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The spatial coding mechanism of ordinal symbols: a study based on the ordinal position effect

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Abstract
The ordinal position effect refers to a phenomenon in which items positioned early in an ordinal sequence receive a faster response with the left key than with the right key, and the opposite response pattern occurs when items are positioned later in an ordinal sequence. Previous studies have suggested that ordinal symbols are spatially represented from left to right, thus leading to the ordinal position effect; however, the spatial coding mechanism of ordinal symbols remains unclear. Therefore, the present study explored the ordinal position effect as an index to judge the spatial coding of ordinal symbols, and three experiments were performed to investigate the spatial coding mechanism of ordinal symbols. In particular, a novel transitory ordinal sequence was induced by presenting successive dots of different colors centrally (Experiment 1), from left to right or from right to left (Experiments 2 and 3), and participants were asked to memorize the successive dots in the correct order. Then, the participants were asked to press a key to provide a response corresponding to a probe dot's ordinal position (Experiments 1 and 2) or its spatial location (Experiment 3). The following results were identified: (1) The ordinal position effect occurred when responses were based on the ordinal position regardless of the presentation direction, and (2) the ordinal position effect was overridden when responses were based on the spatial locations of the ordinal symbols. From these results, we concluded that the spatial coding of ordinal symbols is flexible and that ordinal symbols are encoded depending on the specific experimental context.

Keywords SNARC effect · Ordinal position effect · Polarity · Encode · Ordinal symbol

Dehaene and colleagues presented Arabic numbers centrally and randomly on a screen and instructed participants to indicate whether the probe number was odd or even by pressing the left key or the right key on a keyboard. The results indicated that the participants responded to smaller numbers more rapidly than to larger numbers with the left key, but that they responded to larger numbers more rapidly than to smaller numbers with the right key. This phenomenon was defined as the spatial numerical association of response codes (SNARC) effect (Dehaene, Bossini, & Giraux, 1993). The SNARC effect provides direct evidence for the spatial representation of numbers and supports the concept of the mental number line, which claims that numbers are represented spatially from left to right in long-term memory according to numerical magnitude (Dehaene et al., 1993; Restle, 1970). Since that study, the SNARC effect has been regarded as an effective index that can be used to estimate whether stimuli are represented spatially, and it has been widely used in research (Cho, Bae, & Proctor, 2012; Fischer, Riello, Giordano, & Rusconi, 2013; Fumarola et al., 2014; Holmes & Lourenco, 2011; Ishihara, Keller, Rossetti, & Prinz, 2008; Kirjakovski & Utsuki, 2012; Viarouge, Hubbard, & Dehaene, 2014).

Although the SNARC effect was originally found in the processing of Arabic numbers, given that numbers can be described by both magnitude and ordinal sequences (Jacob & Nieder, 2008), Gevers et al. explored letters as ordinal symbols to investigate whether the SNARC effect could extend to the processing of ordinal symbols (Gevers, Reynvoet, & Fias, 2003). In their study, they replaced numbers with letters and instructed participants to judge where the probe letter was positioned (before or after *O*) in the alphabet by pressing a specified key on a keyboard. They observed the ordinal position effect in letter processing because letters positioned

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before *O* in the alphabet received a more rapid response with the left key than with the right key, and letters positioned after *O* received a more rapid response with the right key than with the left key. Dodd et al. replicated this ordinal position effect using a probe detection task in which a letter was positioned at the fixation point before the target stimuli, and participants were asked to press the space key as quickly as possible when they detected target stimuli. The results revealed that target stimuli presented in the left square frame received a more rapid response than those presented in the right square frame when the letters positioned before *O* in the alphabet were presented at the fixation point; conversely, target stimuli presented in the right square frame received a more rapid response than those presented in the left square frame when the letters positioned after *O* in the alphabet were presented at the fixation point (Dodd, Van der Stigchel, Leghari, Fung, & Kingstone, 2008). The occurrence of the ordinal position effect in letter processing suggested that similar to numbers, letters are also represented spatially from left to right according to their original ordinal sequence in the alphabet (Gevers et al., 2003). Recently, increasing studies have replicated the ordinal position effect in the processing of other types of ordinal symbols and have extended this effect to the processing of various types of ordinal symbols (Gevers, Reynvoet, & Fias, 2004; Ginsburg, Archambeau, Van Dijck, Chetail, & Gevers, 2017; Ginsburg, & Gevers, 2015; Huber, Klein, Moeller, & Willmes, 2016; Previtali, de Hevia, & Girelli, 2010; Treccani & Umiltà, 2011; van Dijck, Abrahamse, Majerus, & Fias, 2013; Wang, Nie, Zhang, & Shi, 2019; Zhang et al., 2016). For example, van Dijck et al. centrally and randomly presented five successive numbers from 1 to 10 on a screen during the learning stage and instructed participants to memorize these successive numbers in the order of presentation. During the test stage, a go/no-go paradigm was used in which all 10 numbers were presented; however, the participants were instructed to respond only to the numbers presented in the learning section depending on their parity. Numbers that were not previously presented were to be ignored. The results indicated that the ordinal position effect occurred in serial order processing in which retrieving early items in the presented number series facilitated a left-hand response, while later items facilitated a right-hand response. Similar results were also obtained when researchers used fruit and vegetable names in a task (van Dijck & Fias, 2011). The findings for the ordinal position effect during the processing of multiple types of ordinal symbols further strengthen evidence that ordinal symbols are represented spatially from left to right according to their original ordinal sequence. To more clearly explain how ordinal symbols are represented, Abrahamse et al. proposed the mental whiteboard hypothesis, positing that items in an ordinal sequence are bound to specific internal spatial templates, thus leading to the ordinal position effect in the processing of ordinal symbols (Abrahamse, van Dijck, & Fias, 2016; Abrahamse, van Dijck, Majerus, & Fias, 2014). The mental whiteboard hypothesis sufficiently explained the ordinal position effect in the processing of all types of ordinal symbols. In addition, further studies found that the use of internal spatial templates was very creative and flexible and easily influenced by the experiential and experimental contexts (Abrahamse et al., 2016; Abrahamse et al., 2014; Botvinick & Watanabe, 2007; Darling, Allen, & Havelka, 2017; Wang, Liu, Shi, & Kang, 2018). These findings suggest that the spatial coding of ordinal symbols may be flexible because the binding of ordinal symbols depends on the choice of internal spatial templates, which is creative and flexible. Previous studies investigated the ordinal position effect only when the ordinal sequence of ordinal symbols was used. The spatial locations of ordinal symbols were not examined in those studies. As a result, those studies could not investigate the influence of the spatial locations of ordinal symbols on the spatial coding of ordinal symbols. Several studies found that the spatial locations of numbers and letters had an important impact on number and letter representations (Bächtold, Baumüller, & Brugger, 1998; Jacob, & Nieder, 2008; Jin, Wang, & Wang, 2017; Wang, Kang, & Lan, 2015). For example, when participants imagined numbers as times on a clock, the numbers could be represented according to their spatial locations on the clock, thus reversing the SNARC effect in number processing (Bächtold et al., 1998). These studies imply that the spatial locations of stimuli have a more important influence on stimulus representations. According to these studies and the mental whiteboard hypothesis, we can speculate that the spatial locations of ordinal symbols can likely provide new internal spatial templates for participants when binding ordinal symbols and therefore influence the spatial coding of ordinal symbols, and we can then conclude that the spatial coding of ordinal symbols is very flexible and depends on the specific context. Unfortunately, few studies have investigated this probability; therefore, whether the spatial locations of ordinal symbols can influence the spatial coding of ordinal symbols remains unclear. Thus, the current study was conducted to further investigate the spatial coding mechanism of ordinal symbols when the spatial locations of ordinal symbols were induced by presenting successive dots of different colors in different presentation directions (centrally, left to right or right to left). Specifically, in Experiment 1, we centrally presented five successive dots of different colors and instructed participants to memorize the presented dot sequence in the initiating stage. In the classification stage, a probe dot was centrally presented on the screen, and the participants were asked to judge the position at which the probe dot belonged in the serial order (before or after the middle dot). When the successive dots were centrally presented, the spatial location of the ordinal symbol could not be induced. Thus, the aim of Experiment 1 was to investigate how the ordinal symbols were encoded when the spatial location of the ordinal position was ruled out. In this experiment, we can produce an original representation of ordinal symbols and obtain baseline results for comparison with those of later experiments in the current study. Previous studies suggested that ordinal symbols were represented from left to right in the mind according to ordinal sequences, which was consistent with reading and writing directions (Gevers et al., 2003, 2004; Ginsburg et al., 2017; Guida et al., 2018; Previtali et al., 2010). Considering these studies, we assumed that the ordinal position effect can occur during ordinal symbol processing in Experiment 1.

In Experiment 2, similar to Experiment 1, five successive dots of different colors were presented on the screen, and the participants were instructed to memorize the presentation sequence of these dots before a probe dot was centrally presented. Then, the participants were asked to judge the ordinal position at which the probe dot belonged (before or after the middle dot). However, five colored dots were presented on the screen from left to right or from right to left in Experiment 2 instead of the central presentation explored in Experiment 1. Although the experimental task was the same as that in Experiment 1, the presentation direction was different. This presentation format could induce the spatial locations of ordinal symbols, providing new internal spatial templates for participants when binding ordinal symbols. Thus, from this experiment, we can investigate whether the ordinal position effect was moderated by the spatial locations of ordinal symbols in a task context involving the ordinal position. Moreover, we can also deduce whether the spatial locations of ordinal symbols automatically influence the spatial coding of ordinal symbols in this experimental context.

In Experiment 3, we also presented successive dots from left to right or from right to left. The participants were instructed to memorize each dot in the correct sequence before the probe dot was presented, but they were asked to judge the spatial location at which the probe dot was presented (left or right of the middle dot) in the initiating stage instead of judging the ordinal position. The aim of Experiment 3 was to further investigate whether the ordinal position effect was moderated by the spatial locations of ordinal symbols in a spatial location classification task context, and therefore deduce how ordinal symbols were encoded in the mind in this experiment context.

Experiment 1

Method

Participants A total of 36 (22 females, 14 males, M_{age} = 21.89 years, *SD* = 2.09 years, age range: 18–28 years) university students from Shanghai Normal University in China voluntarily participated in our experiment. All of the participants were right-handed and had normal or corrected-to-normal vision. In addition, all of the participants read and wrote from left to right. No participants had a diagnosis of color blindness. They received a payment of 15 yuan RMB when they completed the experiment. Informed consent was obtained prior to the start of the experiment. The experimental protocol was approved by the Ethics Committee of the Shanghai Psychological Society (which also applies to the other experiments in the current study).

Stimuli and apparatus The stimuli consisted of five dots of different colors (red, yellow, black, blue, and green), and the visual angle at approximately 47 cm of visual distance was 2.28°. The five dots were presented in various sequences at a rate of one dot per second. The stimuli were presented on a 19-in. computer screen with a 1,024 × 768 resolution and a refresh rate of 60 Hz.

Task and procedure The experiment was conducted with E-Prime software, Version 1.0. The experimental paradigm used in Wang et al.'s (2018) study was used to induce the ordinal sequence. Specifically, the entire experimental procedure consisted of two stages: an initiating stage and a classification stage. In the initiating stage, five successive dots of different colors (e.g., red-yellow-black-blue-green) were centrally and continuously presented on the computer screen with a white background. The participants were instructed to memorize all of the dots in the correct order. Each dot was presented for 1 second. Five dots were selected in the experiment because the adult memory capacity is 7 ± 2 blocks (Baddeley, 2012; Shipstead, Harrison, & Engle, 2015). In the classification stage, a random dot among the successive dots learned in the initiating stage (with the exception of the black dot, which was always presented third) was centrally presented on the screen, and the participants were instructed to distinguish whether the probe dot was positioned before or after the middle dot in serial order by pressing the left or right key on a QWERTY keyboard as quickly and as accurately as possible. Each stage of the test was initiated after a red "+" was centrally displayed on the computer screen for 500 ms. Once the participants responded to the probe dot, a blank screen was presented for 1500 ms before the next trial started (Fig. 1). The respondents had 3 seconds to respond to each dot. The successive dot presentation sequence was as follows: red-yellow-black-blue-green, yellow-blue-black-green-red, blue-green-black-red-yellow, and green-red-black-yellow-blue. Among the five dots, the black dot was always presented third (the ordinal position of the black dot was told to the participants prior to all of the experiments in the present study, including the two subsequent experiments), whereas the remaining four dots were presented in various sequences. Each of the

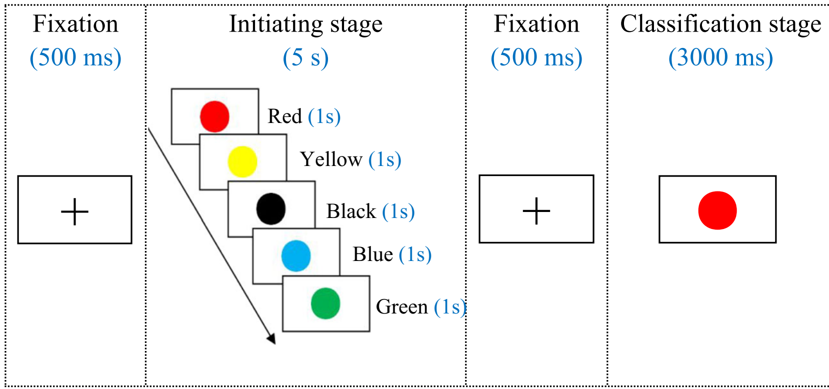

Fig. 1 Schematic of a single trial used in Experiment 1. Each trial included two stages: the initiating stage and the classification stage. Four different serial orders (red-yellow-black-blue-green, yellow-blue-black-green-red, blue-green-black-red-yellow, and green-red-black-yellow-blue) were presented in 148 trials, including 20 practice trials. (Color figure online)

remaining four dots was presented in every sequential position with an equal frequency to eliminate interference caused by a difference in the color in each position of the sequence. The experiment included two blocks. In one block, the subjects were instructed to press the left key on the keyboard with their left index finger in response to dots before the middle dot in the memory sequence, or to press the right key with their right index finger in response to dots after the middle dot in the memory sequence. In the other block, the participants were asked to press the left key with their left index finger for dots after the middle dot in the memory sequence and the right key with their right index finger for dots before the middle dot in the memory sequence. The left and right keys corresponded to the "F" and "J" keys on the QWERTY keyboard, respectively, which were covered with stickers to prevent potential confounding caused by the letters because the letters of the alphabet are also spatially coded (Gevers et al., 2003). The two blocks were balanced between the subjects. The entire experiment included 148 trials (128 trials for the formal experiment and 20 trials of practice) and lasted approximately 20 minutes. The subjects had a rest period after every 32 trials in the formal experiment. In addition, only five colored dots were presented, and the black dot was always presented third in the initiating stage in the experiment. In this context, if the participants simply remembered the first two colored dots, then they could also successfully fulfill the experimental task. Once this phenomenon occurred, the serial order could not be induced; therefore, the ordinal position effect would have been difficult to investigate in this experiment. To avoid this phenomenon, we emphasized to the participants that they must memorize all of the dots in the correct order. At the same time, to ensure that they indeed remembered all five of the colored dots in every trial, we inquired about how they thought during the experiment and whether they responded by simply remembering the first two dots in the experiment when the experiment ended. The participants responded by simply remembering that the first one or two dots were excluded. No participants were excluded from this experiment.

Results and discussion

Repeated-measures analysis of variance (ANOVA) and linear trend methods were used to investigate the ordinal position effect in this experiment. These methods have been commonly used to examine the SNARC effect and the ordinal position effect (Ginsburg & Gevers, 2015; Pinhas, Tzelgov, & Ganor-Stern, 2012). The methods consist of three steps. First, the existence of the ordinal position effect should be investigated depending on the interaction between the side of the response and the ordinal position. A significant interaction between the side of the response and the ordinal position suggests that the ordinal position effect may occur. Then, the regression analysis for dRT (the RT of the right hand minus the RT of the left hand) with the position (coded as 1–4 in the current study) as the predictor is used to examine the nature of the ordinal position effect. Finally, a one-tailed *t* test is performed to test whether the regression weight of the group deviates significantly from zero. A negative regression weight indicates that the ordinal position effect occurs, and a positive regression weight indicates that the ordinal position effect is absent.

RT analysis Errors and deviant RTs (more than three standard deviations for each treatment) were excluded from the analysis, resulting in the exclusion of 7.99% of the trials. A 2 (side of the response: left hand vs. right hand) × 4 [ordinal position: 1–4 (1 indicates that the dot was presented first, 2 indicates that the dot was presented second, 3 indicates that the dot was presented fourth, and 4 indicates that the dot was presented last in the initiating stage)] within-subject ANOVA revealed a significant main effect of ordinal position, $F(3, 105) = 16.78$, $p < .001$, $\eta^2 = 0.324$. The average RTs per position, except for the last one, increased gradually (661, 683, 767, and 715 ms for each position, respectively). Previous studies indicated that a serial search strategy is often used to retrieve sequential information in the memory, where the retrieval of early and later items is more automatic than that of middle items (Bjork & Whitten, 1974; Cornell, & Bergstrom, 1983; Guo, Zhu, & Shen, 2008). Therefore, the fact that items in the last position received a more rapid response than those in the third ordinal position in this experiment may have contributed to the high automation level in the processing of the last item. Generally, this result suggests that a serial search strategy was used in ordinal symbol processing and that the strategy was moderated by the automation level in the processing of items. No significant main effect was identified for the side of the response. A clear interaction between the side of the response and the ordinal position was identified, $F(3, 105) = 7.47$, $p < .001$, $\eta^2 = 0.176$), suggesting that the ordinal position effect may occur in this experiment. To confirm the nature of the ordinal position effect, regression analysis was performed, and the results indicated that the dRTs decreased by 48.81 ms per position and that the regression weight for position was reliably different from zero, $t(35) = -4.72$, $p < .001$, suggesting that the ordinal position effect was observed in the experiment (see Fig. 2).

Error rate analysis A 2 (side of the response: left hand vs. right hand) × 4 [ordinal position: 1–4 (1 indicates that the dot was presented first, 2 indicates that the dot was presented second, 3 indicates that the dot was presented fourth, and 4 indicates that the dot was presented last in the initiating stage]) within-subject ANOVA revealed no significant main effects in this experiment; however, a clear interaction between the side of the response and ordinal position was identified, $F(3, 105) = 4.96$, $p < .01$, $\eta^2 = 0.124$. The results suggest that the ordinal position effect may have occurred in this experiment. To confirm the nature of the ordinal position effect, regression analysis was performed, and the results indicated that the error rate decreased by 1.6% per position and that the regression weight for position was reliably different from zero, $t(35) = -2.38$, $p < .05$. The results for the error rate also suggest that the ordinal position effect was observed in the experiment (see Table 1).

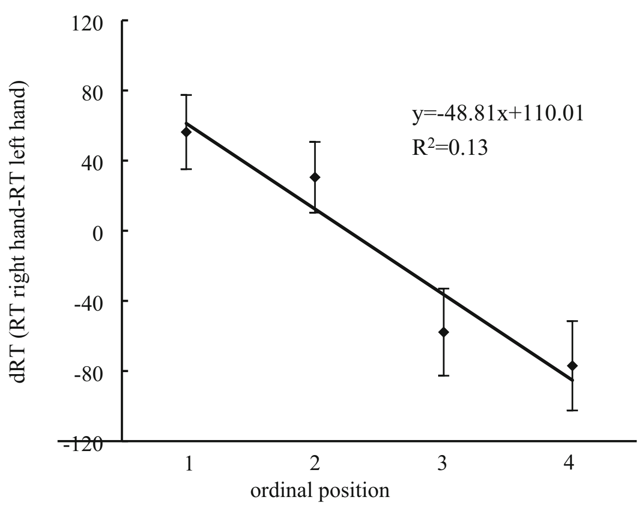

Fig. 2 The ordinal position effect was identified in ordinal symbol processing when the five successive dots were centrally presented on the screen, and the participants were asked to perform the ordinal position classification task. The error bars correspond to the standard error. R^2 corresponds to the adjusted R-squared

Table 1 Error rates (%) of the different treatment levels ($M \pm SE$)

	Position 1	Position 2	Position 3	Position 4
Left hand	3.82 ± 0.008	6.66 ± 0.013	8.68 ± 0.012	5.73 ± 0.009
Right hand	7.29 ± 0.012	5.21 ± 0.010	5.73 ± 0.012	4.51 ± 0.010

Previous studies identified the ordinal position effect in the processing of multiple types of ordinal symbols, such as letters, days, months, overlearned sequences and temporary ordinal sequences (Gevers et al., 2003, 2004; Previtali et al., 2010; van Dijck & Fias, 2011; Wang et al., 2019). These studies indicated that the occurrence of the ordinal position effect suggests that ordinal symbols, similar to numbers, are represented spatially from left to right according to their original ordinal sequence and depending on one's reading and writing habits. The results of Experiment 1 supported the ordinal position effect in the processing of ordinal symbols. Given that all participants in this experiment read and wrote from left to right, the results of this experiment further reinforce the viewpoint that mental organization of ordinal symbols is consistent with one's reading and writing habits in this experimental context.

Experiment 2

In Experiment 1, we investigated the spatial coding of ordinal symbols in the condition that the spatial locations of ordinal symbols were ruled out by centrally presented successive dots. In Experiment 2, we induced the spatial locations of ordinal symbols by presenting successive dots in the left-to-right or right-to-left direction (each presentation direction was equal and random) instead of the central presentation used in Experiment 1. Then, we still employed the ordinal position classification task to investigate whether the spatial coding of ordinal symbols was moderated by their spatial locations in the ordinal position classification task context.

Method

Participants A total of 34 university students (20 females, 14 males, $M_{age} = 24.71$ years, $SD = 3.66$ years, age range: 21–39 years) from Shanghai Normal University in China voluntarily participated in our experiment. All of the participants were right-handed and had normal or corrected-to-normal vision.

In addition, all of the participants read and wrote from left to right. No participants had a diagnosis of color blindness. They received a payment of 15 yuan RMB when the experiment ended.

Stimuli and apparatus The stimuli and apparatus were the same as those used in Experiment 1.

Procedure and task The procedure used was similar to the procedure employed in Experiment 1, with the exception of the stimulus presentation pattern. In Experiment 2, the successive dots were presented in the vertical middle of a computer screen from left to right or from right to left (the left-to-right or right-to-left presentation direction was random and equal). The horizontal spatial position of each dot was at 20%, 35%, 50%, 65%, and 80% of the screen width (the visual angles of the width relative to the central screen position were 17.06°, 8.58°, 0°, 8.58°, and 17.06° at approximately 47 cm of visual distance, respectively). The task in this experiment was to judge whether the probe dot was presented before or after the middle dot during the initiating stage.

Results and discussion

Repeated-measures ANOVA and linear trend methods were used to investigate the ordinal position effect in Experiment 2.

RT analysis Errors and deviant RTs (more than three standard deviations for each treatment) were excluded from the analysis, resulting in the exclusion of 8.87% of the trials. A 2 (side of the response: left hand vs. right hand) × 4 [(ordinal position: 1–4, 1 indicates that the dot was presented first, 2 indicates that the dot was presented second, 3 indicates that the dot was presented fourth, and 4 indicates that the dot was presented last in the initiating stage)] × 2 (presentation direction: left to right vs. right to left) within-subject ANOVA revealed a significant main effect of ordinal position, $F(3, 99) = 7.46$, $p < .001$, $\eta^2 = 0.184$. The average RTs per position, except for the last one, increased gradually (723, 757, 775, and 757 ms for each position, respectively). Similar to Experiment 1, the last position received a more rapid response than the third ordinal position, which may be attributed to the high automation level in the processing of the last item. Generally, this result also suggests that a serial search strategy was used during ordinal symbol processing and that the strategy was moderated by the automation level in the processing of the items. No other main effects were observed. In addition, a significant interaction was identified between the side of the response and ordinal position, $F(3, 99) = 8.28$, $p < .001$, $\eta^2 = 0.201$, suggesting that a stimulus–response compatibility effect occurred in this experiment (whether the stimulus–response compatibility effect can be categorized as the ordinal position effect or the Simon-like effect must be confirmed via further analysis. The Simon-like effect pertains to the corresponding relationship between the remembered previous spatial location of the probe dot during the presentation sequence and the side of the response in the present study; therefore, we temporarily call this effect the stimulus–response compatibility effect in general terms). No other interaction was observed. More notably, an interaction effect among the side of the response, ordinal position, and presentation direction was not identified in this experiment, suggesting that the presentation direction did not influence the stimulus–response compatibility effect when the participants judged whether the probe dot was presented before or after the middle dot. To further investigate the nature of the stimulus–response compatibility effect of different presentation directions and to confirm which effect (the ordinal position effect or the Simon-like effect) characterized the stimulus–response compatibility effect in this experiment, we again analyzed the stimulus–response compatibility effect in the right-to-left and left-to-right presentation directions in the subsequent regression analysis, although no significant interaction effect was found among the side of the response, ordinal position, and presentation direction. When the successive dots were presented from right to left, the dots before the middle dot were the dots located to the right of the middle dot, and the dots after the middle dot were the dots located to the left of the middle dot. In addition, when the successive dots were presented from left to right, the dots before the middle dot were the dots located to the left of the middle dot, and the dots after the middle dot were the dots located to the right of the middle dot. Therefore, the ordinal position effect and Simon-like effect were isolated when successive dots were presented in the right-to-left direction, but could not be distinguished in the left-to-right presentation direction. Thus, if the ordinal position effect was absent and the Simon-like effect occurred in the right-to-left presentation direction, we can conclude that the ordinal position effect was overridden by the Simon-like effect in this experiment, and the stimulus–response compatibility effect identified in this experiment was therefore the Simon-like effect. In contrast, if the ordinal position effect occurred and the Simon-like effect was absent in the right-to-left presentation direction, we can conclude that the stimulus–response compatibility effect that occurred in this experiment was the ordinal position effect. To confirm the nature of the stimulus–response compatibility effect, regression analysis was performed, and the results indicated that the dRTs decreased by 56.65 ms per position and that the regression weight for position reliably differed from zero, $t(33) = -4.19$, $p < .001$, when the successive dots were presented from right to left, suggesting that the ordinal position effect occurred in this condition. Therefore, we can conclude that the stimulus–response compatibility effect identified in this experiment was the ordinal position effect. When the successive dots were presented from left to right, the results also

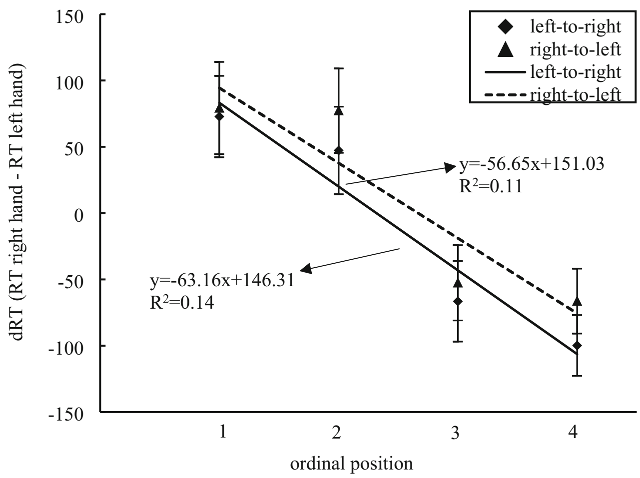

Fig. 3 The ordinal position effect occurred during the ordinal position classification task in the conditions of both the left-to-right and right-to-left presentation directions. The error bars correspond to the standard error. R^2 corresponds to the adjusted *R*-squared

indicate that the dRTs decreased by 63.16 ms per position and that the regression weight for position reliably differed from zero, $t(33) = -4.80$, $p < .001$, suggesting that the ordinal position effect occurred (see Fig. 3). Therefore, from these results, we can conclude that the ordinal position effect was not influenced by the spatial locations of ordinal symbols induced by the presentation direction when the ordinal position classification task was performed.

Error rate analysis A 2 (side of the response: left hand vs. right hand) × 4 [ordinal position: 1–4 (1 indicates that the dot was presented first, 2 indicates that the dot was presented second, 3 indicates that the dot was presented third, and 4 indicates that the dot was presented last in the initiating stage)] × 2 (presentation direction: left to right vs. right to left) within-subject ANOVA revealed a clear interaction only between the side of the response and ordinal position, $F(3, 99) = 2.84$, $p < .05$, $\eta^2 = 0.079$. The results for the error rate suggested that the ordinal position effect may have occurred in this experiment. No other main effects and interaction effects were identified in the experiment. In particular, an interaction between the presentation direction and other independent variables was not identified, suggesting that the presentation direction did not influence the ordinal position effect. To confirm the nature of the ordinal position effect, regression analysis was performed, and the results indicated that the error rate decreased by 2.3% per position and that the regression weight for position was reliably different from zero, $t(33) = -1.69$, $p < .05$. The results for the error rate also suggested that the ordinal position effect occurred in Experiment 2 (see Table 2).

Table 2 Error rates (%) of the different treatment levels ($M \pm SE$)

	Left to right		Right to left	
	Left hand	Right hand	Left hand	Right hand
Position 1	6.25 ± 0.016	9.93 ± 0.022	5.51 ± 0.015	8.09 ± 0.020
Position 2	5.88 ± 0.018	6.25 ± 0.015	5.88 ± 0.014	8.82 ± 0.018
Position 3	8.46 ± 0.020	6.25 ± 0.012	7.25 ± 0.013	6.26 ± 0.016
Position 4	11.03 ± 0.021	4.41 ± 0.013	5.88 ± 0.016	6.62 ± 0.013

Experiment 2 induced the spatial locations of ordinal symbols by presenting successive dots from left to right or from right to left to investigate how the ordinal symbol was represented when the ordinal position classification task was performed. The results also identified the ordinal position effect in this experiment, suggesting that although the spatial locations of ordinal symbols were induced, the participants still represented ordinal symbols from left to right according to the original ordinal sequence during the ordinal position classification task. From this result, we can conclude that the spatial locations of ordinal symbols did not influence the spatial encoding of ordinal symbols when the ordinal sequence was strongly activated. The representation direction of ordinal symbols was in line with the reading and writing direction in this experimental context. Therefore, the results of this experiment again strengthen the previous viewpoint that mental organization of ordinal symbols stems from one's reading and writing habits. In addition, the results further suggested that even when new binding cues were induced for participants when binding ordinal symbols in the experiment, the participants still bound the ordinal symbols according to their reading and writing habits during the ordinal position classification task.

Experiment 3

In Experiment 2, although the spatial locations of ordinal symbols were induced, the results revealed that the ordinal symbols were also spatially represented from left to right according to its original ordinal sequence and depending on one's reading and writing habits when the ordinal position classification task was performed. In Experiment 3, we induced the spatial locations of ordinal symbols using different presentation directions, but the spatial location classification task was used to further investigate how an ordinal symbol was represented when the spatial location of the ordinal symbol was stressed.

Method

Participants A total of 34 university students (18 females, 16 males, $M_{age} = 25.06$ years, $SD = 3.65$ years, age range: 22–39 years) from Shanghai Normal University, China, voluntarily participated in our experiment. All of the participants were right-handed and had normal or corrected-to-normal vision. In addition, all participants read and wrote from left to right.

No participants had a diagnosis of color blindness. They received a payment of 15 yuan RMB when the experiment ended.

Stimuli and apparatus The stimuli and apparatus were the same as those used in Experiment 1.

Procedure and task The procedure used in Experiment 3 was the same as that employed in Experiment 2. The task performed by the participants in Experiment 3 was different from that in Experiment 2. Specifically, the participants were asked to judge where the probe dots were presented in the initiating stage (to the left or right of the middle dot) in Experiment 3.

Results and discussion

Repeated-measures ANOVA and linear trend methods were used to investigate the ordinal position effect in Experiment 3.

RT analysis Errors and deviant RTs (more than three standard deviations for each treatment) were excluded from the analysis, resulting in the exclusion of 8.11% of the trials. A 2 (side of the response: left hand vs. right hand) × 4 [ordinal position: 1–4 (1 indicates that the dot was presented first, 2 indicates that the dot was presented second, 3 indicates that the dot was presented fourth, and 4 indicates that the dot was presented last in the initiating stage)] × 2 (presentation direction: left to right vs. right to left) within-subject ANOVA revealed a significant main effect of ordinal position, $F(3, 99) = 2.96$, $p < .05$, $\eta^2 = 0.082$. The average RTs per position, except for the last one, increased gradually (713, 737, 743, and 715 ms for each position, respectively). Similar to Experiments 1 and 2, the last position received a more rapid response than the third ordinal position, which could be attributed to the high automation level in the processing of the last item. Generally, this result also suggests that a serial search strategy was used during ordinal symbol processing and that the strategy was moderated by the automation level in the processing of items. A significant interaction effect among the side of the response, ordinal position and presentation direction was identified, $F(1, 33) = 11.86$, $p < .001$, $\eta^2 = 0.264$, suggesting that the stimulus–response compatibility effect[1] was moderated by the presentation direction. Thus, we then analyzed the stimulus–response compatibility effect in each presentation direction. The other main effects and interaction effects were not significant. Further simple effect analysis revealed a clear interaction effect between the side of the response and ordinal position when successive dots were presented from left to right, $F(1, 33) = 10.49$, $p < .001$, $\eta^2 = 0.241$, suggesting that the stimulus–response compatibility effect occurred when successive dots were presented from left to right. In addition, a clearly significant effect between the side of the response and ordinal position was identified when successive dots were presented from right to left, $F(1, 33) = 10.05$, $p < .001$, $\eta^2 = 0.233$, suggesting that the stimulus–response compatibility effect was also present when successive dots were presented from right to left.

Similar to Experiment 2, the ordinal position effect and Simon-like effect were isolated when successive dots were presented in the right-to-left direction, but they could not be distinguished in the left-to-right presentation direction. Thus, we can confirm which effect (the ordinal position effect or Simon-like effect) characterized the stimulus–response compatibility effect according to the results of the right-to-left presentation direction. Specifically, if the ordinal position effect was absent in the right-to-left presentation direction, then we can conclude that the ordinal effect was overridden by the Simon-like effect; therefore, the stimulus–response compatibility effect identified in this experiment was the Simon-like effect. In contrast, if the ordinal position effect occurred in the right-to-left presentation direction, then we can conclude that the stimulus–response compatibility effect in this experiment was the ordinal position effect. To confirm the nature of the stimulus–response compatibility effect with both the left-to-right and right-to-left presentation directions, and further confirm which effect (the ordinal position effect or Simon-like effect) characterized the stimulus–response compatibility effect in this experiment, regression analysis was performed. The results indicated that the dRTs increased by 90.61 ms per position and that the regression weight for position was reliably far greater than zero, $t(33) = 5.29$, $p < .001$, when the successive dots were presented from right to left. The results suggest that the ordinal position effect was absent in this condition. From this result, we can conclude that the stimulus–response compatibility effect in this experiment was substantially characterized by the Simon-like effect, as the dots located to the left of the middle dot received a more rapid response than those located to the right of the middle dot with the left key, while the dots located to the right of the middle dot received a more rapid response than those located to the left of the middle dot with the right key. When the successive dots were presented from left to right, the results indicated that the dRTs decreased by 83.12 ms per position and that the regression weight for position was reliably different from zero, $t(33) = -5.62$, $p < .001$. Because the stimulus–response compatibility effect was the Simon-like effect as concluded from the results of the right-to-left presentation direction, the results of the left-to-right presentation direction substantially suggest that the Simon-like effect occurred in this experiment (see Fig. 4). In general, from the results of Experiment 3, we can

[1] Whether the stimulus–response compatibility effect was the ordinal position effect or the Simon-like effect must be confirmed via further analysis. The Simon-like effect also pertains to the corresponding relationship between the previous spatial position of a memorized ordinal symbol and the side of the response; therefore, we temporarily call this effect the stimulus–response compatibility effect in general terms.

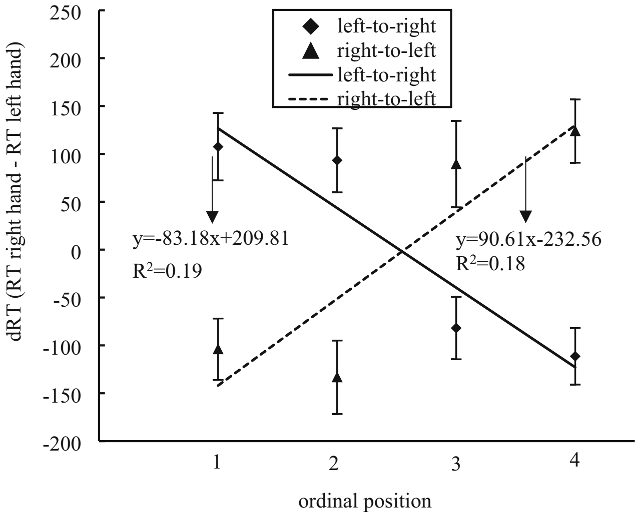

Fig. 4 The ordinal position effect was overridden when responses were based on the spatial locations of ordinal symbols. The stimulus–response compatibility effect identified in both the left-to-right and the right-to-left presentation directions was substantially characterized by the Simon-like effect, as the dots located to the left of the middle dot received a more rapid response with the left key than with the right key, while the dots located to the right of the middle dot received a more rapid response with the right key than with the left key. The error bars correspond to the standard error. R^2 corresponds to the adjusted R-squared

conclude that the ordinal position effect could be overridden by the Simon-like effect when responses were based on the spatial locations of ordinal symbols.

Error rate analysis A 2 (side of the response: left hand vs. right hand) × 4 [ordinal position: 1–4 (1 indicates that the dot was presented first, 2 indicates that the dot was presented second, 3 indicates that the dot was presented third, and 4 indicates that the dot was presented last in the initiating stage)] × 2 (presentation direction: left to right vs. right to left) within-subject ANOVA revealed a significant main effect of ordinal position, $F(3, 99) = 4.96, p < .01, \eta^2 = 0.131$. The average error rate per position decreased gradually (7.6%, 7.4%, 5.3%, and 3.6% for each position, respectively). A marginally significant interaction between the side of the response and presentation direction was identified, $F(3, 99) = 3.70$, $p = .06$, $\eta^2 = 0.101$, suggesting that the stimulus–response compatibility effect was moderated by the presentation direction. No other main effects or interaction effects were identified in the experiment. Thus, we then analyzed the nature of the stimulus–response compatibility effect in each presentation direction. Regression analysis indicates that the error rate increased by 2.0% per position and that the regression weight for position was reliably different from zero, $t(33) = 2.19$, $p < .05$, when the successive dots were presented from right to left. The results for the error rate also suggest that the ordinal position effect was overridden by the Simon-like effect in this experiment. However, the results showed that when the successive dots were presented from left to right, the regression weight for position was not different from zero, $t(33) = -1.18$, $p = .24$. In general, the results for the error rate also suggest to some extent that the ordinal position effect was overridden by the Simon-like effect (see Table 3).

Table 3 Error rates (%) of the different treatment levels ($M \pm SE$)

	Left-to-right		Right-to-left	
	Left hand	Right hand	Left hand	Right hand
Position 1	5.15 ± 0.107	7.72 ± 0.097	11.03±0.150	6.62 ± 0.120
Position 2	6.25 ± 0.099	7.72 ± 0.087	8.09±0.102	7.35 ± 0.103
Position 3	5.88 ± 0.077	5.15 ± 0.088	6.99±0.088	3.31 ± 0.071
Position 4	2.94 ± 0.069	2.94 ± 0.062	2.57 ± 0.060	5.88 ± 0.070

Experiment 3 also induced the spatial locations of ordinal symbols with different presentation directions and further investigated how the ordinal symbol was represented when the spatial location classification task was performed. The results showed that the ordinal position effect was overridden by the Simon-like effect. Therefore, we can conclude that the ordinal symbol was not spatially represented from left to right according to one's reading and writing habits, but seemed to be encoded spatially according to the new internal spatial templates provided by the spatial locations of ordinal symbols in this context. Although the participants in this experiment also read and wrote from left to right, the ordinal symbols were not bound according to their reading and writing habits in this experimental context, suggesting that the influence of one's reading and writing habits on the spatial coding of ordinal symbols can be overridden. Therefore, these results imply that the spatial coding of ordinal symbols is very flexible and depends on the specific context.

Discussion

Many studies have indicated that ordinal symbols are represented spatially from left to right according to their original ordinal sequence and depending on one's reading and writing habits. Therefore, the ordinal position effect can occur in the processing of ordinal symbols. However, according to several studies and the mental whiteboard hypothesis, the spatial representation of ordinal symbols may be influenced by the spatial locations of ordinal symbols (Abrahamse et al., 2016; Abrahamse et al., 2014; Bächtold, et al., 1998; Botvinick, & Watanabe, 2007; Darling et al., 2017). Previous studies have not investigated the influence of the spatial locations of ordinal symbols on ordinal symbol coding. In addition, the spatial coding mechanism of ordinal symbols remains unclear. Thus, the present study investigated the spatial coding mechanism of ordinal symbols.

In the first two experiments, successive dots of different colors were presented centrally (Experiment 1) or from left to right or right to left (Experiment 2), and the participants were asked to memorize the dots in the correct order. Then, they were asked to judge whether the probe dots were presented before or after the middle dot. The results showed that the ordinal position effect occurred during the processing of the ordinal symbol when responses were based on the ordinal position regardless of whether the spatial location of the ordinal symbol was induced. These results suggest that the ordinal symbols were represented spatially from left to right according to their original ordinal sequence, which was in line with the participants' reading and writing habits when the ordinal position classification task was performed. In addition, the results also suggested that the ordinal position effect could not be influenced by the spatial locations of the ordinal symbols in the ordinal position classification task. Previous studies indicated that the ordinal position effect occurred during the processing of ordinal symbols acquired by overlearning (e.g., letters) and those induced by successively presented stimuli (e.g., numbers) when participants were asked to judge the ordinal positions of probe stimuli (Fischer et al., 2010; Gevers et al., 2003; Ginsburg et al., 2017; Ginsburg & Gevers, 2015; Huber et al., 2016; Treccani & Umiltà, 2011; van Dijck & Fias, 2011; Wang et al., 2019). Therefore, these studies consistently indicated that the occurrence of the ordinal position effect implied that ordinal symbols, similar to numbers, were represented spatially from left to right according to their original ordinal sequence and consistent with one's reading and writing habits. The results of the first two experiments further replicated the results of these previous studies both when the spatial locations of ordinal symbols were ruled out (Experiment 1) and when the spatial locations were well controlled (Experiment 2). In addition, these results further strengthened the idea that mental organization of ordinal symbols stems from one's reading and writing habits and that the influence of reading and writing habits on ordinal symbol coding extends to a context in which the spatial locations of ordinal symbols are induced. Notably, this mental organization stemming from one's reading and writing habits applied only to the experimental context in which the ordinal positions of ordinal symbols were stressed, and the spatial locations of ordinal symbols were induced.

According to the mental whiteboard hypothesis, the ordinal position effect occurs during the processing of ordinal symbols because ordinal symbols are bound to the internal spatial templates provided by the original ordinal sequence of ordinal symbols (the representation direction is generally in line with one's reading and writing habits). The spatial locations of ordinal symbols induced by the presentation direction may have provided the participants with new internal spatial templates for binding the ordinal symbols in Experiment 2, and the results showed that the ordinal position effect still occurred in this situation. This result implies that the participants still used the internal spatial templates provided by the original ordinal sequence of ordinal symbols to bind the ordinal symbols when the ordinal position classification task was performed. The reason for this phenomenon may be that the selection of internal spatial templates was moderated by the task performed. Consequently, an internal spatial template provided by the ordinal sequence of the original ordinal symbols was selected when the ordinal position classification task was stressed in the first two experiments. On the contrary, new internal spatial templates provided by the spatial locations of ordinal symbols will likely be selected when the ordinal spatial location classification task is performed. Thus, in Experiment 3, the participants performed the ordinal symbol spatial location classification task after the ordinal sequence was induced by presenting successive dots with different presentation directions.

The results of Experiment 3 showed that the ordinal position effect was overridden by the Simon-like effect, as the memorized dots located to the left of the middle dot received a more rapid response than the dots located to the right of the middle dot with the left key, while the memorized dots located to the right of the middle dot received a more rapid response than the dots located to the left of the middle dot with the right key. Numbers are known to be represented spatially from left to right according to their numerical magnitude on the mental number line (Cho & Proctor, 2003; Dehaene et al., 1993; Treccani, & Umiltà, 2011). Therefore, regardless of whether the external numerical spatial locations were induced by presenting numbers on the left or the right of a screen or whether the memorized numerical spatial locations were induced by presenting successive numbers from left to right or from right to left, the SNARC effect could not be overridden by the numerical spatial location even when numerical spatial location classification was the task to be performed (Mapelli, Rusconi, & Umiltà, 2003; Wang et al., 2018). Thus, the association effect between the representation space of a stimulus and the response space is strong and cannot be influenced by either the external (physical) spatial location or the internal (mental) spatial location of stimulus. For example, small numbers were represented on the left of the mental number line, and larger numbers were represented on the right of the mental number line; thus, although the external numerical location or the internal representation location (the memorized spatial location) was activated, the SNARC effect could occur during a numerical spatial location classification task. Therefore, if the ordinal symbol was represented spatially from left to right according to its original ordinal sequence, then this spatial representation would result in the ordinal position effect even in the spatial location of the ordinal symbol classification task. Experiment 3 revealed that the ordinal position effect was absent; specifically, the effect was overridden by the Simon-like effect. Therefore, from this result, we can conclude that the participants did not use the internal spatial templates provided by the ordinal sequence of ordinal symbols to bind the ordinal symbols in this context, and the ordinal symbols seemed to be bound to new internal spatial templates, which were provided by the spatial locations of the ordinal symbol. The reason for this phenomenon may be that when the successive dots were presented with different directions and the task of processing the spatial location of the ordinal symbol was stressed, the spatial location of the ordinal symbol could provide a new internal spatial template for participants when binding ordinal symbols. Therefore, the participants bound the ordinal symbol depending on the new internal spatial templates provided by the spatial location of the ordinal symbol. Thus, the ordinal position effect was absent, but the Simon-like effect occurred in Experiment 3. Previous studies have indicated that reading and writing habits shape our thought direction; therefore, ordinal symbols were bound on the internal spatial templates from left to right according to reading and writing habits (Ginsburg et al., 2017; Guida et al., 2018). In Experiment 3, the spatial location of the ordinal position was induced, and the participants were asked to provide a response for probe dots depending on their spatial locations. The results revealed that in this experimental context, the participants bound ordinal symbols with a new internal spatial template provided by the spatial locations of ordinal symbols. This result implied that if the experimental context strongly induced a new internal spatial template for participants when binding ordinal symbols, then the participants would bind ordinal symbols with the new internal spatial template. In other words, the influence of reading and writing habits on the mental organization of ordinal symbols was overridden by the new cue provided in the experimental context.

Although both numbers and ordinal symbols were represented spatially and therefore led to the SNARC effect and ordinal position effect in the processing of numbers and ordinal symbols, respectively, several studies have found that the processing mechanisms for numbers and ordinal symbols differ (Dodd et al., 2008; Mapelli et al., 2003; Wang et al., 2018). For example, Dodd et al. (2008) found that numbers can shift individual attention automatically, but that ordinal symbols shifted one's attention only when the ordinal position was strongly activated. As a result of this finding, Dodd et al. indicated that numbers are special. In addition, Mapelli et al. (2003) randomly presented numbers on the left or right side of a screen and asked participants to perform a parity classification task. The results showed that the SNARC effect and Simon effect could coexist. In the last two experiments of the present study, we simultaneously induced the ordinal positions and spatial locations of ordinal symbols, and the results consistently showed that the ordinal position effect and Simon-like effect could not coexist. Comparing the results of the last two experiments in the current study with those of Mapelli et al.'s (2003) study, the mechanisms of numbers and ordinal symbols clearly differ. Thus, the results of the present study indirectly strengthen Dodd et al.'s (2008) view that numbers are special.

The present results can also be explained by polarity correspondence. Polarity correspondence was proposed by Proctor and Cho to explain various types of stimulus–response compatibility effects, including the ordinal position effect (Proctor & Cho, 2006). According to polarity correspondence, stimuli were coded as positive or negative polarity according to their salience, which was determined by the classification task rule performed (Cho & Proctor, 2003, 2007; Proctor & Xiong, 2015). In the coding of response alternatives, the left response was often coded as negative polarity, and the right response was often coded as positive polarity; therefore, polarity correspondence (perceptual similarity, conceptual similarity, or structural similarity) was sufficient to produce such stimulus–response compatibility effects, including the ordinal position effect (Proctor & Cho, 2006). In the first two experiments of the present study, the participants were asked to perform the ordinal position classification task. Thus, the ordinal sequence of ordinal symbols was salient in these experiments, and the participants coded probe dots before the middle dot as negative polarity and probe dots after the middle dot as positive polarity. In addition, they coded the left response as negative polarity and the right response as positive polarity. Thus, polarity correspondence led to the occurrence of the ordinal position effect in the first two experiments. However, the spatial location classification task was performed in Experiment 3. In this experimental context, the spatial locations of ordinal symbols were salient, and the participants coded stimulus polarity according to spatial location. In particular, they coded the left spatial location as negative polarity and the right spatial location as positive polarity. Similar to the first two experiments, they also coded the left response as negative polarity and the right response as positive polarity. Thus, polarity correspondence led to the Simon-like effect in Experiment 3.

Conclusion

From this study, we can propose the following conclusions: (1) the ordinal position effect can be identified when an ordinal position task is performed, (2) the ordinal position effect was overridden when a spatial position task was performed, and (3) the ordinal position effect was moderated by the relevant task performed.

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