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Brief article

Flexible spatial mapping of different notations of numbers in Chinese readers

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Abstract

The spatial component of numerical and ordinal information has been explored in previous research. However, how such mapping emerges and how it is affected by the learning experience are issues still under debate. In the current study, we examined the orientation of the mental number line for different numerical notations (e.g., "1", "一", "壹") in Chinese readers. Our data demonstrated that Arabic numbers are mentally aligned horizontally with a left-to-right directionality, while Chinese number words are aligned vertically with a top-to-bottom directionality. These findings indicate that different notations of the same concept have flexible mappings within space, which is plausibly shaped by the dominant context in which the numerical notations appear.

Keywords: The SNARC effect; Mental number line; Chinese reading/writing system; Numerical cognition; Parity judgment

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1. Introduction

The original report of the SNARC effect (Spatial Numerical Association Response Code) (Dehaene, Bossini, & Giraux, 1993) showed that in a parity judgment task, small numbers were responded to faster with the left hand while large numbers were responded to faster with the right hand. It was also found that the SNARC effect was not obtained in sequential stimuli, such as letters, when the ordinal information is not required to perform the task (Dehaene et al., 1993). However, a recent report has demonstrated the association between order (e.g., letters of the alphabet and months of the year) and space (Gevers, Reynvoet, & Fias, 2003). Although it is still under debate that numbers are aligned in the mental space due to their underlying magnitude or order, these and other similar findings (e.g., Fias, Brysbaert, Geypens, & d'Ydewalle, 1996; Nuerk, Wood, & Willmes, 2005) have consistently demonstrated that small to large numbers are mapped onto an abstract mental line with the left-to-right orientation.

Despite the clear indication of a close correspondence between numbers and space, the directionality of the mapping seems to be subject to the influence of the reading/writing experience. Dehaene et al. (1993) found that the magnitude of the SNARC effect was modulated by the number of years for which Iranian participants, who were used to reading text from right to left, had been exposed to French, whose text was printed from left to right. Zebian (2005) also demonstrated that the orientation of the mental number line was modified by the cultural artifact of writing. Lebanese illiterates who only read numerals showed no SNARC effect, while the reserved SNARC effect was found in Arabic monoliterates who only read text from right to left and weakened in Arabic-English biliterates. These previous reports imply a general number line underlying different numerical notations, despite the flexibility of its spatial mapping and subjectivity to the influence of the reading/writing experience.

Ito and Hatta (2004) examined the mental alignment of Arabic numbers in Japanese participants by asking them to perform parity judgment. In addition to reporting the typical horizontal SNARC effect, they also observed a bottom-to-top mapping of small to large numbers in the same population. Although this finding is consistent with the spatial metaphor of magnitude being "added up", the authors did not find the same behavioral pattern in the task of magnitude comparison. Hence, Ito and Hatta argued that it was the information of parity rather than magnitude of numbers being mapped onto space. However, it is not obvious that why the parity information should be aligned both horizontally and vertically with certain orientations. Moreover, the orientation of the vertical number line (i.e., bottom-to-top) is opposite to the dominant writing direction in Japanese participants, which is from top to bottom. Further evidence is needed to resolve the puzzling findings from participants with different cultural experience.

To investigate the influence of a reading/writing system on the spatial component of numbers and to further examine whether such influence applies to all notations of numbers, we employed Chinese numerical words as well as Arabic digits to study the orientation of the mental number line in a parity judgment task. For readers in Taiwan, Arabic numbers are printed horizontally in text. On the other hand, Chinese characters (including number words) appear in vertical text with a top-to-bottom directionality dominantly (i.e., in over 60% of printed books), though horizontal text is also common. If the mapping between space and the concept behind different notations of numbers has an intrinsic, "default" orientation, both Arabic numbers and Chinese number words should be mentally aligned in a similar way. If the mapping between numbers and space is flexible and determined by experience/context, however, we would expect to detect the SNARC effect with different directions for different numerical notations in the same group of participants.

2. Experiment 1: horizontally aligned manual responses

2.1. Methods

Thirty right-handed graduate and undergraduate students from National Central University and National Yang-Ming University in Taiwan were tested. All of them were native speakers of Chinese (age range: 19–30) with normal or corrected-to-normal vision. All participants have been exposed to English text no later than age 13 when they entered the high school.

The participants were instructed to make a parity judgment on numbers with their hands aligned horizontally. Numbers (0–9) in three notations (Arabic numbers, Chinese numerical words in the simple form (e.g., 一) and in the complex form (e.g., 壹,)) were employed as stimuli. According to the database of Hong Kong, Mainland China & Taiwan Chinese Character Frequency (Ho, 1998), which includes 657813 characters that consists of 4846 character tokens, all the Chinese number words in the simple form are among the most frequent 330 characters (rank order: 2–330), while the Chinese number words in the complex form are less frequent (rank order: 540–4766). The latter numerical notion is actually only used in formal financial transactions (e.g., writing checks) nowadays.

Every number in each notation was presented 10 times in two kinds of response assignment (explained below), which resulted in 600 trials in total. In each trial, a fixation cross appeared for 300 ms. Following the fixation, the stimulus appeared until the participant made a parity judgment via a manual response or the time limit (1000 ms) was reached. For half of the trials, the participants had to indicate whether the stimulus was an odd or even number by pressing the left-most or right-most button on the response box via their left or right index finger, respectively. For the other half of the trials, the assignment of the manual responses was reversed. The order of the response assignment was counterbalanced across participants. There was an inter-trial interval of 1000 ms.

2.2. Results and discussion

The trials with incorrect responses (7.2%) and erratic reaction times (i.e., more than two standard deviations from the mean) (3.9%) were removed from further analyses. There was no trade-off between speed and accuracy, as indicated by a positive correlation between the mean reaction time and the error rate among participants ($r = 0.34$, $p = 0.008$). A 3 (notation: Arabic, Chinese numerical words in the simple and complex form) $\times$ 2 (magnitude category: 0–4, 5–9) $\times$ 2 (parity: odd and even) $\times$ 2 (responding hand: right and left) repeated analysis of variance (ANOVA) was performed on the remaining reaction times.

The ANOVA revealed a significant notation effect, $F(2, 58) = 68.4$, MSE = 4348, $p < 0.0001$, showing that Arabic numbers were responded to the fastest ($M = 496$ ms), followed by Chinese numerical words in the simple form ($M = 507$ ms) and in the complex form ($M = 562$ ms). The main effect of parity was also significant, $F(2, 29) = 6.80$, MSE = 1235, $p = 0.014$, indicating faster responses to even numbers ($M = 518$ ms) than to odd numbers ($M = 525$ ms). The other main effects of the magnitude category and the responding hand were not significant (ps > 0.11). Most importantly, the interaction between the magnitude category and the responding hand (i.e., the SNARC effect) reached significance, $F(2, 29) = 4.99$, MSE = 1031, $p = 0.033$. Furthermore, the triple interaction between these two factors and the factor of notation was also significant, $F(2, 58) = 3.59$, MSE = 718, $p = 0.034$, reflecting a more pronounced SNARC effect in Arabic numbers than in Chinese numbers. Post-hoc analyses confirmed this finding: when the data were analyzed in the three notations separately, the SNARC effect was only detected in Arabic numbers ($F(1, 29) = 12.88$, MSE = 728, $p = 0.001$), but not in the other two kinds of Chinese numerals (ps > 0.36).

We also employed regression analyses below to further examine the SNARC effect. To perform the regression analysis, we first obtained the reaction time difference (dRT) between two responding hands for every number in each notation by subtracting the reaction time of the left hand from that of the right hand to the same stimulus. These dRTs were then submitted to regression analyses. If small numbers are responded to faster with the left hand while large numbers are responded to faster with the right hand, a negative slope from small to large numbers should be detected, signifying the typical SNARC effect. Consistent with the results of the ANOVA, the regression analyses revealed a significant SNARC effect only in Arabic numbers, $B = -4.10$, $t(29) = -3.32$, $SD = 12$, $p = 0.001$, but not in the other two notations, ps > 0.36 (see Fig. 1a–c).

In summary, Chinese participants only map Arabic numbers but not Chinese numbers onto a horizontal mental line with a left-to-right orientation. In the next experiment, we examined whether the SNARC effect of the three notations would be expressed along a vertical number line.

3. Experiment 2: vertically aligned manual responses

3.1. Methods

Thirty new participants were recruited from the same pool as Experiment 1. All of the stimuli and procedures were identical to Experiment 1, except for the following

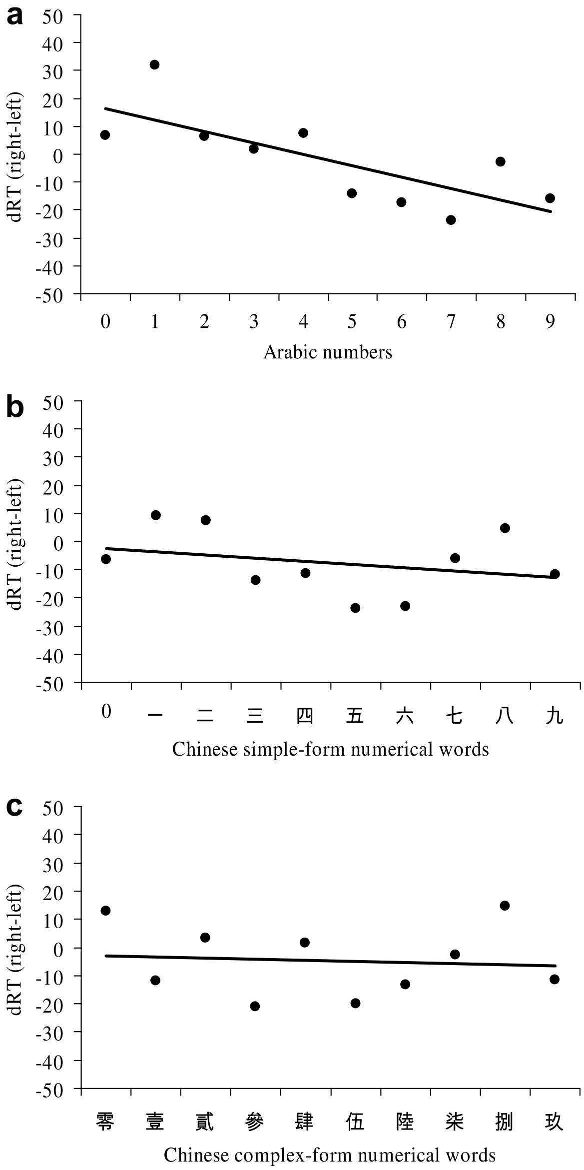

Fig. 1. Mean reaction time differences between the right- and left-handed responses of 10 numbers in (a) Arabic digits, (b) Chinese simple-form numerical words, and (c) Chinese complex-form numerical words from Experiment 1.

changes. First, the response keys were vertically rather than horizontally aligned. Every participant performed two sessions of parity judgment. In one session, the participants pressed the top (i.e., “7”) and bottom (i.e., “n”) key on a standard keyboard to indicate an odd and even number, respectively. In the other session, the key assignment was reversed. Second, throughout the experiment, half of the participants used their left hand to press the top key and their right hand to press the bottom key, while the other half of the participants used a reversed hand assignment. Both the order of the responding-key assignment and the hand position were counterbalanced across participants.

3.2. Results and discussion

The trials with incorrect responses (7.8%) and erratic reaction times (3.9%) were removed from further analyses. There was no trade-off between speed and accuracy, as indicated by a positive correlation between the mean reaction time and the error rate among the participants ($r = 0.39$, $p = 0.002$). A 3 (notations: Arabic, Chinese numerical words in the simplified form and in the complex form) × 2 (magnitude category: 0–4, 5–9) × 2 (parity: odd or even) × 2 (side of response: top and bottom) repeated ANOVA with the assignment of hand position as a between-participant variable was performed on the remaining data.

Similar to Experiment 1, the reaction times were the fastest to Arabic numbers (497 ms), followed by that to Chinese numerical words in the simple form (520 ms) and to Chinese numerical words in the complex form (584 ms) ($F(2, 56) = 110.65$, $\text{MSE} = 4418$, $p < 0.0001$). The participants pressed the top key (529 ms) faster than the bottom key (538 ms), $F(1, 28) = 5.7$, $\text{MSE} = 2292$, $p = 0.024$. Responses to the large numbers (536 ms) were marginally slower than to the small numbers (532 ms), $F(1, 28) = 3.6$, $\text{MSE} = 814$, $p = 0.068$, while no difference was observed between responses to odd and even numbers ($p > 0.53$). Different from Experiment 1, no interaction among these factors were detected (ps > 0.23).

The lack of significant interaction between numbers and the side of responding hand in the previous ANOVA might be due to the variances from other factors which mask the SNARC effect. As clearly pointed out by Fias et al. (1996), the regression analysis which detects the SNARC effect as a main effect of linear correlation between numbers and dRTs is more appropriate in capturing the spatial mapping of numbers than the ANOVA which detects the same effect as an interaction between numbers and responding hands. Other reports have also employed this sensitive measure to document the SNARC effect (e.g., Fischer, Warlop, Hill, & Fias, 2004; Ito & Hatta, 2004). Following these examples in the previous literature, we continued the examination of the current data with the regression analysis.

Similar regression analyses as in Experiment 1 were conducted, with the dRT being obtained by subtracting the reaction time of pressing the top key from that of pressing the bottom key, irrespective of the responding hand, for each number in each notation (see Fig. 2a–c). Given that the slopes of the regression lines did not differ between different assignments of the hand positions across the three notations (ps > 0.6), this factor was excluded from further analyses. The regression analyses on these dRTs showed a vertical SNARC effect only in Chinese numerical words in the simple form, $B = -3.61$, $t(29) = -2.36$, $p = 0.019$, $SD = 10.37$, but not in the other two notations (ps > 0.25).

In sharp contrast with the lack of spatial mapping of Chinese numerical words in the simple form in Experiment 1, the results from Experiment 2 indicated that numbers in this notation were mapped onto a top-to-bottom orientation more strongly

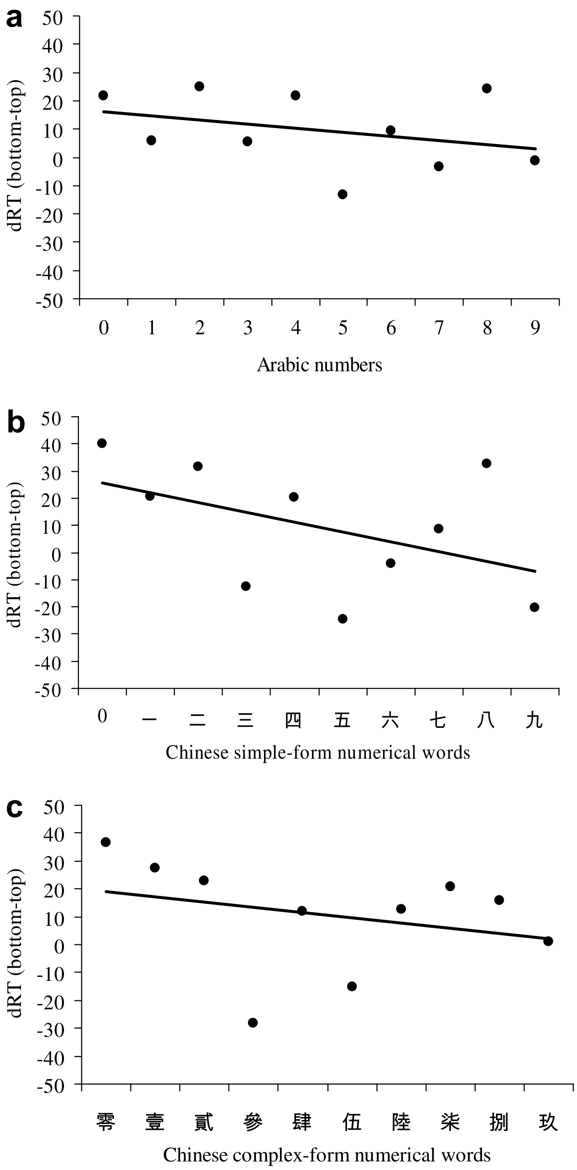

Fig. 2. Mean reaction time differences between the top and bottom manual responses across different numbers in (a) Arabic digits, (b) Chinese simple-form numerical words, and (c) Chinese complex-form numerical word from Experiment 2.

than the other two notations. This finding suggests that the mapping between numbers and space is influenced, if not determined, by the dominant reading/writing experience. As for complex Chinese number words, the lack of any kind of spatial mapping in both Experiment 1 and 2 is likely due to the unfamiliarity of these materials, as indicated by their low frequency in printed text (see Section 2.1).

4. General discussion

The results from the current study revealed that Chinese participants mentally map Arabic numbers onto a left-to-right line, while Chinese number words (in their simple form) are represented vertically with a top-to-bottom orientation. The different orientations of the mental number lines are consistent with the dominant context in which the numerical materials are often encountered. In line with the previous literature (e.g., Dehaene et al., 1993; Zebian, 2005), these findings support the influence from reading/writing experience on the mapping between numbers and space in a notation specific fashion in the same group of participants.

To account for the flexible spatial alignment of different notations of numbers, we hypothesize that the (numerical and/or ordinal) concept behind numbers is mapped onto space readily, though the orientation of such mapping is determined by experience. Zebian (2005) reported a similar effect in Lebanese participants, whose experience with a right-to-left writing system modulated the strength of a reversed SNARC effect in making oral responses of same–different judgments on pairs of east Arabic numerals that were horizontally presented. The current study extends Zebian's findings by presenting the numerical materials centrally to avoid the veridical spatial alignments of numerals. Moreover, we demonstrate that the flexible spatial mapping of numbers can be observed in different notations of the same concept. That is, the alignment of the number line is notation specific and mainly depends on the context in which the number appears. Following this reasoning, we suspect that the spatial component of a number is not equivalent to the numerical concept itself. This is also supported by the report that children do not demonstrate the SNARC effect until few years after they acquire the knowledge of numerical magnitude and parity (Berch, Foley, Hill, & Ryan, 1999), indicating a developmental lag between these two kinds of concepts.

One interesting finding of Zebian (2005) was that the reversed SNARC effect of Arabic numerals was only observed in Arabic monoliterates but not in illiterates who read numerals, although Arabic numerals are actually printed from left to right in text. Such result suggests that the influence from the dominant writing direction results in a general "bias" that shapes the orientation of the mental number line. Moreover, this context-like bias even modulates the spatial mapping of Arabic numerals that are printed in the opposite direction. This contextual effect might account for the non-significant tendency of Arabic digits being mapped onto a vertical line in the current study. For readers in Taiwan, although Arabic digits almost never appear in vertical text, the dominant experience in reading Chinese words vertically might provide a default frame accordingly. Hence, Arabic digits are clearly mapped onto a horizontal line as demonstrated in Experiment 1, while such mapping onto a vertical line is not observed in Experiment 2.

Ito and Hatta (2004) examined the mental alignment of Arabic numbers in Japanese participants and reported a horizontal as well as a vertical SNARC effect. Different from the current finding, however, they found that small numbers were associated with space at the bottom while large numbers were associated with space on top. Such pattern has also been reported in Gevers, Lammertyn, Notebaert, Verguts, and Fias (2006) and Schwarz and Keus (2004). It should be noted that, however, this bottom-to-top orientation of the number line is in the opposite direction of the dominant reading/writing experience of Japanese participants. Ito and Hatta proposed both horizontally and vertically aligned representations of the parity rather than the magnitude information of numbers to account for the data. Even when the parity information is clearly needed in the current study, however, we found no support for the bottom-to-top alignment of the number line. Instead, our results converge nicely with earlier evidence (e.g., Dehaene et al., 1993; Zebian, 2005) for the influence from cultural artifacts in showing a top-to-bottom vertical SNARC effect of Chinese number words. Further research is needed to determine whether the parity information is spatially aligned and is interacted with reading/writing experience.

The current study, together with other empirical findings in the literature, suggests that the spatial mapping of numbers is notation specific and is influenced by the context in which the numeral is embedded. Moreover, the dominant context such as the reading/writing experience might be powerful enough to bias the alignment the numbers that usually occur in a different orientation. Although the spatial component of numbers can shift covert attention (e.g., Fischer, Castel, Dodd, & Pratt, 2003) and does not necessarily require the involvement of effectors, it might not equal to the core concept of numbers, such as magnitude and parity. Further examination of the mapping between numbers and space under the impact of different cultural artifacts and in various tasks would shed light on the different aspects of numerical concepts.

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