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Short Research Article

Mental Numerosity Line in the Human's Approximate Number System

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Abstract: Previous studies have demonstrated existence of a mental line for symbolic numbers (e.g., Arabic digits). For nonsymbolic number systems, however, it remains unresolved whether a spontaneous spatial layout of numerosity exists. The current experiment investigated whether SNARC-like (Spatial-Numerical Association of Response Codes) effects exist in approximate processing of numerosity, as well as of size and density. Participants were asked to judge whether two serially presented stimuli (i.e., dot arrays, pentagons) were the same regarding numbers of dots, sizes of the pentagon, or densities of dots. Importantly, two confounds that were overlooked by most previous studies were controlled in this study: no ordered numerosity was presented, and only numerosity in the approximate number system (beyond the subitizing range) was used. The results demonstrated that there was a SNARC-like effect only in the numerosity-matching task. The results suggest that numerosity could be spontaneously aligned to a left-to-right oriented mental line according to magnitude information in human's approximate number system.

Keywords: numerosity, SNARC effect, mathematical cognition, numerical processing, mental number line

The symbolic number systems (i.e., Arabic digits, number words) can be spatially stored in the human brain (e.g., Bueti & Walsh, 2009; Bulf, Macchi Cassia, & de Hevia, 2014; Dehaene, Bossini, & Giraux, 1993; Fias & Fischer, 2005; Zorzi, Priftis, & Umilta, 2002; see reviews by Fischer & Shaki, 2014; Wood, Willmes, Nuerk, & Fischer, 2008). More than a century ago, Francis Galton demonstrated spatial layout of numbers in the mind (Galton, 1880). Dehaene et al. (1993) showed that subjects responded more quickly to smaller numbers with the left hand and more quickly to larger numbers with the right hand when they were instructed to decide whether numbers were odd or even with their hands (parity judgment task). This phenomenon was referred to as the Spatial-Numerical Association of Response Codes (SNARC) effect. Several studies have also shown that the SNARC effect was evident even when numbers were presented as written words (e.g., Dehaene et al., 1993). Besides one-digit numbers, two-digit numbers also exhibit spatial layout (Zhou, Chen, Chen, & Dong, 2008). Zhou et al. (2008) used a number-matching task to investigate mental representations of two-digit numbers from 12 to 98. The subjects were asked to judge whether two numbers were

physically the same. The SNARC effect occurred only for whole numbers and decade digits, regardless of whether the two numbers were presented simultaneously or serially. The results suggest that two-digit numbers can also be coded on a mental number line. The mental number line assumption has been supported by neuropsychological studies (Zorzi et al., 2002). Zorzi et al. (2002) showed that when asked to report the midpoint of number intervals (e.g., 11–19), patients with left neglect due to right brain injury lesions consistently had right-shift errors (e.g., reporting 17 as the midpoint of 11–19). The error pattern closely resembles the one from the bisection of physical lines (e.g., Schenkenberg, Bradford, & Ajax, 1980). Neuropsychological evidence thus suggests that the mental number line for number representations is indeed existent other than a metaphor (Zorzi et al., 2002).

The left-to-right oriented layout of numbers could be due to the effects of culture and education, that is, human beings in most cultures read and write from left to right. Thus, the SNARC effect is weaker or even reversed for cultures with right-to-left reading and writing systems (e.g., Shaki, Fischer, & Petrusic, 2009; Zebian, 2005). Some studies further showed that the direction of the mental number line

can also be reshaped by short-term experience (e.g., Fischer, Mills, & Shaki, 2010; Shaki & Fischer, 2008).

Although spatial mapping of symbolic numbers has been established, that of nonsymbolic numbers is still under research. Nonsymbolic numerosity processing is considered as the origin of human's symbolic number system by some researchers (e.g., Butterworth, 1999; Nieder & Dehaene, 2009). Numerosity is defined based on the number of discriminable elements that the stimulus contains. Any life form, from very simple life forms to human being, has to process numerosity information in the environment. Previous studies have demonstrated the ability of magnitude discrimination in monkeys (e.g., Brannon & Terrace, 1998; Nieder, Freedman, & Miller, 2002), birds (e.g., Brannon, Wusthoff, Gallistel, & Gibbon, 2001; Rugani, Fontanari, Simoni, Regolin, & Vallortigara, 2009), amphibians (e.g., Uller, Jaeger, Guidry, & Martin, 2003), and fish (e.g., Agrillo, Dadda, & Bisazza, 2007; Agrillo, Dadda, Serena, & Bisazza, 2009). The ability to manipulate numerosity was also demonstrated in human infants (e.g., Starkey & Cooper, 1980; Wynn, 1992). Recently, the approximate number system (ANS), the ability of estimating magnitudes without relying on formal symbolic math knowledge, has been shown to be fundamental to the development of mathematical performance (e.g., Halberda, Mazzocco, & Feigenson, 2008; Inglis, Attridge, Batchelor, & Gilmore, 2011; Landerl, Bevan, & Butterworth, 2004; Sasanguie, De Smedt, Defever, & Reynvoet, 2012), though some studies did not support the claim (e.g., de Oliveira Ferreira et al., 2012; Fuhs & McNeil, 2013; Sasanguie, Gobel, Moll, Smets, & Reynvoet, 2013; Zhou & Cheng, 2015; Zhou, Wei, Zhang, Cui, & Chen, 2015).

Several studies have demonstrated the relation between numerosity and space in animals. Rhesus monkeys were shown to be capable of learning ordinal rules for numerosities 1–4 and transferring the rules to numerosities 5–9 (Brannon & Terrace, 1998). Rugani, Kelly, Szelest, Regolin, and Vallortigara (2010) trained domestic chicks and nutcrackers to peck at either the fourth or sixth element in a series of 16 identical and aligned positions. They found that the birds had a bias of locating target positions from the left but not from the right end of the series. Rhesus macaques also had similar left-to-right performance in a counting-like task (Drucker & Brannon, 2014). A recent study showed left-to-right oriented numerosity-space mapping in newborn chicks (Rugani, Vallortigara, Priftis, & Regolin, 2015). After the chicks were habituated to numerosity "5" (i.e., 5 dots) in the center of a box, they typically walked to the left when a small numerosity (2 dots) was presented at both sides of the box and to the right when a large numerosity (8 dots) was presented at both sides of the box. The studies thus demonstrated that animals either intrinsically have or could learn explicit mapping of space and numerosity.

The oriented spatial layout of numerosity was also found in infants and kindergarteners before they acquire formal education on mathematics (Bulf, de Hevia, & Macchi Cassia, 2015; de Hevia, Girelli, Addabbo, & Macchi Cassia, 2014; de Hevia & Spelke, 2010; Patro, Fischer, Nuerk, & Cress, 2015; Patro & Haman, 2012). For example, preverbal infants who were habituated to dot arrays (i.e., nonsymbolic numerosity) presented in either increasing or decreasing order looked longer to line lengths in a novel order (either decreasing or increasing order, respectively; de Hevia & Spelke, 2010). de Hevia et al. (2014) further showed that infants had preference for left-to-right oriented increasing nonsymbolic numerical sequences. Patro and Haman (2012) instructed preliterate precounting preschoolers to point to one of two sets with colored rectangles. The preschoolers needed to point to either the set with fewer rectangles or the one with more. The results showed that for small-quantity sets (2–4 rectangles), the preschoolers responded quicker to the smaller set if the smaller set was presented on the left side, and quicker to the larger set if the larger set was presented on the right side. This result suggests left-to-right mapping of nonsymbolic numerosity to space in preverbal children. One caveat of these infant studies is that these studies relied on explicit presentation of ordered numerosity, which could hint participants to order numerosity or to access memory of ordered numerosity. Thus, it remains unclear whether mental spatial layout of numerosity exists without explicit presentation of ordered numerosity.

Some studies have tried to explore spontaneous mapping of nonsymbolic numerosity to space without explicit presentation of ordered numerosity (e.g., Bulf et al., 2014, 2015; Luccio et al., 2012; Mitchell, Bull, & Cleland, 2012; Nuerk, Wood, & Willmes, 2005). For example, Nuerk and colleagues (2005) showed the SNARC effect in a parity decision task for Arabic numerals, written number words, and auditory number words, and SNARC-like effect for visual dice patterns ranging from 1 to 9 items. Using a visual attention bias task, Bulf et al. (2014) showed that participants' attention could be shifted to the left side of the screen by a stimulus with smaller magnitude (e.g., 2) presented at the center of the screen and to the right side of the screen by a stimulus with larger magnitude (e.g., 9). The stimulus could be one from symbolic Arabic digits, nonsymbolic arrays of dots, or shapes of different sizes. Bulf et al. (2015) extended this finding and showed that 8–9-month-old infants' eye movement was modulated by numerical magnitude presented at the center of the screen: small numerosity (e.g., 2 dots) led eye gaze to the left side and larger numerosity (e.g., 9 dots) led eye gaze to the right side.

A caveat of these studies is that they typically used numerosity with numbers of items covering both subitizing (i.e., fewer than or equal to four items) and counting

(i.e., more than four items) ranges (e.g., Bulf et al., 2014; Mitchell et al., 2012; Nuerk et al., 2005; Tamburini, Fumarola, Luccio, & Agostini, 2012). Subitizing is a preattentive, automatic process (e.g., Trick & Pylyshyn, 1993, 1994). Nonsymbolic numerosities in the subitizing range may be easy for the participants to map to symbolic numbers. For example, the number of dots in Mitchell et al. (2012) and Nuerk et al. (2005) ranged from 1 to 9. Bulf et al. (2014) used dot arrays involving 2 or 9 dots. Participants in Nuerk et al.'s study (2005) were instructed to transcode visual dice patterns to specific numerals obligatorily. Thus, these studies do not exclude the possibility that mapping of numerosity and space without explicit presentation of ordered numerosity is mediated by numerals.

Luccio, Fumarola, Tamburini and Agostini (2012), Mitchell et al. (2012), and Patro and Haman (2012) analyzed mapping of numerosity and space by separating numerosity arrays into ones in the subitizing range and others in the counting range. The findings, however, were inconsistent. Luccio et al. (2012) found a left-to-right oriented mental line of nonsymbolic quantities only for numerosities in the counting range (7–23 dots in dot arrays) in an attention shift paradigm (Fischer, Castel, Dodd, & Pratt, 2003). Mitchell et al. (2012) found a SNARC-like effect in the subitizing range (1–4) other than in the counting range (6–9) in both an orientation decision and an attention shift paradigms. As mentioned above, Patro and Haman (2012) found that preschoolers could map 2–4 items but not 5–10 items to space in a numerosity comparison task.

Combining previous studies on the mapping of number and space, it remains unclear whether there is mapping of nonsymbolic quantity and space in the approximate number system. In the current investigation, we used a numerosity-matching task based on a number-matching paradigm (Zhou et al., 2008) to explore spontaneous mapping of nonsymbolic numerosity and space in the approximate number system. The typical parity judgment paradigm was not used, because it could not be used for processing numerosities in the approximate number system. To avoid confounding factors of explicitly presented ordered numerosities and subitizing, no ordered numerosity was presented, and double-digit numerosities beyond the subitizing range were used in this experiment. Given previous results of numerosity processing for animals (e.g., Rugani et al., 2015), and infants and preschoolers (e.g., de Hevia et al., 2014; de Hevia & Spelke, 2010; Patro et al., 2015; Patro & Haman, 2012), we predict spontaneous spatial layout of numerosities that vary with the number of objects (e.g., dots). That is, small numerosities would be represented at the left side, whereas large numerosities at the right side in human's mind.

Although most previous studies were focused on spatial mapping of discrete quantities (e.g., numerosity), some studies also examined spatial mapping of some continuous quantities (e.g., area and density). Spatial representations of continuous magnitudes were observed in pitch (Lidji, Kolinsky, Lochy, & Morais, 2007; Rusconi, Kwan, Giordano, Umilta, & Butterworth, 2006), size/area (e.g., Bulf et al., 2014, 2015; Shaki, Petrusic, & Leth-Steensen, 2012; Ren, Nicholls, Ma, & Chen, 2011), and luminance (e.g., Ren et al., 2011, but Bulf et al., 2014). For example, musically trained participants showed an association between "right" responses to high-pitched tones and "left" responses to low-pitched tones in a timbre judgment task (Rusconi, Umilta, & Galfano, 2006). To further study spatial representations of continuous quantities, we also examined spatial representations of two types of continuous quantities (i.e., area size and density) in area- and density-matching paradigms. Given that area size and density are important visual properties of numerosity (Gebuis & Reynvoet, 2011), the answer to this question could help us understand whether the possible spatial representation of numerosity is mediated by continuous perceptual quantities (Szűcs, Nobes, Devine, Gabriel, & Gebuis, 2013).

Methods

Participants

Forty-eight college students (half males and half females) from Beijing Normal University were recruited. The average age was 20.9 years, ranging from 18.4 to 26.5 years. All participants had normal or corrected-to-normal eyesight. They did not participate in any experiment with number tasks during the past half year prior to this study. They gave written informed consent before the experiment. After the experiment, each participant was paid RMB 20 yuan (about US$3.2).

Materials

For the numerosity-matching task, the materials were dot arrays including 11, 14, 17, 20, 23, 26, and 29 dots (coded as 1–7, respectively). The total combined size of all dots was the same for all dot arrays. In each dot array, the size of each dot varied from 2 to 20 pixels in radius, and the location of each dot in a gray circle was random with a restriction on the distance of any two dots larger than 2 pixels.

For the area-matching task, the materials were noncongruent irregular pentagons with sizes ranging from 1.04, 2.08, 3.12, 4.16, 5.20, 6.24, to 7.28 cm^2 (coded as 1–7, respectively). The noncongruent irregular pentagon shapes were randomly generated by an in-house MATLAB

(A)

(B)

(C)

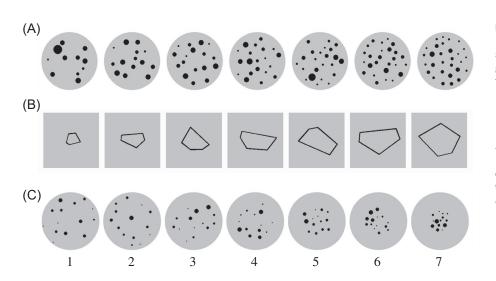1   2   3   4   5   6   7

Figure 1. Examples for seven types of numerosity, area (pentagons), and density used in the current study (The gradually-increased magnitudes of each type are coded as 1–7). (A) Numerosity-matching task: dot arrays including 11, 14, 17, 20, 23, 26, and 29 dots (coded as 1–7). (B) Area-matching task: irregular pentagons with sizes of 1.04, 2.08, 3.12, 4.16, 5.20, 6.24, and 7.28 cm^2 (coded as 1–7). (C) Density-matching task: radius of the inner invisible circle being 100, 90, 80, 70, 60, 50, and 40 pixels (coded as 1–7).

program. The shapes of all the pentagons for the area-matching task were different. For matched trials, the two pentagons had different shapes but the same size. For non-matched trials, the two pentagons had different shapes and different sizes.

For the density-matching task, the materials were dot arrays with the same number of dots (14, close to half of the maximum number of dots in the dot arrays used for the numerosity-matching task) but varied density. Density is defined as the number of items per unit area (e.g., Anobile, Cicchini, & Burr, 2014; Tinelli et al., 2015) and was calculated as the number of dots in a surface area in this study. All dots were presented in an invisible circle, whose radius ranged from 100, 90, 80, 70, 60, 50, to 40 pixels (coded as 1–7, respectively).

The examples of materials for the three tasks are shown in Figure 1.

The materials were separately generated for each participant. Sixteen participants performed the numerosity-matching task, 16 participants performed the area-matching task, and the other 16 participants performed the density task.

For the matched condition, the seven types of magnitude in each task were used to construct 70 pairs of matched stimuli, with each type of magnitude being constructed 10 times. Each trial included two stimuli constructed from the same type of magnitude. For the non-matched condition, 70 pairs of non-matched stimuli were constructed, with each type of magnitude being constructed 10 times. Each trial included two stimuli constructed from different types of magnitude. The difference between codes of two stimuli in a non-matched trial was larger than two to ensure enough difference for the participants to make matched or non-matched judgment. Thus, the matched and non-matched conditions included 140 trials total. The 140 trials were repeated twice with different response modes. In the first 140 trials, the participants used the left hand for "Matched" response and the right hand for "Non-matched" response; in the second 140 trials, the participants used the left hand for "Non-matched" response and the right hand for "Matched" response. The 140 trials for each type of response mode were randomly separated into two 70-trial sessions. The trial order in each session was random for each participant. The last five trials in each session were duplicated and added to the beginning of this session to habituate the participants to the task. Thus, each session included 75 trials, although the beginning five trials were excluded from analyses.

Procedure

The participants were randomly divided into three groups, each group performing a different task. Each task included four sessions of a delayed matching paradigm. For the numerosity-matching task, the participants were asked to judge whether two sequentially presented dot arrays had the same or different numbers of dots. For the area-matching task, the participants were asked to judge whether two sequentially presented nonidentical pentagons had the same or different sizes. For the density-matching task, participants were asked to judge whether two sequentially presented dot arrays had the same or different densities.

The participants were seated in a sound-attenuated room and faced a screen 60 cm away. All stimuli were presented visually in black at the center of the screen against a gray background. In each trial, a dot array or pentagon was first presented for 200 ms, followed by a 1,300 ms blank screen. A second dot array or pentagon was then presented at the same location as that of the first stimulus and remained on the screen until the participants made a judgment of either "Matched" or "Non-matched." After response and a 2,000 ms blank, the next trial began. The participants were encouraged to respond as quickly and accurately as possible.
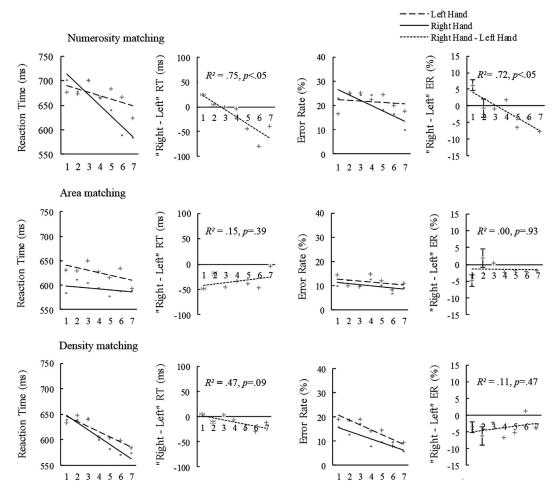
Figure 2. SNARC-like effect for numerosity and no SNARC-like effects for area and density in the matching tasks. The X-axis 1–7 stands for the gradually-increased magnitude.

There was a practice session before the first session of each response mode. There were thus two practice sessions for each participant. The practice sessions were similar in materials and procedure as the formal testing sessions, except that the participants were given feedback in the practice sessions. For correct responses, the words "Could you go faster?" were presented. For incorrect responses, the words "Error! Try again" were presented. Each practice session included 10 trials (5 matched trials and 5 non-matched trials).

Results

Only matched trials were analyzed for SNARC-like effects in the numerosity-, area-, and density-matching tasks. Non-matched trials were not analyzed, because responses could not be exclusively attributed to the first or the second stimulus. The three-standard-deviations convention was used to trim reaction times (RT) of correct trials for each

subject. Approximately 0.8% trials were discarded, because the reaction times were three standard deviations above or below individual subjects' mean reaction time. Error rates (ER) were arcsin-transformed to approximate normal distribution. Figure 2 shows mean reaction times and error rates by response hand (left and right) and magnitude (codes 1–7) for each task (i.e., numerosity, area, and density).

ANOVAs on Reaction Time and Error Rates

The ANOVAs were conducted to examine whether there was an interaction effect between response hand and magnitude, which can indicate the presence of the SNARC effect. Table 1 shows reaction times and error rates of correctly matched trials by hand (left and right), magnitude (small magnitude: codes 1–3; large magnitude: codes 5–7), and task (numerosity, area, and density) (see the Electronic Supplementary Material ESM 1 for raw data). Reaction times were entered into a three-way mixed-effect ANOVA, with hand (left and right) and magnitude (small and large)

Table 1. Reaction times (milliseconds) and error rates (percentage) by response hand, size, and task (standard error in parentheses)

Hand	Size	Numerosity		Area		Density	
		RT	ER	RT	ER	RT	ER
Left	Small	684 (36)	22.2 (3.2)	635 (36)	11.4 (3.2)	594 (36)	10.7 (3.2)
	Large	657 (43)	20.6 (3.5)	614 (43)	10.2 (3.5)	639 (43)	18.9 (3.5)
Right	Small	692 (41)	23.6 (2.6)	597 (41)	10.5 (2.6)	575 (41)	8.2 (2.6)
	Large	600 (42)	14.7 (3.1)	584 (42)	8.4 (3.1)	642 (42)	15.1 (3.1)

Notes. RT = reaction time, ER = error rate.

as within-subject variables and task (numerosity, area, and density) as the between-subject variable. The two-way interaction of magnitude and task was significant, $F(2, 45) = 17.80$, $p < .001$, $\eta_p^2 = .44$, as well as the three-way interaction, $F(2, 94) = 3.67$, $p = .033$, $\eta_p^2 = .14$. No main or other interaction effect was found. Simple effect tests on the three-way interaction showed that for the numerosity-matching task, left-hand response had no difference between small and large magnitude, $F(1, 47) = 2.02$, $p = .162$, $\eta_p^2 = .141$, and that right-hand response was associated with faster response to large than to small magnitude, $F(1, 47) = 18.71$, $p < .001$, $\eta_p^2 = .66$. This reversed magnitude effect for the right hand was shown only in the numerosity-matching task. Considering that the effect might be confounded by the bias of the right hand to larger numerosity, we collapsed responses from both hands and found that the reversed numerosity size effect remained significant, $F(1, 15) = 25.67$, $p < .001$, $\eta_p^2 = .631$.

For the area-matching task, no difference between small and large areas was found for either the left hand, $F(1, 47) = 1.45$, $p = .235$, $\eta_p^2 = .128$, or the right hand, $F(1, 47) = .45$, $p = .507$, $\eta_p^2 = .025$. For the density-matching task, faster responses to large density than to small density were found for both the left hand, $F(1, 47) = 4.76$, $p = .046$, $\eta_p^2 = .240$, and the right hand, $F(1, 47) = 11.54$, $p = .004$, $\eta_p^2 = .435$.

The same three-way mixed-effect ANOVA on error rates did not show any significant effect associated with hand.

T-Test on Individual SNARC-Like Slopes

Following the procedures proposed by Fias, Brysbaert, Geypens, and d'Ydewalle (1996) and Hoffmann, Mussolin, Martin, and Schiltz (2014) to calculate individual SNARC slopes, we conducted linear regression analysis on reaction times for the numerosity, area, and density tasks separately for each subject. For each task, differences of reaction times between two hands (reaction time of right hand – reaction time of left hand) for the 7 magnitude levels were used as the dependent measure, and magnitude level was used as the independent variable. Following individual subject regressions, two types of regression slopes (i.e., unstandardized and standardized coefficients, beta values) indexing

the SNARC effect for all participants were tested with one-sample *t*-tests against zero. For unstandardized coefficients, the *t*-test result was significant for the numerosity-matching task, $t(15) = -2.67$, $p = .018$, $d = .97$, but not for the area-matching task, $t(15) = .53$, $p = .605$, $d = .19$, or the density-matching task, $t(15) = .79$, $p = .441$, $d = .28$. *T*-test on beta values (standardized coefficients) which was transformed to Fisher Z was significant for the numerosity-matching task, $t(15) = -2.62$, $p = .019$, $d = .96$, but not for the area-matching task, $t(15) = .01$, $p = .994$, $d < .001$, or the density-matching task, $t(15) = 1.21$, $p = .246$, $d = .44$. Similar analyses were also conducted on error rates, but no significant effect was found.

The SNARC-Like Slopes Based on Reaction Time and Error Rate Across Participants

To clearly show the effect of manual response on the three types of stimuli, gross mean RT and ER for each magnitude level and task across participants were computed (Figure 2). Differences of RT and ER between right-hand response and left-hand response, denoted as "Right – Left" RT and "Right – Left" ER, respectively, were calculated for each magnitude level and task across participants (Figure 2). For each task, "Right – Left" RT and ER were separately entered into linear regression analyses using magnitude level as the independent variable. Figure 2 shows the regression results. The regression slope for "Right – Left" RT was $R^2 = .75$, $B = -14.61$, $t(6) = -3.89$, $p = .012$ in the numerosity-matching task, $R^2 = .15$, $B = 3.05$, $t(6) = .93$, $p = .39$ in the area-matching task, and $R^2 = .47$, $B = 4.13$, $t(6) = 2.12$, $p = .087$ in the density-matching task. The regression slope for "Right – Left" ER was $R^2 = .72$, $B = -1.85$, $t(6) = -3.40$, $p = .019$ in the numerosity-matching task, $R^2 = .00$, $B = -.035$, $t(6) = -.08$, $p = .942$ in the area-matching task, and $R^2 = .11$, $B = -.41$, $t(6) = -.77$, $p = .48$ in the density-matching task. Thus, the results show that magnitude level predicted "Right – Left" RT and ER in the numerosity-matching task but not in the area- or density-matching task.

Table 2. Correlation coefficients of ratio, visual properties, and numerosity-matching performance

	Matched trials		Non-matched trials	
	RT (p)	Error (p)	RT (p)	Error (p)
Ratio	–	–	−.146 (9E-10)*	−.262 (4E-36)*
First dots array				
Envelope area	−.088 (.0003)*	−.049 (.0210)	−.016 (.5040)	.054 (.0105)
Total area	−.117 (1E-06)*	−.049 (.0214)	−.015 (.5425)	.047 (.0277)
Diameter	.111 (4E-06)*	.045 (.0356)	−.004 (.8680)	−.042 (.0500)
Circumference	−.123 (3E-07)*	−.058 (.0061)	−.015 (.5418)	.04 (.0583)
Density	−.131 (5E-08)*	−.057 (.0076)	−.007 (.7737)	.024 (.2656)
Second dots array				
Envelope area	−.083 (.0006)*	−.050 (.0180)	.061 (.0109)	.141 (2E-11)*
Total area	−.113 (3E-06)*	−.055 (.0103)	.076 (.0014)	.139 (5E-11)*
Diameter	.112 (3E-06)*	.047 (.0275)	−.071 (.0031)	−.152 (6E-13)*
Circumference	−.123 (3E-07)*	−.056 (.0090)	.069 (.0038)	.132 (5E-10)*
Density	−.131 (3E-08)*	−.056 (.0088)	.065 (.0066)	.118 (2E-08)*

Notes. (1) Each correlation analysis was based on all trials from all participants. Reaction time or error was not averaged, because each trial had its own visual properties. There were 1,716 valid matched trials and 1,747 valid non-matched trials for the analyses on reaction time, and 2,198 valid matched trials and 2,220 valid non-matched trials for the analyses on error. (2) The two dot arrays for each matched trial have equal numerosity. Therefore matched trials could not be used to calculate partial correlation between ratio and performance (reaction time and error). (3) The alpha value was not corrected. After Bonferroni's correction for multiple comparisons (46 times of correlation = 42 times of original correlation in Table 2 + four times of correlation described in the section Roles of Visual Properties in the Numerosity-Matching Task), the .05 level significance should be $p < .0011$ in the table (marked with *).

Roles of Visual Properties in the Numerosity-Matching Task

Previous studies showed that some visual properties (e.g., total area, envelope area or convex hull, diameter, circumference, and density) might affect participants' performance in numerosity tasks (Gebuis & Reynvoet, 2011; Szűcs et al., 2013). To make sure that participants responded in the numerosity-matching task on the basis of numerosity other than visual properties, we examined whether the numerosity matching is ratio-dependent after controlling for visual properties, an approach used in previous studies as well (e.g., Starr, Libertus, & Brannon, 2013; Zhou et al., 2015).

Table 2 shows correlation coefficients of five critical visual properties and performance for the numerosity-matching task. According to Table 2, numerosity matching was indeed affected by visual properties, especially by density. However, the correlation between ratio and numerosity-matching performance (−.262) is the strongest among all the correlations shown in Table 2. Even after controlling for the five visual properties, reaction time and error in the non-matched condition were still affected by the ratio between the large numerosity and the small numerosity. The correlation between ratio and reaction time for each non-matched trial was .089 ($p = .0002$), and the correlation between ratio and error for each non-matched trial was .168 ($p = $ 2E-15). The result suggests that numerosity-matching performance is partially based on numerosity other than visual properties.

After Bonferroni's correction for multiple comparisons, the partial correlation remained significant (see the note of Table 2). The results suggest that performance in the numerosity-matching task is ratio-dependent, which is the signature of ANS (e.g., Jones & Brannon, 2012; Zhou et al., 2015). The partial correlation analysis could not be conducted on the matched trials because the dot arrays in a trial had the same numerosity.

The reversed size effect on reaction time for matched trials was $r(1,712) = −.124$, $p = $ 2E-7, which is consistent with the effect found in the ANOVA (2 hand × 2 magnitude × 3 task) on reaction time introduced above. The effect, however, disappeared after controlling for the impacts of density of the first and the second dot arrays, $r(1,712) = .041$, $p = .093$.

Discussion

The present study was aimed to investigate whether numerosity could be spatially organized in a way resembling a number line in human memory. By using a numerosity-matching task, this study demonstrated the existence of SNARC-like effects for numerosities from 11 to 29 in the approximate number system. In contrast, no SNARC-like effect was found for area- or density-matching task. The results suggest that numerosity-based quantities in human's approximate number system can be autonomously mapped onto a left-to-right oriented mental line.

The current study used the item-matching paradigm for the spatial matching of numerosity in ANS. The item-matching paradigm has been used to show holistic spatial representations of two-digit numbers (Zhou et al., 2008), and hence it was one of the tasks that can be used for both nonsymbolic and symbolic numbers in studies of mapping of number and space.

The Mental Numerosity Line in the Approximate Number System

This study shows that in a numerosity-matching task, the participants responded more quickly to large numerosities using the right hand and more quickly to small numerosities using the left hand. This result is consistent with the SNARC effect (Dehaene et al., 1993) and indicates the existence of a left-to-right oriented mental numerosity line in the approximate number system. The preference for the left-to-right oriented numerosity line to those of other orientations is consistent with results from both animal and human studies. Animal studies have shown that animals (e.g., monkeys, chicks) preferred a left-to-right layout of elements (Drucker & Brannon, 2014; Rugani, et al., 2010). Preschool children were shown to have better performance at finding an object hidden in a numbered compartment when the compartment numbers increased from left to right rather than from right to left (Opfer & Furlong, 2011; Opfer, Thompson, & Furlong, 2010). de Hevia et al. (2014) and Bulf et al. (2015) also showed human infants' preference for left-to-right oriented increasing number sequences. Combining these evidence, it appears that the left-to-right spatial layout of the mental numerosity line may have deep roots in human and animal mind.

Several previous studies also investigated the spontaneous mapping of numerosity and space. These studies, however, typically are different from the present study in at least one of two aspects. First, some studies presented ordered numerosity, which could hint the participants to order numerosity or to access memory of ordered numerosity (e.g., de Hevia & Spelke, 2010; Patro & Haman, 2012). Second, some studies used numerosities with number of items covering both subitizing (e.g., fewer than or equal to four items) and counting (e.g., more than four items) ranges (e.g., Bulf et al., 2014; Luccio et al., 2012; Mitchell et al., 2012; Nuerk et al., 2005; Patro & Haman, 2012). Subitizing is a preattentive, automatic process (e.g., Trick & Pylyshyn, 1993, 1994). Numerosities in the subitizing range are easy to be mapped into symbolic numbers. For example, Bulf et al. (2014) used dot arrays including 2 or 9 dots, and the number of dots in Mitchell et al. (2012) and Nuerk et al. (2005) ranged from 1 to 9. The participants in Nuerk et al.'s study (2005) were also asked to perform

obligatory transcoding from visual dice patterns to specific numerals. Thus, the participants in these studies could have mapped numerosities in the subitizing range to symbolic numbers, instead of using the approximate number system to make judgments. To address these issues, the present study did not present ordered numerosity, and it used only numerosities in the counting range (11–29) to avoid potential confounding factors from the symbolic number system.

It is also possible that the participants used a translation strategy to enumerate the dot arrays and relied on the exact symbolic number system to perform the tasks. This possibility, however, does not appear to be likely, given that the first dot array in the current study was presented for only 200 ms, which was too brief for the participants to count individual dots. Thus, the participants had to rely on the approximate number system (ANS) to estimate the numbers of dots. Number sense from using the ANS could then lead to the spatial layout of dot arrays in the mind.

The studies that investigated the spatial mapping of numerosities beyond the subitizing range produced inconsistent results. Luccio et al. (2012) showed spatial mapping of numerosities in the counting range (7–23 dots in dot arrays) in an attention shift paradigm. In contrast, Mitchell et al. (2012) did not find spatial mapping effect for numerosities in the counting range (6–9) in either an orientation decision or an attention shift paradigm. Patro and Haman (2012) also did not show the effect for 5–10 items in a numerosity comparison task. Combining these studies and the current investigation, it is possible that spatial mapping of numerosity could be observed only where the numerosities cover a large range, such as 11–29 in the current study and 7–23 in Luccio et al. (2012). Future study could directly examine the possibility.

The current study also showed evidence of impacts of visual properties in the numerosity-matching task. Reversed size effect was found in both the numerosity- and the density-matching tasks. Given that dot arrays with large numerosity also had large density, it is possible that the reversed size effect for the numerosity-matching task was due to reversed size effect for density. This possibility appears likely, because, the reversed size effect for numerosity disappeared after impacts of five typical visual properties, including density, were controlled for (Gebuis & Reynvoet, 2011). The result suggests that participants could make decision at least partially according to the visual properties.

Although the numerosity-matching task could be affected by dot density, no SNARC-like effect was found for the density-matching task in which density was directly manipulated. Meanwhile, performance in the numerosity-matching task was still ratio-dependent even after impacts of all five typical visual properties were controlled for. Thus, the spatial representation of numerosity may have little relation with density. Additionally, the SNARC-like effect

is an automatic effect. Even if participants could make a matching judgment solely based on some visual properties, the automatic SNARC-like effect associated with nonsymbolic numerical quantity could still be observed. Thus, the left-to-right oriented spatial representation of numerosity can be independent from the impacts of density in the numerosity-matching task.

The Dissociation of Spatial Representations for Discrete and Continuous Magnitude

The current investigation showed a dissociation between discrete (e.g., numerosity) and continuous (e.g., size, density) magnitudes regarding their spatial representations. SNARC-like effects were found only for numerosity, but not for size or density. This result is consistent with a similar dissociation found in infants (Bulf et al., 2015). However, some continuous stimuli, such as pitch, were shown to exhibit an organized spatial representation (e.g., Lidji et al., 2007; Rusconi, Kwan, et al., 2006). Thus, it appears that the dissociation between numerosity and size/density is not due to the distinction between discrete and continuous stimuli, but rather likely due to learning experience. When children acquire verbal or written symbolic numbers, the learning experience typically involves discrete objects. The experience could be helpful for children to form left-to-right oriented alignment of numerosity. In contrast, area and density were seldom used to help children learn symbolic numbers (e.g., Arabic digits). Meanwhile, the continuous magnitude such as physical size can be used as index to order objects, but the direction could be bidirectional – either smaller or larger size could be placed on the left. Thus, the experience with area and density could not be helpful to form a long-term fixed spatial mapping on the magnitude. Notably, this hypothesis does not deny the impact of short-term experience on spatial-numerical associations. For example, van Dijck and Fias (2011) showed that short-term experience on the ordering of objects (such as in working memory) could affect the spatial-numerical associations. The spatial-numerical association formed through short-term experience, however, may need repeated reinforcement to be consolidated into long-term memory.

Based on this hypothesis, people may form long-term association between spatial representation and any type of stimulus, as long as they receive enough exposure to this type of stimulus in an organized, oriented manner. For example, pitch in music could be typically practiced in sequences, such as singing or playing a musical instrument in pitch sequences from low to high or high to low frequencies. Rusconi, Kwan, et al. (2006) found that only musicians had spontaneous left-to-right representation of pitch, likely due to training on musical instruments like piano, which consists of left-to-right sequences of keys. Likely due to these exposures, pitch was shown to be associated with spatial representations in human (Lidji et al., 2007; Rusconi, Umilta, et al., 2006). Thus, experience would be important for the presence of common quantity representations as suggested by Cohen Kadosh, Lammertyn, and Izard (2008) and Walsh (2003).

Conclusion

This study shows that an autonomous left-to-right oriented mental numerosity line can be observed in human's approximate number system. The autonomously-activated left-to-right oriented quantity-space mapping could only be found for numerosity other than for area size or density in an item-matching paradigm. It seems that only discrete variables (e.g., numerosity) other than continuous variables (i.e., area size and density) lead to spatial layout of objects in the item-matching paradigm, though the continuous magnitudes (e.g., area size, pitch) could have spatial layout in some other tasks (e.g., Ren et al., 2011; Rusconi, Umilta, et al., 2006; Shaki et al., 2012). The mapping between numerosity and space may be related to people's extensive experience in numerosity presented in sequences through either preverbal or verbal learning. The question whether symbolic numbers mediate the mental numerosity line in the approximate number system is worthwhile to explore in future studies.

Electronic Supplementary Materials

The electronic supplementary material is available with the online version of the article at http://dx.doi.org/10.1027/1618-3169/a000324

ESM 1. Data file (sav).
Raw data.

References

Agrillo, C., Dadda, M., & Bisazza, A. (2007). Quantity discrimination in female mosquitofish. *Animal Cognition, 10*, 63–70. doi: 10.1007/s10071-006-0036-5

Agrillo, C., Dadda, M., Serena, G., & Bisazza, A. (2009). Use of number by fish. *PLoS One, 4*, e4786. doi: 10.1371/Journal.Pone.0004786

Anobile, G., Cicchini, G. M., & Burr, D. C. (2014). Separate mechanisms for perception of numerosity and density. *Psychological Science, 25*, 265–270. doi: 10.1177/0956797613501520

Brannon, E. M., & Terrace, H. S. (1998). Ordering of the numerosities 1 to 9 by monkeys. *Science, 282*, 746–749. doi: 10.1126/science.282.5389.746

Brannon, E. M., Wusthoff, C. J., Gallistel, C. R., & Gibbon, J. (2001). Numerical subtraction in the pigeon: Evidence for a linear subjective number scale. *Psychological Science, 12*, 238–243. doi: 10.1111/1467-9280.00342

Bueti, D., & Walsh, V. (2009). The parietal cortex and the representation of time, space, number and other magnitudes. *Philosophical Transactions of the Royal Society B-Biological Sciences, 364*, 1831–1840. doi: 10.1098/rstb.2009.0028

Bulf, H., de Hevia, M. D., & Macchi Cassia, V. (2015). Small on the left, large on the right: Numbers orient visual attention onto space in preverbal infants. *Developmental Science, 19*, 1–8. doi: 10.1111/desc.12315

Bulf, H., Macchi Cassia, V., & de Hevia, M. D. (2014). Are numbers, size, and brightness equally efficient in orienting visual attention? Evidence from an eye-tracking study. *PLoS One, 9*, e99499. doi: 10.1371/journal.pone.0099499

Butterworth, B. (1999). *The mathematical brain*. London, UK: Macmillan.

Cohen Kadosh, R., Lammertyn, J., & Izard, V. (2008). Are numbers special? An overview of chronometric, neuroimaging, developmental and comparative studies of magnitude representation. *Progress in Neurobiology, 84*, 132–147. doi: 10.1016/j.pneurobio.2007.11.001

de Hevia, M. D., Girelli, L., Addabbo, M., & Macchi Cassia, V. (2014). Human infants' preference for left-to-right oriented increasing numerical sequences. *PLoS One, 9*, e96412. doi: 10.1371/journal.pone.0096412

de Hevia, M. D., & Spelke, E. S. (2010). Number-space mapping in human infants. *Psychological Science, 21*, 653–660. doi: 10.1177/0956797610366091

de Oliveira Ferreira, F., Wood, G., Pinheiro-Chagas, P., Lonnemann, J., Krinzinger, H., Willmes, K., & Haase, V. G. (2012). Explaining school mathematics performance from symbolic and nonsymbolic magnitude processing: Similarities and differences between typical and low-achieving children. *Psychology & Neuroscience, 5*(1), 37.

Dehaene, S., Bossini, S., & Giraux, P. (1993). The mental representation of parity and number magnitude. *Journal of Experimental Psychology – General, 122*, 371–396. doi: 10.1037/0096-3445.122.3.371

Drucker, C. B., & Brannon, E. M. (2014). Rhesus monkeys (Macaca mulatta) map number onto space. *Cognition, 132*, 57–67. doi: 10.1016/j.cognition.2014.03.011

Fias, W., Brysbaert, M., Geypens, F., & d'Ydewalle, G. (1996). The importance of magnitude information in numerical processing: Evidence from the SNARC effect. *Mathematical Cognition, 2*, 95–110.

Fias, W., & Fischer, M. H. (2005). Spatial representation of numbers. In J. I. D. Campbell (Ed.), *Handbook of Mathematical Cognition* (pp. 43–54). New York, NY: Psychology Press.

Fischer, M. H., Castel, A. D., Dodd, M. D., & Pratt, J. (2003). Perceiving numbers causes spatial shifts of attention. *Nature Neuroscience, 6*, 555–556.

Fischer, M. H., Mills, R. A., & Shaki, S. (2010). How to cook a SNARC: Number placement in text rapidly changes spatial-numerical associations. *Brain and Cognition, 72*, 333–336. doi: 10.1016/j.bandc.2009.10.010

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

Fuhs, M. W., & McNeil, N. M. (2013). ANS acuity and mathematics ability in preschoolers from low-income homes: Contributions of inhibitory control. *Developmental Science, 16*, 136–148. doi: 10.1111/desc.12013

Galton, F. (1880). Visualised numerals. *Nature, 21*, 494–495. doi: 10.2307/2841651

Gebuis, T., & Reynvoet, B. (2011). Generating nonsymbolic number stimuli. *Behavior Research Methods, 43*, 981–986. doi: 10.3758/s13428-011-0097-5

Halberda, J., Mazzocco, M. M., & Feigenson, L. (2008). Individual differences in non-verbal number acuity correlate with maths achievement. *Nature, 455*, 665–668. doi: 10.1038/nature07246

Hoffmann, D., Mussolin, C., Martin, R., & Schiltz, C. (2014). The impact of mathematical proficiency on the number-space association. *PLoS One, 9*, e85048. doi: 10.1371/journal.pone.0085048

Inglis, M., Attridge, N., Batchelor, S., & Gilmore, C. (2011). Non-verbal number acuity correlates with symbolic mathematics achievement: But only in children. *Psychonomic Bulletin & Review, 18*, 1222–1229. doi: 10.3758/s13423-011-0154-1

Jones, S. M., & Brannon, E. M. (2012). Prosimian primates show ratio dependence in spontaneous quantity discriminations. *Frontiers in Psychology, 3*, 550. doi: 10.3389/fpsyg.2012.00550

Landerl, K., Bevan, A., & Butterworth, B. (2004). Developmental dyscalculia and basic numerical capacities: A study of 8–9-year-old students. *Cognition, 93*, 99–125. doi: 10.1016/j.cognition.2003.11.004

Lidji, P., Kolinsky, R., Lochy, A., & Morais, J. (2007). Spatial associations for musical stimuli: A piano in the head? *Journal of Experimental Psychology: Human Perception and Performance, 33*, 1189–1207.

Luccio, R., Fumarola, A., Tamburini, G., & Agostini, T. (2012). The spatial representation of non-symbolic numerical quantities. *Proceedings of Fechner Day, 28*, 321–327.

Mitchell, T., Bull, R., & Cleland, A. A. (2012). Implicit response-irrelevant number information triggers the SNARC effect: Evidence using a neural overlap paradigm. *The Quarterly Journal of Experimental Psychology, 65*, 1945–1961. doi: 10.1080/17470218.2012.673631

Nieder, A., & Dehaene, S. (2009). Representation of number in the brain. *Annual Review of Neuroscience, 32*, 185–208.

Nieder, A., Freedman, D. J., & Miller, E. K. (2002). Representation of the quantity of visual items in the primate prefrontal cortex. *Science, 297*, 1708–1711.

Nuerk, H. C., Wood, G., & Willmes, K. (2005). The universal SNARC effect: The association between number magnitude and space is amodal. *Experimental Psychology, 52*, 187–194. doi: 10.1027/1618-3169.52.3.187

Opfer, J. E., & Furlong, E. E. (2011). How numbers bias preschoolers' spatial search. *Journal of Cross-Cultural Psychology, 42*, 682–695. doi: 10.1177/0022022111406098

Opfer, J. E., Thompson, C. A., & Furlong, E. E. (2010). Early development of spatial-numeric associations: Evidence from spatial and quantitative performance of preschoolers. *Developmental Science, 13*, 761–771. doi: 10.1111/j.1467-7687.2009.00934.x

Patro, K., Fischer, U., Nuerk, H. C., & Cress, U. (2015). How to rapidly construct a spatial-numerical representation in preliterate children (at least temporarily). *Developmental Science, 19*, 126–144. doi: 10.1111/desc.12296

Patro, K., & Haman, M. (2012). The spatial-numerical congruity effect in preschoolers. *Journal of Experimental Child Psychology, 111*, 534–542. doi: 10.1016/j.jecp.2011.09.006

Ren, P., Nicholls, M. E. R., Ma, Y. Y., & Chen, L. (2011). Size matters: Non-numerical magnitude affects the spatial coding of response. *PLoS One, 6*, e23553. doi: 10.1371/journal.pone.0023553

Rugani, R., Fontanari, L., Simoni, E., Regolin, L., & Vallortigara, G. (2009). Arithmetic in newborn chicks. *Proceedings of the Royal Society B-Biological Sciences, 276*, 2451–2460. doi: 10.1098/rspb.2009.0044

Rugani, R., Kelly, D. M., Szelest, I., Regolin, L., & Vallortigara, G. (2010). Is it only humans that count from left to right? *Biology Letters, 6*, 290–292. doi: 10.1098/rsbl.2009.0960

Rugani, R., Vallortigara, G., Priftis, K., & Regolin, L. (2015). Number-space mapping in the newborn chick resembles humans' mental number line. *Science, 347*, 534–536. doi: 10.1126/science.aaa1379

Rusconi, E., Kwan, B., Giordano, B. L., Umilta, C., & Butterworth, B. (2006). Spatial representation of pitch height: The SMARC effect. *Cognition, 99*, 113–129. doi: 10.1016/j.cognition.2005.01.004

Rusconi, E., Umilta, C., & Galfano, G. (2006). Breaking ranks: Space and number may march to the beat of a different drum. *Cortex, 42*, 1124–1127. doi: 10.1016/S0010-9452(08)70224-7

Sasanguie, D., De Smedt, B., Defever, E., & Reynvoet, B. (2012). Association between basic numerical abilities and mathematics achievement. *British Journal of Developmental Psychology, 30*, 344–357. doi: 10.1111/j.2044-835X.2011.02048.x

Sasanguie, D., Gobel, S. M., Moll, K., Smets, K., & Reynvoet, B. (2013). Approximate number sense, symbolic number processing, or number-space mappings: What underlies mathematics achievement? *Journal of Experimental Child Psychology, 114*, 418–431. doi: 10.1016/j.jecp.2012.10.012

Schenkenberg, T., Bradford, D. C., & Ajax, E. T. (1980). Line bisection and unilateral visual neglect in patients with neurologic impairment. *Neurology, 30*, 509.

Shaki, S., & Fischer, M. H. (2008). Reading space into numbers – A cross-linguistic comparison of the SNARC effect. *Cognition, 108*, 590–599. doi: 10.1016/j.cognition.2008.04.001

Shaki, S., Fischer, M. H., & Petrusic, W. M. (2009). Reading habits for both words and numbers contribute to the SNARC effect. *Psychonomic Bulletin & Review, 16*, 328–331. doi: 10.3758/Pbr.16.2.328

Shaki, S., Petrusic, W. M., & Leth-Steensen, C. (2012). SNARC effects with numerical and non-numerical symbolic comparative judgments: Instructional and cultural dependencies. *Journal of Experimental Psychology: Human Perception and Performance, 38*, 515–530. doi: 10.1037/a0026729

Starkey, P., & Cooper, R. G. (1980). Perception of numbers by human infants. *Science, 210*, 1033–1035.

Starr, A., Libertus, M. E., & Brannon, E. M. (2013). Infants show ratio-dependent number discrimination regardless of set size. *Infancy, 18*, 927–941. doi: 10.1111/infa.12008

Szűcs, D., Nobes, A., Devine, A., Gabriel, F. C., & Gebuis, T. (2013). Visual stimulus parameters seriously compromise the measurement of approximate number system acuity and comparative effects between adults and children. *Frontiers in Psychology, 4*, 444. doi: 10.3389/fpsyg.2013.00444

Tamburini, G., Fumarola, A., Luccio, R., & Agostini, T. (2012). Is there a spatial representation of non-symbolic numerical quantities? *Perception ECVP abstract, 41*, 144–144.

Tinelli, F., Anobile, G., Gori, M., Aagten-Murphy, D., Bartoli, M., Burr, D. C., ... Morrone, M. C. (2015). Time, number, and attention in very low birth weight children. *Neuropsychologia, 73*, 60–69.

Trick, L. M., & Pylyshyn, Z. W. (1993). What enumeration studies can show us about spatial attention: Evidence for limited capacity preattentive processing. *Journal of Experimental Psychology: Human Perception and Performance, 19*, 331–351. doi: 10.1037/0096-1523.19.2.331

Trick, L. M., & Pylyshyn, Z. W. (1994). Why are small and large numbers enumerated differently – A limited-capacity preattentive stage in vision. *Psychological Review, 101*, 80–102.

Uller, C., Jaeger, R., Guidry, G., & Martin, C. (2003). Salamanders (Plethodon cinereus) go for more: Rudiments of number in an amphibian. *Animal Cognition, 6*, 105–112. doi: 10.1007/s10071-003-0167-x

van Dijck, J. P., & Fias, W. (2011). A working memory account for spatial-numerical associations. *Cognition, 119*, 114–119. doi: 10.1016/j.cognition.2010.12.013

Walsh, V. (2003). A theory of magnitude: Common cortical metrics of time, space and quantity. *Trends in Cognitive Sciences, 7*, 483–488.

Wood, G., Willmes, K., Nuerk, H. C., & Fischer, M. H. (2008). On the cognitive link between space and number: A meta-analysis of the SNARC effect. *Psychology Science Quarterly, 50*, 489–525.

Wynn, K. (1992). Addition and subtraction by human infants. *Nature, 358*, 749–750.

Zebian, S. (2005). Linkages between number concepts, spatial thinking and directionality of writing: The SNARC effect and the REVERSE SNARC effect in English and in Arabic monoliterates, biliterates and illiterate Arabic speakers. *Journal of Cognition and Culture, 5*, 165–190. doi: 10.1163/1568537054068660

Zhou, X., Chen, C., Chen, L., & Dong, Q. (2008). Holistic or compositional representation of two-digit numbers? Evidence from the distance, magnitude, and SNARC effects in a number-matching task. *Cognition, 106*, 1525–1536. doi: 10.1016/j.cognition.2007.06.003

Zhou, X., & Cheng, D. (2015). When and why numerosity processing is associated with developmental dyscalculia. In S. Chinn (Ed.), *The Routledge international handbook of dyscalculia and mathematical learning difficulties* (pp. 78–89). New York, NY: Routledge.

Zhou, X., Wei, W., Zhang, Y., Cui, J., & Chen, C. (2015). Visual perception can account for the close relation between numerosity processing and computational fluency. *Frontiers in Psychology, 6*, 1364. doi: 10.3389/fpsyg.2015.01364

Zorzi, M., Priftis, K., & Umilta, C. (2002). Brain damage – Neglect disrupts the mental number line. *Nature, 417*, 138–139. doi: 10.1038/417138a

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