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Spatial structure of quantitative representation of numbers: Evidence from the SNARC effect

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Dehaene, Bossini, and Giraux (1993) revealed that subjects responded to large numbers faster with the choice on the right than with the choice on the left, whereas the reverse held true for small numbers (SNARC effect). According to Dehaene et al. (1993), the SNARC effect depends on the quantitative representation of number, such as a left-to-right-oriented analog number line. The main goal of the present study was twofold: first, to investigate whether the vertical SNARC effect could be observed, and, second, to verify whether Dehaene et al.'s (1993) explanation of the SNARC effect is correct. Experiments 2A and 2B showed the vertical SNARC effect in a parity judgment task. Subjects responded to large numbers faster with the top choice than with the bottom choice, whereas the reverse held true for small numbers. However, Experiment 3 failed to show the SNARC effect in a number magnitude judgment task, suggesting that the quantitative representation could be dissociated from the spatial code that produces the SNARC effect.

One unique feature of the number is that it represents a particular aspect of reality—that is, quantitative information (Noel, 2001). Psychologists have tried to answer the question of how quantitative information is internally represented (e.g., Dehaene, 1989; Moyer & Landauer, 1967; Reynvoet & Brysbaert, 1999). More than 100 years ago, Galton (1880a, 1880b) surveyed a mental representation of number and found that subjects saw each number as a stable spatial mental structure. More recently, Seron, Pesenti, Noel, Deloche, and Cornet (1992) surveyed the mental representation of number and found that 10 of 15 subjects possessed a left-to-right-oriented mental representation. These studies indicate that the quantitative representation of numbers has a spatial structure, and that it may orient from left to right.

In line with these introspective data, behavioral data also indicate that the quantitative representation might orient from left to right (Brysbaert, 1995; Fias, 2001; Fias, Brysbaert, Geypens, & d'Ydewalle, 1996; Ratinckx & Brysbaert, 2002). Earlier behavioral data (Dehaene, Bossini, & Giraux, 1993) were collected by asking subjects to conduct a parity (i.e., odd–even) judgment task. These data provided evidence of an association between number magnitude and the spatial location of response. Subjects responded to large numbers faster with the choice on the right than with the choice on the left, whereas the reverse held true for small numbers. Dehaene et al. (1993) called this phenomenon the *spatial–numerical association of response code* (SNARC) *effect*.

Dehaene (1992) proposed a model of number processing called the *triple code model* (also see Dehaene & Cohen, 1995). In this model, three types of internal representations are assumed: *visual Arabic number form*, *verbal word frame*, and *analog magnitude representation*. Both visual Arabic number form and verbal word frame are notation-dependent representations. These are for identification and production of Arabic and verbal numbers, respectively. Analog magnitude representation is a notation-independent representation of numerical quantity, and it is assumed to be a left-to-right-oriented, compressed, analog number line (Dehaene, Dupoux, & Mehler, 1990; Reynvoet & Brysbaert, 1999). According to Dehaene and Akhavein (1995), numbers are automatically translated into analog magnitude representation. In other words, it is assumed that quantitative activation is mandatory even when a task requirement is irrelevant to numerical quantity.

According to the triple code model, the SNARC effect is explained by the spatial structure of quantitative representation (i.e., a left-to-right number line). In the nature of the spatial structure of quantitative representation, small numbers automatically induce a spatial code such as LEFT, whereas large numbers automatically induce a spatial code such as RIGHT. Hence, the SNARC effect must reflect a compatibility between the two spatial codes of response and of number position on the mental number line (Brysbaert, 1995; Dehaene et al., 1990; Vu & Proctor, 2001). If the two spatial codes are incompatible, reaction time (RT) is longer than if they are compatible.

Dehaene et al. (1993) commented that "this SNARC effect bears some similarity to the classical Stroop and

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Simon effects" (p. 387). The Simon effect refers to the finding that RT is shorter if the response corresponds spatially to the stimulus even when the spatial location of the stimulus is irrelevant to the task requirement (see, e.g., Lu & Proctor, 1995; Proctor & Dutta, 1993; Proctor, Lu, & van Zandt, 1992; Proctor & Reeve, 1990; Simon, Acosta, Mewaldt, & Speidel, 1976; Simon, Mewaldt, Acosta, & Hu, 1976). Compatibility effects such as the Simon effect has been used as a beneficial tool for investigating what type of spatial code is activated (see, e.g., Mapelli, Umiltà, Nicoletti, Fanini, & Capezzani, 1996; Roswarski & Proctor, 1996).

The first goal of the present study was to replicate the SNARC effect with Japanese subjects (Experiment 1) and then to expand an observation of this effect (Experiments 2A and 2B). As was mentioned above, Seron et al. (1992) obtained introspective data in which most subjects reported a left-to-right-oriented mental representation. They also found that 9 of 15 subjects showed a bottom-to-top-oriented mental representation. It seems plausible that the association between number magnitude and the spatial location of response could emerge in a vertical response key arrangement. In this case, subjects would respond more quickly to large numbers with the top choice and to small numbers with the bottom choice.

However, Dehaene et al. (1993) observed the symbolic SNARC effect in French subjects, who had a left-to-right writing habit, whereas a reversed SNARC effect emerged in Iranian subjects, who had a right-to-left writing habit. On the basis of this finding, Dehaene et al. (1993) argued that one origin of the SNARC effect relates to writing habit. Japanese have both left-to-right and top-to-bottom writing habits. Hence, according to Dehaene et al.'s (1993) proposal, a different vertical SNARC effect might be observed in Japanese subjects, who would respond to large numbers more quickly with the bottom choice and to small numbers more quickly with the top choice. To the best of our knowledge, no one has investigated the association between number magnitude and the vertical spatial location of response. Thus, in Experiments 2A and 2B we examined whether the vertical SNARC effect could be observed.

The second goal of the present study was to address Dehaene et al.'s (1993) argument that the SNARC effect depends on the spatial structure of quantitative representation. It seems possible that the SNARC effect may depend on the representation of ordinal information, because the number has both cardinal and ordinal information. Therefore, Dehaene et al. (1993) hypothesized that the SNARC effect should be observed with letters if it depends on ordinal information of stimuli but not if it depends on number-specific information. In other words, they predicted that subjects should respond to letters that are closer to the beginning of the alphabet sequence faster with the left choice than with the right choice, and the reverse should hold true for letters closer to the end of the alphabet sequence. However, the SNARC effect was not observed by using letters, and Dehaene et al. (1993) concluded that the SNARC effect depends on the quantitative representation of the number.

However, very recently, Gevers, Reynvoet, and Fias (in press) observed the SNARC effect in nonnumerical ordinal stimuli (i.e., letters and months of the year), indicating that the mental ordinal sequence is represented spatially. On the basis of their findings, they concluded that the SNARC effect of number is not necessarily attributed to number-specific properties. The findings of Gevers et al. brought Dehaene et al.'s (1993) explanation of the SNARC effect into question. That is, the SNARC effect might depend on the representation of ordinal information.

To examine whether Dehaene et al.'s (1993) explanation is correct, the task requirement was changed in Experiment 3. In previous studies, researchers employed a parity judgment task (e.g., Fias et al., 1996), a phoneme-monitoring task (e.g., Fias, 2001), and a number-reading task (e.g., Brysbaert, 1995). Logically, the phoneme-monitoring and number-reading tasks do not require access to numerical quantity. Although parity is one aspect of semantic information of number, the neuropsychological evidence has revealed that the processing of quantity and that of parity information are associated with separate neural substrates, suggesting functionally different processes (see, e.g., Dehaene, 1995; Dehaene & Cohen, 1991, 1997; Dehaene, Spelke, Pinel, Stanescu, & Tsivkin, 1999; Pinel et al., 1999). Therefore, a task that requires accessing quantity information should be applied to investigate the spatial structure of the quantitative representation. Thus, in Experiment 3 we asked subjects to judge whether a presented number was larger or smaller than 5. We hypothesized that a greater SNARC effect would be observed in this number magnitude judgment task if the SNARC effect depended on the spatial structure of quantitative representation.

EXPERIMENT 1

Although the SNARC effect has been observed in several different cultural populations (see, e.g., Brysbaert, 1995; Dehaene et al., 1993; Fias et al., 1996), it has been uncertain whether it would emerge in Japanese subjects. Hence, we tried to replicate the symbolic SNARC effect with Japanese subjects.

Method

Subjects. Thirty native Japanese-speaking undergraduate students of Nagoya University, Aichi Shukutoku University, and Daido Institute of Technology (15 males, 15 females) participated in the experiment for course credit. The average age of the subjects was 20.6 years (*SD* = 1.4 years). All of the subjects had normal or corrected-to-normal vision and were unaware of the purpose of the experiment.

Instructions. The subjects were told that they would see Arabic numbers between 1 and 9 except for 5. They were asked to judge whether each number was odd or even by pressing one of two buttons with the index finger of the left or right hand. The instructions emphasized both speed and accuracy.

Procedure. The subjects took part in two blocks of trials: one with the even response assigned to the left button and the odd response assigned to the right button, and one with the reversed assignment. The order of the blocks was counterbalanced between subjects. Each block started with a training session in which all numbers were presented twice. In each test block, each number was presented 10 times and the order of the numbers was completely randomized. Thus, there was a total of 80 trials per block, with a short resting period between blocks.

This experiment was run on an Apple Performa 6310 computer controlled by the time schedule of PsyScope (Cohen, MacWhinney, Flatt, & Provost, 1993). Bimanual responses were recorded by a buttonbox of PsyScope, in which two buttons were separated from one another by 10.3 cm. One button was located left of body midline, whereas the other was located right of body midline. RT was accurately measured within 2 msec. In each trial, a fixation cross (+) first appeared at the center of the monitor for 500 msec. Following an interval of 500 msec, a black number (15 mm × 12 mm) appeared on a white background. Each trial ended with the subject's response, and the next trial started after an intertrial interval of 1,500 msec. The subjects were seated 60 cm away from the monitor. The entire duration of the experiment was about 15 min.

Results and Discussion

Two subjects were excluded from the analysis because their average error rates over the two blocks exceeded 10%. For the remaining 28 subjects, the average error rate was 3.28% ($SD = 2.28$; see Table 1).

Following Fias et al. (1996), the presence of the SNARC effect was evaluated by a repeated measures regression analysis recommended by Lorch and Myers (1990, Method 3). In the first step, for each subject the median RT of the correct responses was computed for each number, separately for the left and right responses (see Table 1). On the basis of these medians, differences in RT (dRTs) were computed by subtracting the median RT for the left response from the median RT for the right response. If there is a reported association between number magnitude and response side, a negative correlation between number magnitude and dRT can be obtained. Relatively small numbers should elicit faster left response, resulting in positive dRTs, whereas relatively large numbers should elicit faster right responses, resulting in negative dRTs. In the second step, a regression equation was computed for each subject, with number magnitude as a predictor variable. We also included parity as a predictor variable because some studies revealed that subjects responded faster to odd numbers with the left choice than with the right choice, whereas the reverse held true for even numbers (Reynvoet & Brysbaert 1999; Willmes & Iversen, 1995). In accordance with Reynvoet and Brysbaert, we coded odd numbers as -0.5 and even numbers as $+0.5$. In the third step, one-tailed t tests were performed to test whether the regression weight of the group deviated significantly from zero. The repeated measures regression analysis revealed the following equation (see Figure 1):

$$\text{dRT} = 7.23 - 2.52\,(\text{magnitude}) - 22.17\,(\text{parity}).$$

The regression weight of magnitude deviated significantly from zero [$t(27) = -1.83$, $SD = 7.3$, $p < .05$]. The regression weight of parity tended to deviate significantly from zero [$t(27) = -1.45$, $SD = 80.9$, $p < .08$]. Like the results of previous studies, the latter result revealed that odd numbers were responded to faster with the left choice than with the right choice, whereas the reverse was true for even numbers.

The results of Experiment 1 show that the symbolic SNARC effect could be observed with Japanese subjects. Next, we conducted Experiment 2A to examine whether the vertical SNARC effect could also be observed.

EXPERIMENT 2A

Using a questionnaire, we conducted a survey to examine whether Japanese possess a mental number representation. Fifty undergraduate students of Nagoya University (45 males and 5 females, average age = 19.6 years, SD = 0.9) participated in the survey. We asked the subjects whether or not they possessed vivid and stable mentally visualized numbers and required them to write them down if they said they did. Twelve subjects claimed to possess such a representation. Ten subjects wrote down a mental number representation with a spatial structure such as a line, scale, or grid. The mental number representations of 3 subjects oriented from bottom left to top right. The mental number representations of 2 subjects oriented from top left to bottom right. The remaining 5 subjects had mental number representations oriented only from left to right (no vertical orientation). Although it was not clear in regard to the vertical orientation, this result suggested that the mental number representation might orient from left to right.

To further clarify mental number representation, we asked all 50 subjects to put the numbers 0–9 on both horizontal and vertical lines (about 15 cm long) in accordance with their intuition. For the horizontal line, 46 subjects (92%) put the numbers in a left-to-right sequential

Table 1
Mean Reaction Times of Correct Responses (in Milliseconds) and Proportions of Error (PEs) for Each Experimental Cell in Experiment 1

	Number Magnitude															
	1		2		3		4		6		7		8		9	
Response	M	PE	M	PE	M	PE	M	PE	M	PE	M	PE	M	PE	M	PE
Left	435	.01	492	.05	471	.02	484	.04	485	.03	489	.04	472	.03	507	.05
Right	449	.03	482	.07	484	.03	476	.03	462	.03	488	.04	447	.02	504	.07
dRT (right − left)	14		−10		13		−8		−23		−1		−25		−3	

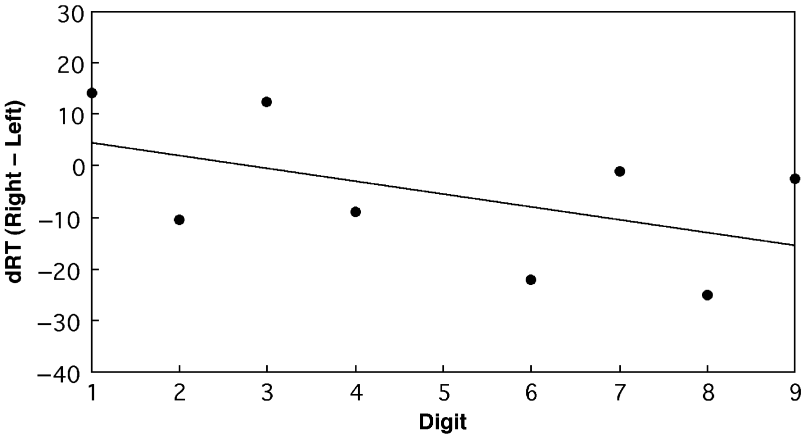

Figure 1. Differences in RT (dRT) between right and left choices (right − left) as a function of number magnitude in Experiment 1. Circles indicate the observed dRTs. The continuous line depicts the predicted dRTs on the basis of the regression analysis.

arrangement (systematic sequential position could not be found for 4 subjects [8%]). For the vertical line, 36 subjects (72%) put the numbers in a bottom-to-top sequential arrangement, whereas 9 subjects (18%) put them in a top-to-bottom sequential arrangement (systematic sequential position could not be found for 5 subjects [10%]). This result indicated that most subjects have left-to-right and bottom-to-top mental number representations. In sum, our survey showed results similar to those of Seron et al. (1992): The mental number representation might orient from left to right and from bottom to top.

On the basis of the introspective data, we predicted that a vertical SNARC effect would be found when the spatial arrangement of the response buttons is vertical. Subjects will respond faster to large numbers with the top choice, whereas they will respond faster to small numbers with the bottom choice.

According to Dehaene et al. (1993), however, the origin of the SNARC effect relates to writing habit. Japanese have two types of writing habits: left to right as in Western culture, and top to bottom, more distinctly associated with Japanese culture. Thus, a different vertical SNARC effect might be observed in Japanese. Japanese subjects should respond faster to large numbers with the bottom choice, and likewise, they should respond faster to small numbers with the top choice. Thus, we tested whether the vertical SNARC effect could be observed in Experiment 2A, addressing the issue of the origin of the SNARC effect.

Method

Subjects. Thirty native Japanese-speaking undergraduate students of Nagoya University, Aichi Shukutoku University, and Daido Institute of Technology (17 males, 13 females) participated in the experiment for course credit. The average age of the subjects was 20.6 years (*SD* = 0.8). They had not participated in Experiment 1. All of the subjects had normal or corrected-to-normal vision and were unaware of the purpose of the experiment.

Instructions and Procedure. The stimuli, apparatus, instructions, and procedure were similar to those of Experiment 1 except for the spatial arrangement of the response buttons. The response buttons were arranged vertically (i.e., top or bottom) on the tabletop. The subjects were asked to judge whether each number was odd or even by pressing the top button with the index finger of the right hand or the bottom button with the index finger of the left hand. The subjects took part in two blocks of trials, one with the even response assigned to the top button and the odd response assigned to the bottom button, and one with the assignment reversed. The order of the blocks was counterbalanced between subjects.

Results and Discussion

Two subjects were excluded from the analysis because the average error rate of 1 of them exceeded 10%, and the data of the other were not recorded because of a computer problem. The remaining 28 subjects had an average error rate of 4.33% (*SD* = 2.50; see Table 2).

Again, the SNARC effect was evaluated by regression analysis. In the first step, for each subject the median RT of the correct responses was computed for each number separately for the top and bottom responses (see Table 2). On the basis of these medians, we calculated dRTs by subtracting the median RT for the bottom choice from the median RT for the top choice. If there is an association between number magnitude and response side in accordance with the introspective data, a negative correlation between number magnitude and dRT should be observed: Relatively small numbers should elicit a faster bottom choice, resulting in positive dRTs, whereas relatively large numbers should elicit a faster top choice, resulting in negative dRTs. In the second step, a regression equation was computed for each subject with number magnitude as a predictor variable. As in Experiment 1, parity was also included as a predictor variable. In the third step, one-tailed *t* tests were performed to test whether the

Table 2
Mean Reaction Times of Correct Responses (in Milliseconds) and Proportions of Error (PEs) for Each Experimental Cell in Experiment 2A

	Number Magnitude															
	1		2		3		4		6		7		8		9	
Response	*M*	PE	*M*	PE	*M*	PE	*M*	PE	*M*	PE	*M*	PE	*M*	PE	*M*	PE
Top	451	.05	445	.05	466	.07	431	.04	452	.04	456	.03	423	.01	473	.07
Bottom	444	.02	468	.04	463	.05	449	.01	485	.04	471	.03	470	.06	481	.08
dRT (top – bottom)	7		−23		3		−18		−33		−15		−47		−8	

regression weight of the group deviated significantly from zero. The repeated measures regression analysis revealed the following equation (see Figure 2):

$$\text{dRT} = -1.58 - 3.04\,(\text{magnitude}) - 26.97\,(\text{parity}).$$

The magnitude coefficient differed significantly from zero [$t(27) = -1.98$, $SD = 8.1$, $p < .03$], as did the regression weight of parity [$t(27) = -2.40$, $SD = 59.5$, $p < .01$]. The latter result revealed that the subjects responded faster to odd numbers with the bottom choice than with the top choice, whereas the reverse was true for even numbers.

In Experiment 2A, the vertical SNARC effect was evident. The result was consistent with the introspective data, indicating that large numbers were associated with the top of internal representational space, whereas small numbers were associated with the bottom of internal representational space.

However, Experiment 2A contained a procedural flaw. We asked the subjects to judge whether each number was odd or even by pressing the top button with the index finger of the right hand and the bottom button with the index finger of the left hand. This procedure produced a confounding between spatial location of response (top or bottom) and response hand.[1] Due to this confounding, the implications of the findings are not clear. That is, the observed vertical SNARC effect might reflect only the fact that the subjects responded faster to large numbers with the right hand than with the left hand, whereas the reverse held true for small numbers (i.e., a symbolic SNARC effect). Hence, we conducted another experiment.

EXPERIMENT 2B

The aim of Experiment 2B was to investigate the vertical SNARC effect when the confounding between spatial location of response and response hand was excluded. For this purpose, the assignment of response hand was changed from that of Experiment 2A.

Method

Subjects. Twenty-eight native Japanese-speaking undergraduate students of Aichi Shukutoku University (5 males, 23 females) participated in the experiment for course credit. The average age of the subjects was 20.4 years ($SD = 0.9$). They had not participated in Experiment 1 or 2A. All of the subjects had normal or corrected-to-normal vision and were unaware of the purpose of the experiment.

Instructions and Procedure. The stimuli, apparatus, instructions, and procedure were identical to those of Experiment 2A except for the assignment of response hands. The subjects were asked to judge whether each number was odd or even by pressing the top button with the index finger of the left hand or the bottom button with the index finger of the right hand, respectively.

Results

The average error rate for Experiment 2B was 2.66% ($SD = 2.66$; see Table 3). A regression analysis identical to that of Experiment 2A was conducted for correct re-

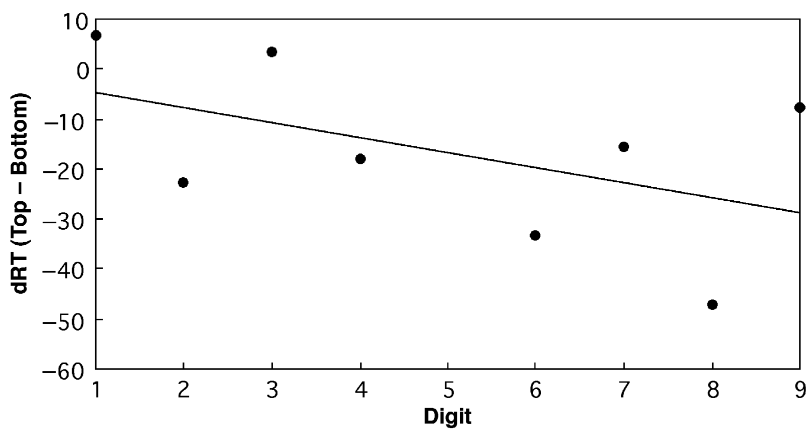

Figure 2. Differences in RT (dRT) between top and bottom choices (top − bottom) as a function of number magnitude in Experiment 2A. Circles indicate the observed dRTs. The continuous line depicts the predicted dRTs on the basis of the regression analysis.

Table 3
Mean Reaction Times of Correct Responses (in Milliseconds) and Proportions of Error (PEs) for Each Experimental Cell in Experiment 2B

	Number Magnitude															
	1		2		3		4		6		7		8		9	
Response	*M*	PE	*M*	PE	*M*	PE	*M*	PE	*M*	PE	*M*	PE	*M*	PE	*M*	PE
Top	432	.03	448	.05	455	.03	430	.01	452	.04	437	.01	428	.02	460	.06
Bottom	425	.03	405	.03	440	.05	407	.03	416	.03	434	.02	425	.03	458	.06
dRT (top – bottom)	7		43		13		23		36		3		3		2	

sponses (Table 3). The repeated measures regression analysis revealed the following equation (see Figure 3):

$$\text{dRT} = 29.54 - 2.57\ (\text{magnitude}) + 19.36\ (\text{parity}).$$

The regression weight of magnitude differed significantly from zero [$t(27) = -2.08$, $SD = 6.5$, $p < .02$]. The regression weight of parity also deviated significantly from zero [$t(27) = 1.81$, $SD = 56.5$, $p < .04$]. The latter result revealed that the subjects responded faster to even numbers with the bottom choice than with the top choice, whereas the reverse held true for odd numbers.

Discussion

The purpose of Experiment 2B was to examine the vertical SNARC effect when the assignment of response hand was changed from that of Experiment 2A. Again, the regression weight of magnitude was significant and negative. The difference of the regression weight of magnitude between Experiments 2A and 2B was not significant [$t(54) = -0.24$, $SD = 7.4$, $p > .8$]. This result indicates that the result of Experiment 2A was not affected by the confounding between spatial location of response and response hand. Furthermore, it indicates that number magnitude associates with the spatial location of response but not with the response hand itself (see Dehaene et al., 1993).

However, we should notice two differences of the results between Experiments 2A and 2B: that of the constant value and that of the regression weight of parity. The constant value of the results of Experiment 2B was larger than that of the results of Experiment 2A [$t(54) = -2.66$, $SD = 43.8$, $p < .01$], indicating that the difference between the top and the bottom responses was larger for small numbers than for large numbers in Experiment 2B, whereas the difference was larger for large numbers than for small numbers in Experiment 2A. The regression weight of parity was negative in Experiment 2A, whereas it was positive in Experiment 2B. It seems that parity associates with response hand itself but not with spatial location of response. Experiments 1–2B showed that the subjects responded faster to odd numbers with their left hands than with their right hands, whereas the reverse held true for even numbers. (We will comment on the association between parity and response hand in Experiments 1–2B and on the difference of constant value between the results of Experiments 2A and those of 2B in the General Discussion.)

Aside from these differences, the observed vertical SNARC effects in Experiments 2A and 2B indicated that large numbers associated with the top of internal representational space, whereas small numbers associated with the bottom of internal representational space. These findings were incompatible with Dehaene et al.'s (1993) proposal that the origin of this effect relates to writing habit. If the origin of the SNARC effect relates to writ-

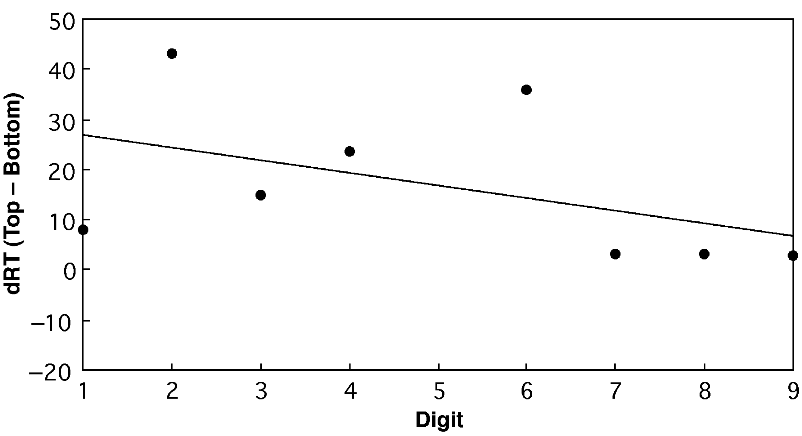

Figure 3. Differences in RT (dRT) between top and bottom choices (top − bottom) as a function of number magnitude in Experiment 2B. Circles indicate the observed dRTs. The continuous line depicts the predicted dRTs on the basis of the regression analysis.

ing habit, the reversed vertical SNARC effect should be observed, because Japanese have a top-to-bottom writing habit. The findings of Bachtold, Baumuller, and Brugger (1998) also indicated that writing habit might not be a critical factor of the origin of the SNARC effect. They found two types of the SNARC effect in the subjects whose mother tongue was Swiss German. In Experiment 1, they encouraged subjects to conceive of the numbers as indicators of distance in centimeters by using the schematic outline of a ruler. In Experiment 2, they induced subjects to conceive of the numbers as indicators of hours of the day by using the schematic outline of a clock. After these preliminary conditioning phases, in both experiments the subjects were required to judge whether numbers were larger or smaller than 6. As a result, the symbolic SNARC effect emerged in Experiment 1, whereas the reversed SNARC effect appeared in Experiment 2.

What factor relates to the origin of the SNARC effect? Berch, Foley, Hill, and Ryan (1999) investigated a developmental change of the SNARC effect with children (Grades 2–8). They found that the SNARC effect emerged in children after Grade 3 (mean age = 9.2 years). This finding indicates that human beings are not endowed with the association between number magnitude and internal representational space, but this association is constructed at a relatively early stage of development. As the results of Bachtold et al. (1998) suggest, we assume that stimuli that denote an association between number magnitude and external space (e.g., rulers, clocks, calculators) might relate to the origin of the SNARC effect. Above all, in education in mathematics from primary school on, most people have seen repeatedly that in mathematical diagrams larger numbers are located in the upper right, whereas smaller numbers are located in the lower left. Through these repeated experiences, the association between number magnitude and external space might be internalized (Dehaene, 1997). As a result, large numbers might be associated with the top right area of internal representational space, whereas small numbers might be associated with the bottom left area of internal representational space. In fact, in our survey 7 (58%) of 12 subjects who had mental number representations claimed that the origin of their mental representations was their primary school mathematics education or early training on the abacus.

Next, we addressed the second aim of the present study. According to Dehaene et al.'s (1993) argument, the vertical SNARC effects of Experiments 2A and 2B suggest that quantitative representation might also orient from bottom to top. This might be valid, because the introspective data of Seron et al. (1992) and those of the present study were in line with this hypothesis. However, one must be cautious in drawing such a conclusion, because the parity judgment task does not require direct access to numerical quantity. To verify whether or not the SNARC effect depends on the spatial structure of quantitative representation, the task requirement was changed in Experiment 3.

EXPERIMENT 3

In Experiment 3, we asked subjects to judge whether a presented number was larger or smaller than 5. If the SNARC effect depended on the spatial structure of quantitative representation per se, a greater SNARC effect should be observed in this experiment than in Experiment 1, because the number magnitude judgment task requires direct access to numerical quantity.

Method

Subjects. Twenty-eight native Japanese-speaking undergraduate students of Nagoya University, Aichi Shukutoku University, and Daido Institute of Technology (13 males, 15 females) participated in this experiment for course credit. The average age of the subjects was 20.6 years (*SD* = 1.3 years). They had not participated in any of the previous experiments. All of the subjects had normal or corrected-to-normal vision and were unaware of the purpose of the experiment.

Instructions and Procedure. The stimuli, apparatus, and procedure were identical to those of Experiment 1 except for a new task requirement. This time, the subjects were told that they would see Arabic numerals between 1 and 9 except for 5, and they were asked to judge whether a presented number was larger or smaller than 5 by pressing one of two buttons with the index finger of the left or right hand. The subjects took part in two blocks of trials, one with the "larger" response assigned to the left button and the "smaller" response assigned to the right button, and one with the reversed assignment. The order of the blocks was counterbalanced between subjects.

Results

The average error rate was 1.16% (*SD* = 1.41; see Table 4). As in Experiment 1, the presence of the SNARC effect was evaluated by a repeated measures regression analysis (see Table 4). The repeated measures regression analysis revealed the following equation (see Figure 4):

$$\text{dRT} = -4.12 - 0.08\ (\text{magnitude}) + 3.43\ (\text{parity}).$$

Table 4
Mean Reaction Times of Correct Responses (in Milliseconds) and Proportions of Error (PEs) for Each Experimental Cell in Experiment 3

	Number Magnitude															
	1		2		3		4		6		7		8		9	
Response	*M*	PE	*M*	PE	*M*	PE	*M*	PE	*M*	PE	*M*	PE	*M*	PE	*M*	PE
Left	384	.00	393	.01	415	.01	448	.05	434	.02	414	.01	405	.00	407	.00
Right	382	.01	383	.01	406	.01	448	.05	438	.02	408	.01	401	.01	397	.01
dRT (right – left)	−2		−10		−9		0		4		−6		−4		−10	

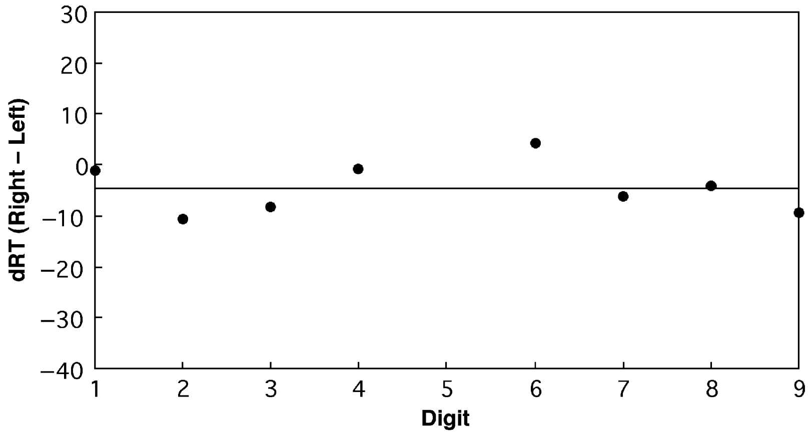

Figure 4. Differences in RT (dRT) between right and left choices (right − left) as a function of number magnitude in Experiment 3. Circles indicate the observed dRTs. The continuous line depicts the predicted dRTs on the basis of the regression analysis.

The magnitude coefficient did not differ significantly from zero [$t(27) = -0.07$, $SD = 6.0$, $p > .4$]. The regression weight of parity also did not deviate significantly from zero [$t(27) = 0.54$, $SD = 33.5$, $p > .3$].

Discussion

Although the stimuli and trial schedule were identical to those of Experiment 1, the SNARC effect was not observed when the subjects conducted the number magnitude judgment task. We predicted that a greater SNARC effect must be observed in the number magnitude judgment task if the SNARC effect depended on the spatial structure of quantitative representation, but this hypothesis was not supported. Rather, the result of Experiment 3 indicated that the quantitative representation can be dissociated from the spatial code on which the SNARC effect might depend, and suggests that Dehaene et al.'s (1993) explanation of the SNARC effect might not be proper.

However, as a possible explanation, one could infer that subjects might conduct the number magnitude judgment task using a specific strategy without mediation of the quantitative representation (e.g., stimulus–response learning; see Naccache & Dehaene, 2001). Thus, we evaluated the *distance effect* by a regression analysis (see Gevers et al., in press). Many previous studies have shown the distance effect, which refers to the finding that RT decreases as numerical distance increases (e.g., Dehaene, 1989; Ito & Hatta, 2003; Marks, 1972; Moyer & Landauer, 1967). It has been considered that the distance effect depends on the quantitative representation.

To evaluate the distance effect, the absolute distance (1–4 units) from the reference number (i.e., 5) was included as a predictor variable for RT. As a result, RT = 451.25 −16.4 (distance). The regression weight of distance differed significantly from zero [$t(27) = -6.88$, $SD = 12.6$, $p < .01$]. A negative correlation between numerical distance and RT indicated that RT decreases as the numerical distance increases (i.e., the distance effect), revealing that the quantitative representation was activated clearly in the present magnitude judgment task. Hence, the disappearance of the SNARC was not due to the fact that the number magnitude judgment task was performed by a nonquantitative strategy.

One may also ask how an elapsed processing time might affect the disappearance of the SNARC effect. Overall RT was shorter in Experiment 3 than in Experiments 1–2B (see Tables 1–4). Thus, in accordance with Fias (2001), we tested whether the SNARC effect depended on the elapsed processing time. For this purpose, we split the data of Experiments 1–3 into two halves on the basis of RT. For each subject, for each number, and for both sides of responses separately, the observations were split into a fast half and a slow half. Next, median RTs, dRTs, and regression equations were computed for the fast-half sets of data in Experiments 1–2B and for the slow-half sets of data in Experiment 3. This analysis revealed the following equations: Fast set in Experiment 1: dRT = 3.31 − 1.73 (magnitude) −19.96 (parity) (with a mean RT of 428 msec); fast set in Experiment 2A: dRT = −3.47 −3.47 (magnitude) −14.99 (parity) (with a mean RT of 410 msec); fast set in Experiment 2B: dRT = 19.53 −1.42 (magnitude) + 16.33 (parity) (with a mean RT of 395 msec); slow set in Experiment 3: dRT = −0.36 −0.36 (magnitude) −10.09 (parity) (with a mean RT of 467 msec).

The regression weights of magnitude were significant in the fast sets in Experiments 1 and 2A [$t(27) = -1.73$, $SD = 5.3$, $p < .05$; $t(27) = -2.38$, $SD = 7.7$, $p < .01$, respectively]. The regression weight of magnitude was marginally significant in the fast set in Experiment 2B [$t(27) = -1.29$, $SD = 5.8$, $p < .1$], but it was not significant in the slow set in Experiment 3 [$t(27) = -0.21$, $SD = 9.0$, $p > .4$].

Fias, Lauwereyns, and Lammertyn (2001) showed that the SNARC effect does not depend on the elapsed processing times (see also Lammertyn, Fias, & Lauwereyns, 2002). The SNARC effect was observed in their Experiment 1 but not in their Experiment 3 even when the overall RT was longer in the latter experiment than in the former. When the subjects were asked to judge the orientation of a triangle that was superimposed on Arabic numerals (Experiment 1), the numbers had an effect on their performance and the SNARC effect emerged. However, when the subjects were asked to judge the color of Arabic numerals (Experiment 3), the numbers did not have an effect on their performance. In sum, both additive analysis of the present study and the findings of Fias et al. (2001) indicate that the SNARC effect does not depend on the elapsed processing time, and the shorter overall RT is not enough to explain the disappearance of the SNARC effect in Experiment 3.

GENERAL DISCUSSION

The main findings of the present study were as follows. First, the symbolic SNARC effect was found in Japanese subjects (see Dehaene et al., 1993). The subjects responded faster to large numbers with the right choice than with the left choice, whereas the reverse held true for small numbers. Second, the vertical SNARC effect was also observed. Experiments 2A and 2B showed that the subjects responded faster to large numbers with the top choice than with the bottom choice, whereas the reverse held true for small numbers. Third, no SNARC effect was evident in the number magnitude judgment task, which required more direct access to information about numerical quantity. In the following sections, we will present a working hypothesis to explain why the results of Experiments 1–2B differed from those of Experiment 3. We will then discuss the observed association between parity and response hand in Experiments 1–2B and the difference between the constant value of the results of Experiment 2A and that of the results of Experiment 2B.

The SNARC Effect in the Parity Judgment Task

According to Dehaene et al. (1993), the SNARC effect depends on the spatial structure of quantitative representation. Hence, the results of Experiments 1–2B (i.e., symbolic and vertical SNARC effects) suggest that the quantitative representation might orient from left to right and from bottom to top. However, the results of Experiment 3 suggest that the quantitative representation of number can dissociate from the spatial code, which produced the SNARC effect.

As was mentioned earlier, it is now debatable whether the SNARC effect depends on the quantitative representation or on the ordinal representation. Dehaene et al. (1993) argued that the SNARC effect depends on the quantitative representation of number. However, Gevers et al. (in press) found the SNARC effect with nonnumerical ordinal stimuli (letters and months), and they concluded that the SNARC effect of number could depend on the ordinal representation of number (i.e., ordered number sequence: 1, 2, 3, 4, . . .; this number sequence is referred to hereafter as the *general number sequence*). On the basis of the results of the present study, we infer that the emergence of the SNARC effect in the parity judgment task (Experiments 1–2B) might depend on the ordinal rather than the quantitative representation. However, this proposal does not mean that the ordinal representation of the general number sequence produced the SNARC effect in the parity judgment task, because there is no logical reason to assume that the parity judgment task induces activation of the general number sequence representation more than the number magnitude judgment task does. Rather, it is plausible that the SNARC effect in the parity judgment task relates to the task requirement (i.e., accessing parity information). We presume that parity information might also be represented internally as number sequences, and the ordinal representation of parity information might relate to the SNARC effects observed in the present study.

Mathematically, odd and even integers are defined in terms of their divisibility by 2. Hence, Clark and Campbell (1991) argued that the parity judgment was based on a mental division by 2. However, studies of mental calculation have demonstrated that subjects took advantage of parity information (the odd–even rule) when they verified simple arithmetic problems (Krueger, 1986; Krueger & Hallford, 1984). For example, the verification time for $7 \times 5 = 38$ is shorter than that for $7 \times 5 = 37$ because the former problem violates the odd–even rule (i.e., odd number $\times$ odd number $=$ odd number). Such findings indicate that subjects can access parity information at an early stage of verification processing. Hence, it is implausible that subjects would quickly perform a mental division by 2 for each operand and then employ the odd–even rule to verify simple arithmetic problems. Rather, it is reasonable that parity information, like arithmetic facts such as the multiplication table, is retrieved directly from long-term memory (Ashcraft, 1992; Dehaene et al., 1993).

At present, it is unclear how parity information is represented in long-term memory (Dehaene et al., 1993). However, we may be able to conjecture that parity information is represented as number sequences. This is due to the fact that most people have recited an even number sequence (2, 4, 6, 8) and an odd number sequence (1, 3, 5, 7, 9) on many occasions, although the even number sequence must be practiced more often than the odd number sequence. As a result, these ordered sequences must be stored in the long-term memory and might be represented as ordered number sequences. The representations of these odd/even number sequences can be based on the one-digit parity judgment. That is, we can judge whether a number is odd or even if we search the representations of odd/even number sequences and know which includes the number. The finding of Dehaene and Cohen (1991) suggested that the representations of odd/even number sequences could be based on the parity judgment. They reported a brain-damaged patient, N.A.U., who could cite the even number sequence but not the odd number sequence. In the parity judgment task, N.A.U. performed better with even numbers than with odd numbers, indicating that N.A.U. performed the parity judgment of even numbers by accessing the representation of the even number sequence.

The results of analyses of variance (ANOVAs) might support our working hypothesis. We performed 2 (response hand[2]: left, right) × 2 (parity: odd, even) × 4 (magnitude: 1–2, 3–4, 6–7, 8–9) ANOVAs for the data of Experiments 1–2B. The ANOVAs revealed that the main effects of magnitude were significant in all the experiments [$F(3,81) = 5.76, p < .01$; $F(3,81) = 4.48, p < .01$; $F(3,81) = 5.24, p < .01$, respectively]. Generally, responses in the parity judgment task slowed as number magnitude increased (in Experiment 1, 1–2 = 465 msec, 3–4 = 479 msec, 6–7 = 481 msec, 8–9 = 483 msec; in Experiment 2A, 1–2 = 452 msec, 3–4 = 452 msec, 6–7 = 465 msec, 8–9 = 461 msec; in Experiment 2B, 1–2 = 427 msec, 3–4 = 432 msec, 6–7 = 434 msec, 8–9 = 443 msec). These results suggest that subjects might perform the parity judgment task by the serial search strategy of the representations of odd/even number sequences. Moreover, ANOVAs showed that even numbers were responded to faster than odd numbers in Experiments 2A and 2B [$F(1,27) = 3.39, p < .1$; $F(1,27) = 29.02, p < .01$, respectively], indicating that the representation of the even number sequence was more accessible than that of the odd number sequence. On the other hand, the same ANOVAs showed that the main effect of magnitude was also significant in Experiment 3 [$F(3,81) = 29.53, p < .01$], but the RT of the number magnitude judgment became shorter as the numerical distance between a criterion number (e.g., 5) and a target number increased (i.e., the distance effect; Experiment 3: 1–2 = 386 msec, 3–4 = 429 msec, 6–7 = 424 msec, 8–9 = 402 msec). This result indicates that subjects do not perform the number magnitude judgment task using the serial search strategy on the representation of the general number sequence. If they did, the RT of the number magnitude judgment would increase as number magnitude increases. Number magnitude judgment must be based on computing, each time, a quantitative relationship between two numbers in the analog quantitative representation (see, e.g., Dehaene, 1989).

Given that subjects access the representations of odd/even number sequences in the parity judgment task, it is predictable that the SNARC effect would appear with an additional assumption that these representations orient from left to right and from bottom to top. Provided that introspective data might reflect on an abstract representation of both quantitative and ordinal information, this assumption might be valid. Likewise, Dehaene et al. (1993) argued that, due to the nature of the spatial structure of the ordinal representation, small numbers automatically induce a spatial code such as LEFT or BOTTOM, whereas large numbers automatically induce a spatial code such as RIGHT or TOP. In this case, the SNARC effect reflects a compatibility between two spatial codes: the spatial code of response and that of number position in the odd/even number sequences.

Our working hypothesis does not reject Dehaene et al.'s (1993) argument that the quantitative information is represented as a compressed analog number line. Actually, the results of Experiment 3 (i.e., the distance effect) did not contradict their argument. Furthermore, we do not intend to claim that every SNARC effect observed in the previous studies depends on the ordinal representations of odd/even number sequences. In fact, in two previous studies it was reported that the SNARC effect was obtained in the number magnitude judgment task when two-digit numbers were employed (Dehaene et al., 1990; Hinrichs, Yurko, & Hu, 1981). In addition to odd/even number sequences and number quantity, it is possible that ordinal information of the general number sequence could relate to the SNARC effect (Gevers et al., in press). Needless to say, further studies are necessary to reveal the extent to which the SNARC effect is due to quantitative information or to ordinal information. However, the results of the present study did not support Dehaene et al.'s (1993) argument that the SNARC effect depends on the quantitative representation of number. Hence, we infer that the SNARC effects in Experiments 1–2B were due to ordinal information of the odd/even number sequences rather than to quantitative information of number (and also to ordinal information of the general number sequence).

The Association Between Parity and Response Hand and the Difference of Constant Value of the Results of Experiment 2A and those of Experiment 2B

Finally, we will mention the association between parity and response hand in Experiments 1–2B and the difference of the constant value between the results of Experiment 2A and those of Experiment 2B. In Experiments 1–2B, the regression analyses revealed that both the regression weight of parity and that of number magnitude were significant. In Experiments 1–2B, the subjects responded faster to odd numbers with their left hands than with their right hands, whereas the reverse held true for even numbers. Basically, these results are consistent with those of previous studies (Berch et al., 1999; Reynvoet & Brysbaert, 1999). Willmes and Iversen (1995) called this observation the *markedness association of response codes* (MARC) *effect* and argued that the MARC effect reflects on a compatibility between the linguistically marked adjectives *left* and *odd* and the unmarked adjectives *right* and *even*.

Why did the constant value of the results of Experiment 2A differ from that of the results of Experiment 2B? In addition to the factors of number magnitude and parity, response hand (left or right) affected RT in the parity judgment task. ANOVAs revealed that the main effects of response hand were significant in Experiments 2A and 2B, indicating that right-hand responses were faster than left-hand responses (in Experiment 2A, left = 466 msec, right = 450 msec, $F(1,27) = 11.17$, $p < .01$; in Experiment 2B, left = 443 msec, right = 426 msec, $F(1,27) = 15.38$, $p < .01$]. Therefore, there were three factors (i.e., number magnitude, parity, and response hand) that affected the RT of the parity judgment in Experiments 2A and 2B. Large numbers induced faster top responses, whereas small numbers induced faster bottom responses. Moreover, odd numbers induced faster left-hand responses, whereas even numbers induced faster right-hand responses. And, generally, right-hand responses were faster than left-hand responses. Therefore, it is predictable that the longest RT would be observed when all three factors act to delay responses, whereas the shortest RT would be observed when all three factors act to accelerate responses. For example, in Experiment 2A "8" would be responded to most slowly with the bottom choice (delay) with the left hand (delay) and most quickly with the top choice (accelerate) with the right hand (accelerate). Likewise, in Experiment 2B, "2" would be responded to most slowly with the top choice (delay) with the left hand (delay), whereas "2" would be responded to most quickly with the bottom choice (accelerate) with the right hand (accelerate). The results of Experiments 2A and 2B were more or less consistent with those patterns predicted by the effects of the three factors (see Tables 2 and 3). The difference between the top and bottom choices were larger for large numbers in Experiment 2A, whereas the difference was larger for small numbers in Experiment 2B. Hence, the constant value of the results of Experiment 2A might differ from that of the results of Experiment 2B.

REFERENCES

Ashcraft, M. H. (1992). Cognitive arithmetic: A review of data and theory. *Cognition*, **44**, 75-106.

Bachtold, D., Baumuller, M., & Brugger, P. (1998). Stimulus–response compatibility in representational space. *Neuropsychologia*, **36**, 731-735.

Berch, D. B., Foley, E. J., Hill, R. J., & Ryan, P. M. (1999). Extracting parity and magnitude from Arabic numerals: Developmental changes in number processing and mental representation. *Journal of Experimental Child Psychology*, **74**, 286-308.

Brysbaert, M. (1995). Arabic number reading: On the nature of the numerical scale and the origin of phonological recoding. *Journal of Experimental Psychology: General*, **124**, 434-452.

Clark, J. M., & Campbell, J. I. D. (1991). Integrated versus modular theories of number skills and acalculia. *Brain & Cognition*, **17**, 204-239.

Cohen, J., MacWhinney, B., Flatt, M., & Provost, J. (1993). PsyScope: An interactive graphic system for designing and controlling experiments in the psychology laboratory using Macintosh computers. *Behavior Research Methods, Instruments, & Computers*, **25**, 257-271.

Dehaene, S. (1989). The psychophysics of numerical comparison: A reexamination of apparently incompatible data. *Perception & Psychophysics*, **45**, 557-566.

Dehaene, S. (1992). Varieties of numerical abilities. *Cognition*, **44**, 1-42.

Dehaene, S. (1995). Electrophysiological evidence for category-specific word processing in the normal human brain. *NeuroReport*, **6**, 2153-2157.

Dehaene, S. (1997). *The number sense: How the mind creates mathematics.* New York: Oxford University Press.

Dehaene, S., & Akhavein, R. (1995). Attention, automaticity, and level of representation in number processing. *Journal of Experimental Psychology: Learning, Memory, & Cognition*, **21**, 314-326.

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

Dehaene, S., & Cohen, L. (1991). Two mental calculation systems: A case study of severe acalculia with preserved approximation. *Neuropsychologia*, **29**, 1045-1074.

Dehaene, S., & Cohen, L. (1995). Towards an anatomical and functional model of number processing. *Mathematical Cognition*, **1**, 83-120.

Dehaene, S., & Cohen, L. (1997). Cerebral pathway for calculation: Double dissociation between rote verbal and quantitative knowledge of arithmetic. *Cortex*, **33**, 219-250.

Dehaene, S., Dupoux, E., & Mehler, J. (1990). Is numerical comparison digital? Analogical and symbolic effects in two-digit number comparison. *Journal of Experimental Psychology: Human Perception & Performance*, **16**, 626-641.

Dehaene, S., Spelke, E., Pinel, P., Stanescu, R., & Tsivkin, S. (1999). Source of mathematical thinking: Behavioral and brain-imaging evidence. *Science*, **284**, 970-974.

Fias, W. (2001). Two routes for the processing of verbal numbers: Evidence from the SNARC effect. *Psychological Research*, **65**, 250-259.

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., Lauwereyns, J., & Lammertyn, J. (2001). Irrelevant digits affect feature-based attention depending on the overlap of neural circuits. *Cognitive Brain Research*, **12**, 415-423.

Galton, F. (1880a). Visualized numerals. *Nature*, **21**, 252-256.

Galton, F. (1880b). Visualized numerals. *Nature*, **21**, 494-495.

Gevers, W., Reynvoet, B., & Fias, W. (in press). The mental representation of ordinal sequences is spatially organized. *Cognition*.

Hinrichs, J. V., Yurko, D. S., & Hu, J. M. (1981). Two-digit number comparison: Use of place information. *Journal of Experimental Psychology: Human Perception & Performance*, **7**, 890-901.

Ito, Y., & Hatta, T. (2003). Semantic processing of Arabic, Kanji, and Kana numbers: Evidence from interference in physical and numerical size judgments. *Memory & Cognition*, **31**, 360-368.

Krueger, L. E. (1986). Why 2 × 2 = 5 looks so wrong: On the odd–even rule in product verification. *Memory & Cognition*, **14**, 141-149.

Krueger, L. E., & Hallford, E. W. (1984). Why 2 + 2 = 5 looks so wrong: On the odd–even rule in sum verification. *Memory & Cognition*, **12**, 171-180.

Lammertyn, J., Fias, W., & Lauwereyns, J. (2002). Semantic influences of feature-based attention due to overlap of neural circuits. *Cortex*, **38**, 878-882.

Lorch, R. F., Jr., & Myers, J. L. (1990). Regression analyses of repeated measures data in cognition research. *Journal of Experimental Psychology: Learning, Memory, & Cognition*, **16**, 149-157.

Lu, C.-H., & Proctor, R. W. (1995). The influence of irrelevant location information on performance: A review of the Simon and spatial Stroop effects. *Psychonomic Bulletin & Review*, **2**, 174-207.

Mapelli, D., Umiltà, C., Nicoletti, R., Fanini, A., & Capezzani, L. (1996). Prelexical representational space. *Cognitive Neuropsychology*, **13**, 229-255.

Marks, D. (1972). Relative judgment: A phenomenon and theory. *Psychophysics*, **11**, 156-160.

Moyer, R. S., & Landauer, T. K. (1967). Time required for judgment of inequality. *Nature*, **215**, 1519-1520.

Naccache, L., & Dehaene, S. (2001). Unconscious semantic priming extends to novel unseen stimuli. *Cognition*, **80**, 223-237.

Noel, M. P. (2001). Numerical cognition. In R. Brenda (Ed.), *The handbook of cognitive neuropsychology: What deficits reveal about the human mind* (pp. 495-518). London: Psychology Press, Taylor & Francis.

Pinel, P., Le Clec'H, G. L., van de Moortele, P. F., Naccache, L., Le Bihan, D. L., & Dehaene, S. (1999). Event-related fMRI analysis of the cerebral circuit for numeral comparison. *NeuroReport*, **10**, 1473-1479.

Proctor, R. W., & Dutta, A. (1993). Do the same stimulus–response relations influence choice reactions initially and after practice? *Journal of Experimental Psychology: Learning, Memory, & Cognition*, **19**, 922-930.

Proctor, R. W., Lu, C. H., & van Zandt, T. (1992). Enhancement of the Simon effect by response precuing. *Acta Psychologica*, **74**, 53-74.

Proctor, R. W., & Reeve, T. G. (Eds.) (1990). *Stimulus–response compatibility: An integrated perspective.* Amsterdam: North-Holland.

Ratinckx, E., & Brysbaert, M. (2002). Interhemispheric Stroop-like interference in number comparison: Evidence for strong interhemispheric integration of semantic number information. *Neuropsychology*, **16**, 217-229.

Reynvoet, B., & Brysbaert, M. (1999). Single-digit and two-digit Arabic numerals address the same semantic number line. *Cognition*, **72**, 191-201.

Roswarski, T. E., & Proctor, R. W. (1996). Multiple spatial codes and temporal overlap in choice-reaction tasks. *Psychological Research*, **59**, 196-211.

Seron, X., Pesenti, M., Noel, M. P., Deloche, G., & Cornet, J. A. (1992). Images of numbers, or "When 98 is upper left and 6 sky blue." *Cognition*, **44**, 159-196.

Simon, J. R., Acosta, E., Jr., Mewaldt, S. P., & Speidel, C. R. (1976). The effect of an irrelevant directional cue on choice reaction time: Duration of the phenomenon and its relation to stages of processing. *Perception & Psychophysics*, **19**, 16-22.

Simon, J. R., Mewaldt, S. P., Acosta, E., & Hu, J. M. (1976). Processing auditory information: Interaction of two population stereotypes. *Journal of Applied Psychology*, **61**, 354-358.

Vu, K. P., & Proctor, R. W. (2001). Determinants of right–left and top–bottom prevalence for two-dimensional spatial compatibility. *Journal of Experimental Psychology: Human Perception & Performance*, **27**, 813-828.

Willmes, K., & Iversen, W. (1995, April). *On the internal representation of number parity*. Paper presented at the Spring Annual General Meeting of the British Neuropsychological Society. London.

NOTES

1. The authors thank Mark Brysbaert for pointing out the confounding between spatial location of response and hand of response.

2. In Experiment 2A, the left hand was assigned to the bottom button and the right hand was assigned to the top button. In contrast, in Experiment 2B the left hand was assigned to the top button and the right hand to the bottom button.

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