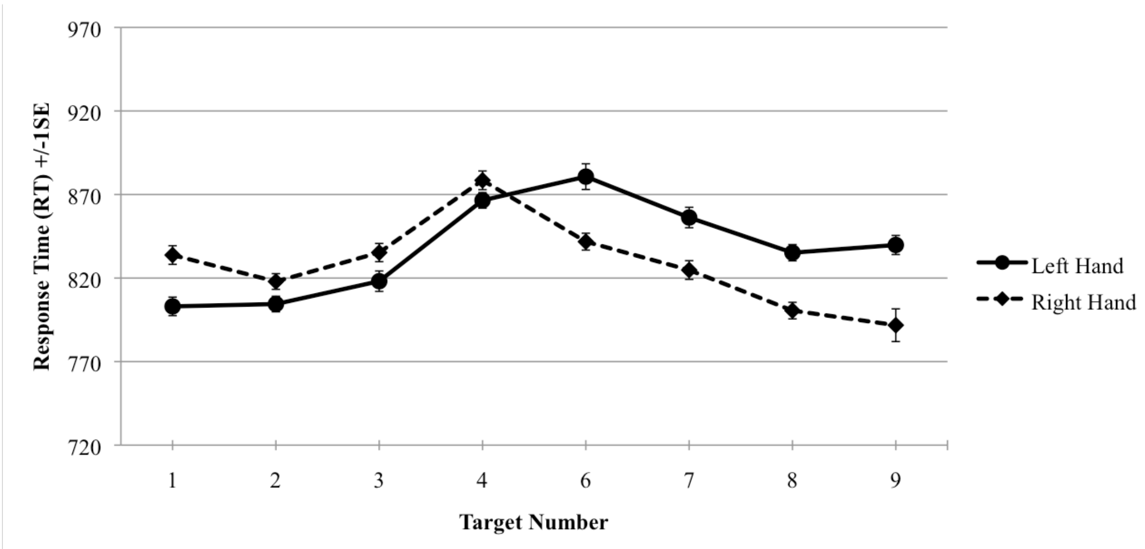
□ Yes, I experience synaesthesia.

□ No, I do not experience synaesthesia.

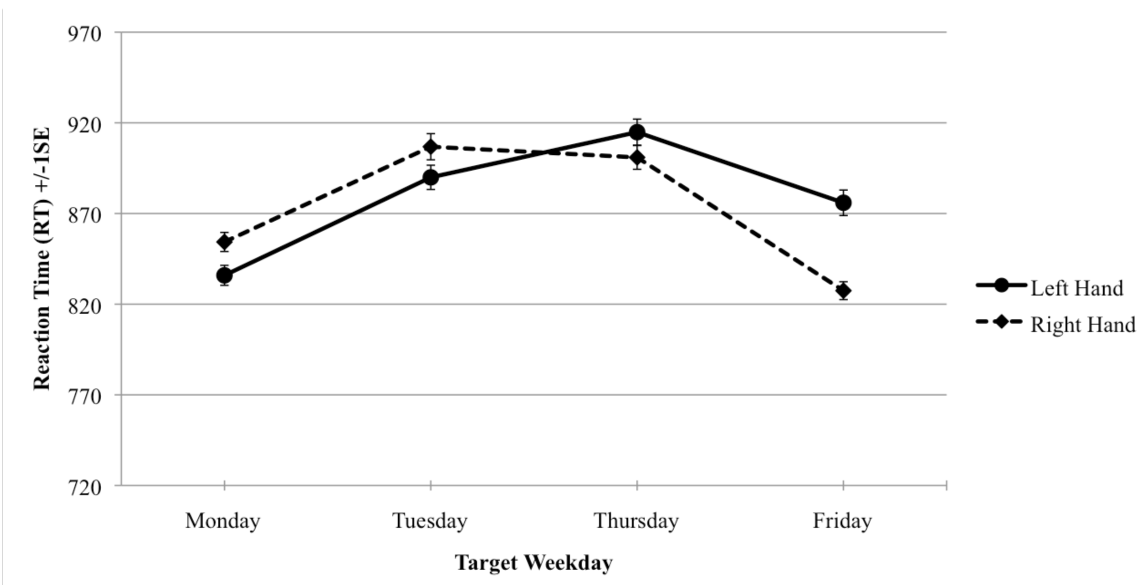
Figure 1. A copy of the synaesthesia questionnaire utilized for the empirical study in presented in Chapter 4.

Appendix 2.

(a)



(b)



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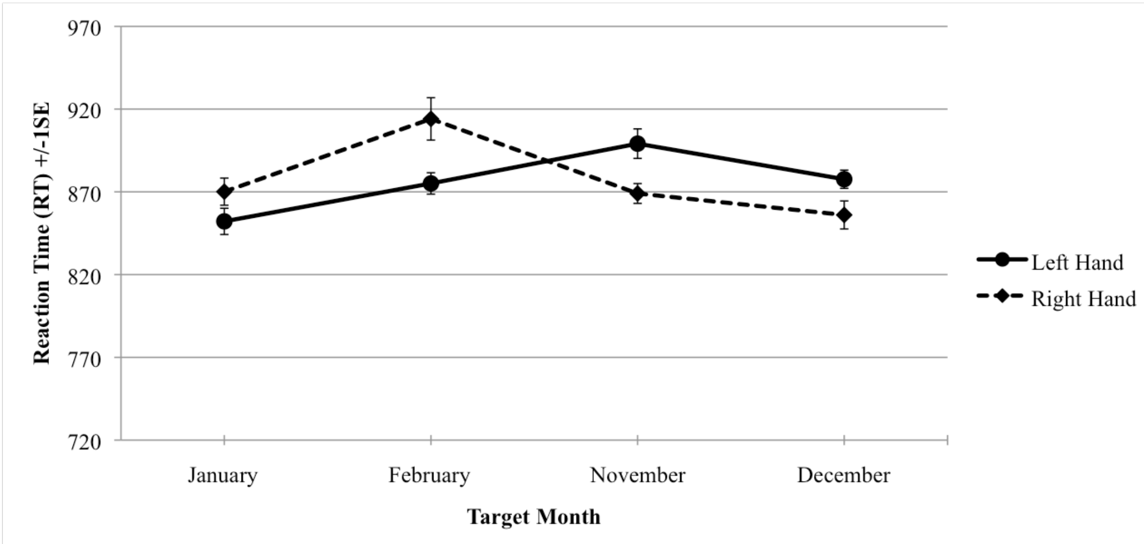

Figure 2. Means of median RTs for each hand for target (a) numbers, (b) weekdays, and (c) months. Standard error bars calculated using within-subjects variability, as described by Cousineau (2005).

General Discussion

In contemporary society, the ability to accurately represent and manipulate numerosity is necessary for an individual to thrive. The vast majority of number and math skills develop during middle childhood and adolescence as the result of education and real-world experience; nevertheless, neonates exhibit behaviours that suggest they possess some primitive number concepts, such as the differentiation of large differences in numerosity and perhaps even rudimentary arithmetic abilities for small numbers (e.g., Xu & Spelke, 2000; Wynn, 1992). There appear to be many factors that influence the rate at which each individual child acquires more refined numeracy and mathematics skills throughout childhood; for example, degree of mathematical knowledge at the beginning of schooling (Aubrey, Dahl, & Godfrey, 2006), language ability (e.g., Donlan, Cowan, Newton, & Lloyd, 2007), and visuospatial memory (Alloway & Passolunghi, 2011) are just some of the measurable traits that have been shown to play roles. There is, however, one mental construct that many researchers have hypothesized to be at the very core of human number sense: the mental sequence line (e.g., Dehaene, 1997).

The mental sequence line is described as a horizontally-oriented, left-to-right (at least for Western cultures) cognitive representation of items within a given ordinal sequence. In speeded tasks with Western adults, the reality of this construct is supported by the findings of faster manual responses to early sequence items with the left hand, and to later items with the right (i.e., the SNARC effect; Dehaene et al., 1993), and faster discrimination of items greatly separated versus close in magnitude (i.e., the distance effect; Moyer & Landauer, 1967). One or both of these effects have been reported for many different ordinal sequences, including numbers, weekdays, months, letters, musical notes, time, and even randomly selected words arranged into an ordered list (Dehaene et al., 1993; Gevers et al., 2003, 2004; Rusconi, Kwan, Giordano, Umiltà, & Butterworth, 2005; Santiago et al., 2007, Previtali et al., 2010).

The first empirical study in this thesis investigated the developmental origins of the mental sequence line. To do so, I employed a novel paradigm designed to compare two prominent competing theories as to its origins: the enculturation hypothesis and the biological hypothesis. The enculturation hypothesis posits that the orientation of a given individual's mental sequence line is determined by the direction in which text is written and read in his/her culture. This hypothesis yields specific predictions about how children will organize sequences: (1) those sequences Western children commonly see in print, even prior learning to read (e.g., ABC, 123), will be the first to be organized from left to right; and (2) as children age and gain more exposure to their cultural text direction, more sequences will be systematically ordered from left to right. The biological theory, on the other hand, hypothesizes that mental sequence line orientation is a byproduct of the brain's right hemispheric bias in visuospatial tasks, a bias which causes humans to attend preferentially to the left visual field. Thus, it follows that the biological hypothesis predicts that children of all ages, even those that are pre-readers, will order all ordinal sequences that they understand from left to right. Some sequences might show the ordering at an earlier age, but that will be simply because young children more easily understand the ordinality of the items in the sequence.

To assess the enculturation and biological hypotheses, I asked groups of 4- and 5-year-olds to put items from four familiar sequences in order within three adjacent, horizontally-organized boxes. Two of the sequences were those children often see ordered in text, even prior to learning to read (i.e., A, B, C and 1, 2, 3); the other two were familiar sequences unlikely to be seen ordered in text (i.e., breakfast, lunch, dinner and morning, afternoon, night). Consistent with the enculturation hypothesis, but not the biological hypothesis, 4-year-olds organized letters, but no other sequence, from left to right. Also consistent with the enculturation hypothesis, by age 5 children also organized numbers and times of day from left to right.

The data in my first empirical chapter are the first reported data to offer compelling support for the two developmental assumptions of the enculturation hypothesis. Specifically, a sequence commonly seen ordered in print (e.g., on daycare walls) even prior to learning to read was the first to be ordered from left to right, and older children ordered more sequences from left to right than younger ones. The results of this experiment speak not only to the order in which ordinal sequences acquire directionality, but also provide behavioural data with which more informed hypotheses concerning the neurological underpinnings of the development of the mental sequence line can be made. For example, based on these data, one might expect children to first exhibit activation in parietal areas encoding spatial information when observing items from sequences they have seen in print, followed by similar activation when exposed to other sequences not seen in print.

Although several previous studies have investigated the directionality of preschool children's number placements (e.g., Opfer & Thompson, 2006; Opfer, et al., 2010; Briars & Siegler, 1984), none of these studies assessed the reading abilities of included participants. As such, this is the first study that can report that these data are unbiased by skill above and beyond the reading of a few letters or simple words by any of the preschoolers within the sample. As the enculturation hypothesis points to literacy as the key variable driving sequence line directionality, assessing the literacy abilities of the participant sample was necessary to accurately assess this hypothesis. For the purposes of this study, I defined literacy as performance on the Wide-Range Achievement Test-3 that was two standard deviations above the mean or more. Using this cutoff as a criterion for exclusion, the participants in the final sample were only able to recognize letters and, at best, a few very simple, familiar words (e.g., cat). Finally, this experiment is the first to investigate the directionality of non-numerical ordinal sequences in children. Non-numerical ordinal sequences are mapped from left to right in Western adults (e.g., Gevers et al., 2003, 2004; Dodd et al., 2008); however, these data are the first to suggest that a cognitive mapping of ordinality onto space for non-numerical sequences, specifically letters and times of day, begins during the preschool years. It is important to note that in addition to ordering letters and numbers from left to right, the pre-reading participants in my 5-year-old group also ordered times of day—a sequence rarely, if ever, seen in print. This suggests that children may be bootstrapping other familiar sequences on to the left-to-right template first established for letters.

The second empirical experiment in this dissertation measured the mental sequence line for numbers in school-aged children, and assessed its relationship to visuospatial and mathematics abilities. One recent experiment has reported a relationship between visuospatial skills in adults, such that participants' mental rotation ability correlated with the strength of their SNARC effect (Viarouge et al., 2014). Further supporting this link, children with visuospatial disorders do not exhibit SNARC effects at the group level, unlike their typically-developing peers (Bachot et al., 2005). However, the relationship between visuospatial skills and measures of the mental sequence line had previously not been assessed in a typically-developing sample of children. Previous studies of the relationship between mathematics ability and mental sequence line strength have yielded inconsistent results. For example, while most studies report a negative relationship between math ability and the symbolic (i.e., participants respond to Arabic digits as opposed to dot arrays) distance effect (e.g., Holloway & Ansari, 2009; Sasanguie et al., 2012a; Vanbinst et al., 2012), not all find this association (Sasanguie et al., 2012b). Similarly, in studies evaluating the SNARC effect and its relation to math achievement, there is one report of no systematic relationship (Schneider et al., 2009), and one report of a negative relationship in 5-year-old boys, but not girls, and not overall at the group level (Schweiter et al., 2005). Additionally, previous experiments using the SNARC paradigm as a measure of the mental sequence line have employed problematic methods to calculate individual SNARC effects that conflate the SNARC and distance effects.

In my study, groups of 6-, 7-, and 8-year-old children performed a SNARC task requiring judgments of magnitude (i.e., is the number on the screen less than or greater than 5?), in addition to two standardized tests: the Developmental Test of Visual Perception-2 (DTVP-2; a measure of visuospatial skills) and the Test of Early Mathematics Ability-3 (TEMA-3; a measure of math skills). Unlike previous studies, the use of a magnitude-relevant SNARC task allowed me to calculate both individual SNARC and distance effects for each participant, thus yielding two independent measures of the mental sequence line for each child. Consistent with previous literature, 7- and 8-year-olds, but not 6-year-olds, exhibited SNARC effects at the group level; all three groups, however, did have robust distance effects. As predicted, the strength of children's distance effects was correlated with their performance on a DTVP-2 subtest that measures mental visual orientation and mental rotation ability. Contrary to predictions, however, there was no correlation between either mental sequence line measure and math ability scores on the TEMA-3. Furthermore, as SNARC and distance effects were calculated for each participant, I was also able determine that these two mental sequence line measures were not correlated in my sample of 6- to 8-year-old children.

The data in this chapter speak to the development of the mental sequence line in several novel ways. First and foremost, these data establish, for the first time, that specific visuospatial abilities are related to a measure of the numerical distance effect in 6- to 8-year-old children. Thus, these data are a starting point in mapping out the developmental trajectory of the relationship between visuospatial skills and mental sequence line strength. These results are also significant in that they indicate the distance effect, but not the SNARC effect, is related to visuospatial abilities in children, thus suggesting that sequence line precision is more closely related to visuospatial abilities (or vice versa) than sequence line directionality, at least in children (see Viarouge et al., 2014). Second, these results contribute to the ongoing investigation into the relationship between math and mental sequence line strength. Despite employing a different SNARC paradigm, a more categorical and unconfounded calculation of the SNARC effect, and a standardized measure of math ability, my results are consistent with, and thus lend credence to, previous studies reporting no systematic relationship between the SNARC effect and mathematics abilities in young school-aged children (i.e., Schneider et al., 2009; Schweiter et al., 2005). These variables are related negatively in adults (e.g., Dehaene et al., 1993; Fischer & Rottmann, 2005; Hoffmann et al., 2014; but see Cipora & Nuerk, 2013); therefore, my finding of no relationship between mental sequence line directionality and math performance suggests that the neural architecture relating sequence directionality and math skill changes after middle childhood.

My finding of a lack of correlation in children between math skills and the mental number line measures also contradicts the hypothesis that the mental number line underlies the learning of mathematics skills (e.g., Dehaene, 1997). Similar to the SNARC effect, distance effects were also not related to math ability in my sample. As these data are inconsistent with (most) previous studies, they suggest that something inherent in my experimental design may have negated the relationship between sequence line precision and math skill. One possible contributor is that I utilized response times from a magnitude-relevant SNARC task to calculate distance effects, as opposed to the typically-employed number comparison task (e.g., Holloway & Ansari, 2009). Thus, my task asked children to indicate if the target number is less than or greater than 5, rather than asking children to compare two target numbers presented simultaneously on the screen One important distinction between these two tasks is in that in my SNARC task the largest comparison distance was 4 (i.e., between 1 and 5, and 9 and 5), while in the digit comparison task using digits 1 through 9, the distance between digits can go up to 8 (although most studies limit digit distance to 6, e.g., Holloway & Ansari, 2009; Lonneman et al., 2011). As the distance effect is defined by significant differences in response time between digits close together versus those further apart, distance effects may be stronger when the maximum distance is larger. Indeed, when one study parsed their 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 mathematics ability (Lonneman et al., 2011). Furthermore, another study employing a magnitude-relevant paradigm similar to mine also found no predictive value of symbolic distance effects on math ability (Ferreira et al., 2012). Therefore, it is possible that my stimuli did not yield distance effects strong enough to reveal true correlations with mathematics skill. Lastly, these data are valuable in that they speak to the development of the relationship between sequence line directionality and precision. My participants' data showed no correlation between these two mental sequence line measures; however, this relationship has been reported in adults (e.g., Viarouge, 2014) and in older children (11-year-olds; Schneider et al., 2009). As such, these data are the first to suggest that sequence line directionality and precision develop independently prior to becoming correlated at an older age.

In the third and last empirical chapter of this dissertation, I report an investigation into the behavioural consistency of mental sequence line measures in adults. Hypothesized measures of individual differences in mental sequence lines such as the SNARC and distance effects are common in the literature, and have been utilized to assess the relationships between sequence-space associations and a variety of other traits as diverse as mental imagery (Price, 2009) and finger-counting habits (Fischer, 2008). As such, measures such as the SNARC and distance effects have often been described in the literature as though they are trait variables. More recently, however, evidence that the SNARC effect can be modulated by context (e.g., Bächtold et al., 1998; Fischer et al., 2009) suggests that this is not the case. Indeed, one recent study in which adults performed a SNARC task twice under the same experimental conditions found only moderate test-retest reliability (Viarouge et al., 2014). In my experiment, I sought to extend these findings by testing the reliability of both the SNARC and distance effects for numbers, as well as for two other ordinal sequences for which adults exhibit these effects: weekdays and months of the year. Furthermore, my paradigm departed from that of Viarouge et al. (2014) in that I employed a magnitude-relevant SNARC task to optimize the chances of observing robust distance effects. Additionally, I estimated participants' SNARC effects utilizing a novel formula that distinguishes the directional and distance measures of the number line, unlike the traditionally used regression analysis. Lastly, examining the same participants' performance on my task across different sequence types allowed me to assess, for the first time, whether mental sequence line directionality and precision (i.e., as measured by SNARC and distance effects) is similar within individuals across various sequence types; similarly, I was able to evaluate whether SNARC and distance effects are correlated with each other for each ordinal sequence tested.

For all three ordinal sequences, participants exhibited significant SNARC and distance effects at the group level. Participants' degree of SNARC effect was moderately but significantly correlated across visits for numbers and months, with a similar trend for weekdays. The consistency data for the numerical SNARC are comparable to those of Viarouge et al. (2014) for numbers, and my data extend their findings to two more, non-numerical ordinal sequences. The evidence of some consistency suggests that individuals do differ among each other in the extent to which they have a left-to-right bias for ordinal sequences. Nevertheless the low level of the correlations provides support for the hypothesis that the mental sequence line is relatively malleable, as opposed to reflecting a precise inflexible directional neural architecture.

For the distance effect, performance across visits showed moderate consistency for numbers and weekdays. Only two previous studies have investigated the consistency of the distance effects for numbers. In the first, adults showed evidence of no (Maloney et al., 2010, Experiment 2) or only moderate stability (Experiment 1, r=.38; Maloney et al, 2010) in the effect when performance was correlated across trial blocks within the same experimental session. In the second study, 11-year-old children exhibited higher, but still modest, levels of distance effect consistency across visits (r=.501; Schneider, Grabner, & Paetsch, 2009). My data are consistent with these findings from adults (Maloney et al., Experiment 1) and children. Akin to my SNARC findings, these data suggest that mental sequence line precision is likely not a trait variable with high test-retest reliability. This study is the first to report the consistency of the distance effect for any non-numerical ordinal sequences.

I also utilized these data to investigate whether, for each sequence type, participants' SNARC and distance effects correlated with one another. I observed a significant correlation between these two measures for number stimuli, which is consistent with previous reports (e.g., Viarouge et al., 2014; Schneider et al., 2009). For the first time, however, I show a comparable relationship between SNARC and distance effects for weekdays; as with numbers, participants with stronger SNARC effects also tended to have larger distance effects for this sequence. My data are in line with the hypothesis that, by adulthood, SNARC and distance effects represent behavioural manifestations of the same mental construct, the mental sequence line—albeit different aspects of that construct (i.e., directionality and precision, respectively)—and suggest that this is the case for at least one non-numerical ordinal sequence (i.e., weekdays). SNARC and distance effects, however, were not correlated for month stimuli—this may be the result a less linear, more circular spatial organization of months, or the different characteristics of the months sequence itself, such as sequence span or familiarity.

Lastly, my paradigm allowed me to assess, for the first time, whether directionality and precision of one's mental sequence lines is consistent across sequence types. The degree of SNARC directionality was moderately correlated between numbers and weekdays, with a similar trend for the distance effects for these two sequences. While these data do imply that individuals' sequence line representations for numbers and weekdays are related, the source of this similarity remains unclear. For example, it is possible that ordinal sequences form connections of varying degrees to a single neural architecture representing sequence-space mappings; alternatively, individual neural architectures may be developed and maintained for each sequence type independently and the correlation could arise from similar environmental influences. The direction and precision of month sequence lines did not correlate with the direction and precision of number or weekday sequence lines. Once again, this is likely a result of differing sequence characteristics; nevertheless, this finding suggests that the representation of mental sequence lines for different ordinal sequences may vary greatly in their acuity and “physical” shape.

Limitations and Future Directions

The experiments presented in this dissertation do have certain limitations, and the results from each experiment suggest specific avenues for future research in this area. My first empirical chapter reports data from an experiment with pre-reading children that supports the enculturation hypothesis of mental sequence line development. However, these children were able to recognize some letters and for some children, a few simple words. All presumably had had extensive exposure to the cultural direction of reading and writing; for example, children see their parents and teachers writing, and parents tend to read to their children while following along the text with an index finger. Ideally, a similar study would be done with populations with little to no exposure to any text, such as adults in isolated hunter-gatherer societies (e.g., the Hazda of Tanzania) or human neonates. In both cases, based on my results, one would expect to see no systematic directional bias. Future studies will also be needed to establish the age at which the left-to-right ordering of letters first emerges, as I observed it in the youngest children I tested (4-year-olds). Data on the ordering of other ordinal sequences familiar to pre-reading children (e.g., yesterday, today, tomorrow) would also be informative. Additionally, testing older children with meals, for which I found no systematic directional bias, may reveal if my results reflect an artifact of the stimuli utilized, or if this sequence simply acquires directionality later than the others.

My second empirical chapter presents evidence that 6- to 8-year-old children's distance effects are correlated with visuospatial ability, but not mathematics skill or their SNARC effects. A magnitude-relevant SNARC task was utilized in this paradigm, which requires recognition of digits 1-9, understanding of ordinality, and consistent response times. As such, one limitation of this study is that I was unable to test whether these associations are present in children younger than 6. Future studies may address this limitation by employing SNARC-like tasks that have been adapted for use with very young children, such as a recently reported SNARC colour paradigm, which revealed a SNARC effect in 5-year-old children (Hoffmann et al., 2013). On a similar note, another limitation of this study is that I was only able to test these associations in children of three ages (i.e., 6 to 8 years). My data and those of others (e.g., Schneider et al., 2009) indicate no relationship between the SNARC effect and mathematics ability; however, as this association has been reported more than once in adults (Dehaene et al., 1993; Fischer & Rottmann, 2005; Hoffmann et al., 2014), it is likely that this association develops during childhood with increased exposure to numbers and mathematics. Future experiments could investigate the developmental trajectory of this relationship. Lastly, the number line estimation task is a behavioural paradigm in which participants estimate the position of a given number on a line anchored by two numbers (e.g., 0 and 100). As this task does not depend on reaction time data, which can be highly variable in children, it would be interesting to see if performance on it is correlated with visuospatial and math measures in young children.

My third empirical chapter describes an experiment in which I investigated the consistency of sequence-space mappings across time in adults, and report moderate consistency in the SNARC effect for numbers and months (and to some degree weekdays), and similarly modest consistency in the distance effect for numbers and weekdays. One of the limitations of this study is that I did not collect data on participants' language experience. As such, it is possible that some of my participants read or write another language in which text runs in a direction different from that of English (e.g., Arabic). As bilingual speakers of Hebrew (written right to left) and Russian (written left to right) exhibit changes in the strength of their SNARC effect based on the type of text most recently read (Shaki & Fischer, 2008), inclusion of any bilingual participants may have lessened the strength of group effects. Alternatively, it is possible that those exposed to more than one text mapping have less reliable sequence lines overall. As such, future experiments could investigate whether the level of consistency of sequence-space mappings observed in English speakers is comparable to that exhibited by those in cultures that read and write from right to left. A second limitation of this study arises from differences in the stimulus characteristics of the ordinal sequences utilized. Specifically, while both number and weekday stimuli included items that were only a one-step distance in magnitude from the comparison item (i.e., 4 and 6 were compared to 5 for numbers; Tuesday and Thursday were compared to Wednesday for weekdays), this was not the case for months (February and November were the closet items to the comparison item, July). I can hypothesize that using only extreme sequence items as targets would not impact my categorical measure of the SNARC effect—which is consistent with the moderate level of consistency observed in my month SNARC data. On the other hand, responses to only extreme targets may not yield accurate distance effect calculations—a possibility that could have caused less consistency across time in the month data, and ultimately a pattern of data inconsistent with that of numbers and weekdays. If this is the case, one might predict a comparable pattern of results when utilizing my paradigm with other ordinal sequences with a greater diversity of distances than I used for months [e.g., letters—Dodd et al. (2008) used the extreme beginnings and ends of the alphabet (e.g., a, b, and y, z) as early and late sequence items—and hence only utilized targets that were a large distance from the comparison item (i.e., m)].

Conclusion

The present dissertation reports data from three empirical experiments, each of which investigated mental sequence lines in either children or adults. The first experiment employed a novel paradigm to assess mental sequence line directionality in pre-reading children, and, for the first time, provides strong evidence in support of the enculturation account of the development of sequence-space associations. The second experiment assessed the relationship between two mental sequence line measures and visuospatial and mathematics skills in children 6 to 8 years old, and reports the first evidence of an association between distance effect strength and particular visuospatial abilities. Finally, the third chapter assessed the consistency of the SNARC and distance effects in adults for three ordinal sequences and found moderate SNARC consistency for numbers and months (with a similar trend for weekdays), and modest distance effect consistency for numbers and weekdays. While the consistency of the SNARC effect in adults has been reported in one previous study (i.e., Viarouge et al., 2014), my study replicated and extends these findings by reporting similar levels of consistency for weekdays and months. Additionally, this experiment is novel in that I have developed what I believe to be an improved, more categorical measure of the SNARC effect.

Overall, the findings in my thesis advance understanding of the origins of the affinity between ordinal sequences in space, and shed light on the developmental trajectory of this association into adulthood. My data show that this affinity is first manifest for letters of the alphabet in Western children, and that the subsequent pattern of development supports an enculturation hypothesis. By middle childhood, individual differences are evident in these effects that, as in adults, correlate with other measures of spatial cognition. By adulthood, those individual differences have become modestly stable.

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