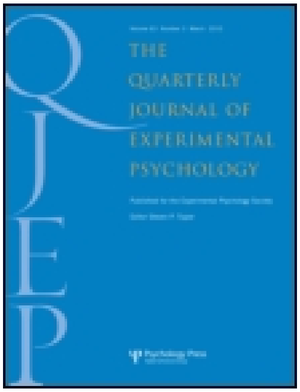

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Coding strategies in number space: Memory requirements influence spatial-numerical associations

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Short article

Coding strategies in number space: Memory requirements influence spatial–numerical associations

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The tendency to respond faster with the left hand to relatively small numbers and faster with the right hand to relatively large numbers (*s*patial *n*umerical *a*ssociation of *r*esponse *c*odes, SNARC effect) has been interpreted as an automatic association of spatial and numerical information. We investigated in two experiments the impact of task-irrelevant memory representations on this effect. Participants memorized three Arabic digits describing a left-to-right ascending number sequence (e.g., *3–4–5*), a descending sequence (e.g., *5–4–3*), or a disordered sequence (e.g., *5–3–4*) and indicated afterwards the parity status of a centrally presented digit (i.e., *1, 2, 8*, or *9*) with a left/right keypress response. As indicated by the reaction times, the SNARC effect in the parity task was mediated by the coding requirements of the memory tasks. That is, a SNARC effect was only present after memorizing ascending or disordered number sequences but disappeared after processing descending sequences. Interestingly, the effects of the second task were only present if all sequences within one experimental block had the same type of order. Taken together, our findings are inconsistent with the idea that spatial–numerical associations are the result of an automatic and obligatory cognitive process but do suggest that coding strategies might be responsible for the cognitive link between numbers and space.

Keywords: Mental number line; SNARC effect; Coding strategy; Dual-task interference; Memory load.

Research in the field of mathematical cognition has accumulated evidence indicating that cognitive representations of numerical magnitudes are closely linked with representations of space. A striking demonstration of this connection is the so called effect of the *s*patial *n*umerical *a*ssociation

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of *r*esponse *c*odes (SNARC effect), which reflects the tendency of participants to respond faster with the left hand toward relatively small numbers and to respond faster with the right hand toward relatively large numbers (Dehaene, Bossini, & Giraux, 1993). This interaction between number size and spatial response features has been consistently interpreted as evidence that numerical magnitude information is spatially coded and is associated with a mental continuum ("mental number line") on which numbers are consecutively arranged in an ascending order from the left side to the right (for recent reviews see, e.g., Fias & Fischer, 2005; Hubbard, Piazza, Pinel, & Dehaene, 2005).

Several authors have proposed that the spatial representation of numbers along the mental number line can be described as an automatic and obligatory process. In this context, automatic coding of numerical magnitude is understood as a process that occurs without the intentional setting of the goal of the behaviour and does not require any conscious monitoring (see, e.g., Ganor-Stern, Tzelgov, & Ellenbogen, 2007). The idea of an automatic coding of numerical magnitude is supported by the findings showing that number magnitude effects on lateralized motor responses emerge even when the processing of a presented numeral is not required and is irrelevant for solving the task (Fias, Lauwereyns, & Lammertyn, 2001; Gevers, Lammertyn, Notebaert, Verguts, & Fias, 2006). Fias et al. (2001), for instance, reported a SNARC effect caused by numerals presented as background stimuli while participants were required to discriminate the orientation of lines and interpreted that both the activation of number meaning and the association of magnitude with space are obligatory cognitive processes. Further support for the idea that merely looking at numbers evokes an activation of spatial cognitive codes is coming from a study on visual–spatial attention reported by Fischer, Castel, Dodd, and Pratt (2003). The authors presented Arabic digits in the centre of the screen while participants preformed a simple detection task and found a shift in covert attention to the left or right side according to the relative size of the number. Although the cueing of visuospatial attention by numerals has often been assessed as important evidence for an automatic activation of the mental number line (Fias & Fischer, 2005; Hubbard et al., 2005), it is important to notice that attentional effects of numbers emerge far slower than effects of other symbolic cues with directional meaning (e.g., the words "left" and "right"; Hommel, Pratt, Colzato, & Godijn, 2001).

There is also a growing body of evidence suggesting that SNARC effects are influenced by top-down factors and that the associations between numbers and space are rather flexible. Since the first report of SNARC effects by Dehaene et al. (1993), it is known that the same number can be linked with either the left or the right side of space, depending on whether it is the smallest or the largest in the used range of numbers. Moreover, it has been shown that the same set of numerals evoke reversed SNARC effects if numbers are intentionally mapped with locations using a different spatial frame of reference (Bächthold, Baumüller, & Brugger, 1998; Galfano, Rusconi, & Umiltà, 2006; Ristic, Wright, & Kingstone, 2006; Vuilleumier, Ortigue, & Brugger, 2004). For example, Bächthold et al. (1998) asked participants to make speeded responses toward numbers ranging from 1 to 11 and instructed participants to conceive them either as distances on a ruler or as hours on an analogue clock face. Participants in the ruler condition showed a regular SNARC effect. Interestingly, in the clock face condition, where smaller numbers had to be associated with the right side of space (e.g., 3 o'clock) and large numbers with the left side (e.g., 9 o'clock), the SNARC effect reversed. This strong impact of the task instruction on the effects of number reading seems to suggest that the spatial coding of numerical magnitude can be dynamically adapted according to current task demands. Further support for the notion that SNARC effects are flexible and not restricted to a left-to-right oriented continuum can also be derived from the observation of large interindividual variability in the preferred default mapping of numbers and space. For example, we know from studies with English, Arabic, and Japanese participants that the spatial associations with numbers are strongly mediated by culturally acquired reading or scanning habits (Dehaene et al., 1993; Ito & Hatta, 2004; Zebian, 2005) as well as by learned finger-counting strategies (Di Luca, Granà, Semenza, Seron, & Pesenti, 2006). Taken together, there is accumulating evidence that spatial–numerical associations vary across different situations and across different groups of subjects. Thus, the SNARC effect may depend on the spatial frame of reference that is intentionally used or required by the task.

In the same vein, Fischer (2006) recently proposed that the spatial representation of numbers might be the result of an individual's strategic decision in the light of current task demands and not the consequence of an automatic activation of the mental number line. Although there is evidence showing that the selection of a spatial–numerical reference frame for magnitude representation depends on task demands as well as on cultural factors, the literature does not provide consistent evidence whether the activation of spatial codes in number cognition is an automatic obligatory process or, conversely, whether it is the result of a volitionally controlled cognitive strategy to deal with magnitude information.

Importantly, a crucial criterion for describing a cognitive process as being automatic is the absence of any dual-task interference (see, e.g., Palmeri, 2002). Consequently, if the association between numbers and space can be described as an automatic process, the presence of a SNARC effect should not be affected by requirements of a second unrelated task and should not interfere with spatial–numerical cognitive codes activated at the same time. To our knowledge, there is no definitive empirical evidence showing that the SNARC effect is either sensitive or insensitive to interference from an unrelated number task. Given this dearth in the literature, the goal of the present study was to test whether the spatial representations of numbers in one task are modulated by the coding requirements of a second simultaneously performed memory task. If number processing results automatically in an activation of the mental number line, the presence of the SNARC effect should not be influenced by the demands of the second task. If the mental number line represents, however, the current cognitive coding strategy of a person, the SNARC effect should be affected by the sequential order of an activated memory representation and by an activation of spatial mnemonic strategies for the second task.

EXPERIMENT 1

Participants were required to judge the parity status of Arabic numerals (parity task) after they had memorized a short sequence of three digits for later recall (memory task). The digits were arranged so that they formed a left-to-right ascending number sequence (e.g., *3–4–5*), a descending sequence (e.g., *5–4–3*), or a disordered sequence (e.g., *5–3–4*). The type of digit sequence was varied between three experimental blocks. Assuming that the mapping of numbers onto space is the result of a cognitive coding strategy (Fischer, 2006), the SNARC effect in the parity task should be affected by the ordering of the digits in the memory task. Specifically, we expect the SNARC effect to be diminished or even reversed in the experimental block of descending number sequences.

Method

Participants

A total of 22 students of the Radboud University Nijmegen (2 males; average age: 21.2 years) participated in the experiment in return for course credits.

Apparatus and stimuli

Participants faced three horizontally aligned square outlines, which served as placeholder boxes for the presentation of the number stimuli. From viewing distance of about 70 cm, each of these frames measured 3.8° of visual angle. All numbers were printed in black sans serif fonts on light-grey background and subtended a horizontal visual angle of about 1.3°. Reaction times were measured with using a custom-built external response box with three horizontally aligned buttons.

The to-be-memorized number sequences were composed of three consecutive Arabic digits between 3 and 7. They could be subdivided in three categories: sequences with a left-to-right *ascending order* (e.g., *3–4–5*), sequences with a left-to-right *descending order* (e.g., *5–4–3*), and sequences with no monotone order (*no order*; e.g., *5–3–4* or *4–5–3*). Only number sequences with no order that did not share any digit location with the corresponding ascending sequence were selected (i.e., sequences like, e.g., *3–5–4* or *4–3–5* were excluded). As target stimuli for the parity task, we used a different set of Arabic digits—namely, the numbers *1*, *2*, *8*, and 9. Thus, half of the target digits in the parity task were smaller than the digits of the memory task, and the other half of the targets were larger.

Procedure

Figure 1 illustrates the sequence of events in one trial. All trials started with the presentation of a number sequence, where each digit was displayed in the centre of another placeholder box. Participants were required to memorize all digits and their relative locations (left, central, and right locations) for later recall. After a presentation time of 2,500 ms, each digit was replaced by a sharp symbol ("#") that remained visible for 50 ms. After a period of 500 ms, a fixation cross appeared in the central placeholder box and was replaced after 1,000 ms by a single digit. Participants' task was to indicate as soon as possible the parity status (odd or even) of this number by means of a left- or right-hand keypress response (i.e., pressing the left or right button of the response box). The assignment of response keys to odd and even digits was balanced across participants. The digit disappeared after responding or if no response was given after 1,000 ms (missing response). Afterwards, one digit of the previously presented number sequence was randomly chosen and displayed in each of the three placeholder boxes. Participants were required to recall the former location of this digit in the sequence and indicate their answer by pressing the corresponding button of the response box (i.e., left, central, or right button). There was no time limit for the location recall. The intertrial interval was 2,000 ms. In the case of an incorrect response in the parity or memory task, a 4,400-Hz beep sound (lasting 200 ms) was presented as acoustic error feedback.

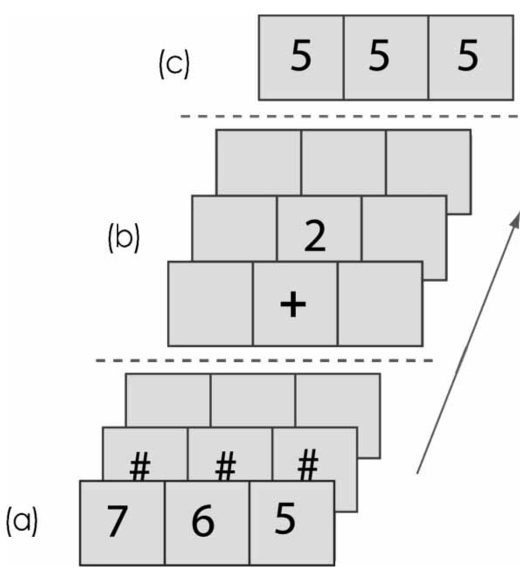

Figure 1. *Illustration of the sequence of events in Experiments 1 and 2. (a) Participants memorized the locations of three digits before (b) judging the parity status of the centrally presented digit. (c) Each trial ended with a recall of the location of one of the three digits. See text for detailed descriptions.*

Design

The digit sequence types (ascending order, descending order, and no order) were systematically varied between three experimental blocks. Thus, for all sequences within one block the digits were arranged in the same order. Each block comprised 72 trials presented in random order. They were composed of all possible combinations of the four target numbers and the digit sequences of this particular experimental block. The order of blocks was permutated across participants. Before the actual experiment started, participants performed 38 randomly chosen training trials.

Data analysis

Trials with incorrect parity judgements or incorrect position recalls were identified and removed from the reaction time (RT) analyses. We calculated the mean RT and error rate in the parity task for each participant and each possible combination of the factors number magnitude (small: *1* and *2*; large: *8* and *9*), response side (left, right), and sequence type (ascending order, descending order, no order) and analysed the data using repeated measures analyses of variance (ANOVA). A one-factorial ANOVA was performed on the error rates in the position recall task to test for effects of the sequence type. In all statistical tests reported here, a Type I error rate of $\alpha = .05$ was used.

The SNARC effect in the present paradigm was represented by an interaction between the factors number magnitude and response side. In order to obtain in this type of ANOVA design a standardized estimate of the size of the observed SNARC effect, we calculated the effect size parameter η^2 of this interaction and its 95% confidence interval, CI (see Smithson, 2001). Since the parameter η^2 provides an estimation of the proportion of variance accounted by the effect, it represents a generalization of the correlation coefficient r^2. The SNARC effect size η^2_{SNARC} allows therefore a direct comparison with studies employing regression analyses (e.g., Fias, Brysbaert, Geypens, & d'Ydewalle, 1996), in which the SNARC effect is quantified by the correlation of the number magnitudes with the reaction time differences between left- and right-hand responses.

Results

The analyses of the error rates in the parity judgement task and the position recall task (see Table 1 for means) did not reveal any effect of the factor sequence type, both Fs$(2, 42) < 1$. Also none of the other effects in the ANOVA of judgement errors reached significance, all Fs < 1.8.

The mean RTs in the parity judgement task are depicted in Figure 2. The ANOVA revealed two significant effects: The two-way interaction between the factors number magnitude and response side, $F(1, 21) = 6.90$, $MSE = 3{,}475$, $p < .05$, indicated the presence of an overall SNARC effect across all sequence types. That is, left-hand responses were faster to small digits (523 ms) than to large digits (547 ms), $t(21) = 2.23$, $p < .05$. This effect tended to be reversed for right-hand responses (535 ms vs. 520 ms), $t(21) = -1.67$, $p = .11$. Most importantly, however, the analysis revealed a significant three-way interaction, $F(2, 42) = 7.36$, $MSE = 935$, $p < .01$, $\hat{\eta}^2 = .26$, which indicates that SNARC effects were affect by the factor sequence type. None of the main effects reached significance, all Fs < 1.3.

To explore the pattern of the high-order interaction, we tested the interactions between number magnitude and response side separately for each experimental block. Interestingly, SNARC

Table 1. *Percentages of errors in Experiments 1 and 2*

		Experiment 1			*Experiment 2*		
Task		*Ascending order*	*Descending order*	*No order*	*Ascending order*	*Descending order*	*No order*
Parity judgement	Left hand–small number	1.28	2.90	1.26	1.83	1.80	1.29
	Left hand–large number	1.81	2.55	2.04	7.07	6.86	6.00
	Right hand–small number	3.57	1.80	2.27	6.47	5.56	6.80
	Right hand–large number	0.52	2.78	1.81	1.91	3.10	0.56
Position recall		1.41	1.18	1.14	3.64	2.46	3.59

Note: Error rates in the parity judgement task are presented as a function of the factors sequence type, response side, and number magnitude. Errors rates in the position recall task are presented as a function for the factor sequence type.

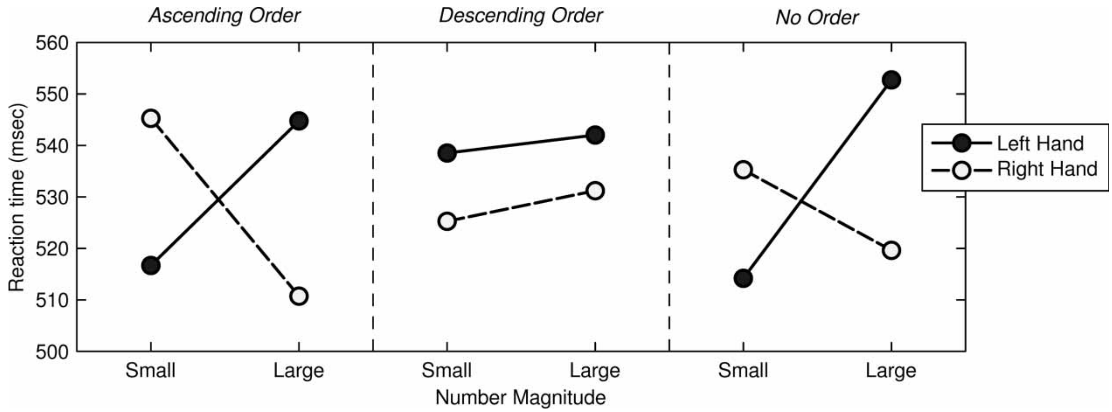

Figure 2. *Mean reaction times in the parity judgement task of Experiment 1 as a function of the factors number magnitude, response side, and sequence type.*

effects were present in the blocks with ascending order, $F(1, 21) = 25.36$, $MSE = 850$, $p < .001$, $\hat{\eta}^2_{SNARC} = .55$, ($CI = [.22, .71]$), and no order, $F(1, 21) = 9.45$, $MSE = 1{,}709$, $p < .01$, $\hat{\eta}^2_{SNARC} = .31$, ($CI = [.03, .54]$), but not in the block with descending order, $F(1, 21) < 1$, $\hat{\eta}^2_{SNARC} < .001$.

Discussion

A SNARC effect was present if participants memorized an ascending number sequence but vanished completely in the block where the order of descending number sequences had to be recalled. Since a SNARC effect was also found for sequences of no monotonic order, we can exclude that the dissociation of the effect was merely the result of a higher task difficulty in the descending block or a general cognitive effect of the increased memory load. Moreover, the lack of a SNARC effect did not reflect any speed–accuracy trade-off because the analysis of error rates in the parity judgement and position recall task did not reveal any effect of the sequence type. Thus, the results of Experiment 1 clearly show that the SNARC effect is modulated by the cognitive coding of short descending number sequences. More specifically, the spatial representations of numbers in the parity task were affected by the specific spatial coding requirements and the resulting memory traces of the second task.

Since the manipulation of the sequence type was varied only between the three experimental blocks, the internal ordering of the digits was known before the trial started. It is therefore likely that the knowledge about the ordering of the upcoming sequence has been used to simplify the coding and recall of the number locations. That is, participants may have used in the block of descending sequences the concept of right-to-left orientated number line as strategy to code the digit location. This mnemonic strategy of a reversed number line, however, is in conflict with the spatial–numerical coding in the parity task and may therefore explain the vanishing of the SNARC effect. Alternatively, it might be also possible that the mere coding of three digits in a descending order automatically activates a spatially reversed mental number line and interferes therefore with the subsequent spatial coding of numbers. In order to distinguish between these two accounts—automatic activation of opposite number lines versus selected memory strategy—we performed a second experiment.

EXPERIMENT 2

Experiment 1 has demonstrated that the SNARC effect vanishes if the actual memory task required a coding of numbers arranged in descending order.

Experiment 2 tests whether the same interference can be observed if the type of ordering is randomized on trial-by-trial basis. If the sequence type is not predictable, participants cannot use their prior knowledge about the sequence ordering to code the digit locations. Consequently, we should expect the SNARC effect to be unaffected by the sequence type in the memory task, if a coding strategy of oriented number lines was responsible for the inhibition of spatial–numerical associations. If, however, the mere representation of three numbers in a descending order results automatically in an activation of a reversed number line, we expect the SNARC effect to be modulated by the sequence coding as was the case in Experiment 1.

Method

Participants

A total of 22 students of the Radboud University Nijmegen (4 males; average age: 22.2 years) participated in Experiment 2 in return for course credits. None of them took part in the previous experiment.

Apparatus, stimuli, procedure, design, and data analysis

The experimental setup, stimuli, procedure and data analysis were identical to those in Experiment 1. The only modification was related to the order of trial presentation. Again, participants ran through three experimental blocks of 72 trials. However, instead of varying the factor sequence type between blocks, all trials were this time fully randomized. Thus, each experimental block comprised trials with all three types of digit ordering.

Results

As found before, there were no effects of the sequence type in the error rates of the parity judgement task and position recall task, $F(2, 42) < 1$, and $F(2, 42) = 1.52$, respectively (see Table 1 for means). The ANOVA of the judgement errors revealed an interaction between response side and number magnitude, $F(1, 21) = 15.15$, $MSE = 1{,}464$, $p < .001, \hat{\eta}^2 = .42$, reflecting a SNARC effect in the accuracy data. That is, participants made fewer judgement errors if the parity of small numbers had to be indicated with the left hand (1.64%) than with the right hand (6.27%), $t(21) = -3.06$, $p < .01$, while this effect reversed for large numbers (6.64% vs. 1.86%), $t(21) = 3.59$, $p < .01$.

The ANOVA of the RT data (see Figure 3 for means) yielded a main effect for the factor response side, $F(1, 21) = 6.27$, $MSE = 2{,}468$, $p < .05$, indicating that right-hand responses (546 ms) were faster than left-hand responses (562 ms). Also the interaction between the response side and number magnitude reached significance, $F(1, 21) = 39.60$, $MSE = 2{,}791$, $p < .001$. That is, left-side responses were faster in response to small numbers (541 ms) than to large numbers (582 ms), $t(21) = 5.01$, $p < .001$, while right-side responses were slower to small (567 ms) than to large numbers (526 ms), $t(21) = -4.56$, $p < .001$. Most important, however, the three-way interaction between the factors response side, number magnitude, and number sequence failed to reach significance, $F(2, 30) < 1$. Since the statistical power[1] was sufficient to detect a three-way interaction effect as observed in Experiment 1, $(1 - \beta) = .80$, the analysis indicates that the SNARC effect was not mediated by the type of number sequence.

As shown by separate tests for interaction between number magnitude and response side, SNARC effect size did not differ for all sequence type conditions: ascending order, $F(1, 21) = 20.98$, $MSE = 2{,}172$, $p < .001$, $\hat{\eta}^2_{SNARC} = .50$, ($CI = [.17, .68]$), descending order, $F(1, 21) = 26.27$, $MSE = 801$, $p < .001$, $\hat{\eta}^2_{SNARC} = .56$, ($CI = [.23, .71]$), and no order, $F(1, 21) = 22.23$, $MSE = 2{,}123$, $p < .001$, $\hat{\eta}^2_{SNARC} = .51$, ($CI = [.18, .69]$).

[1] The statistical power analysis was based upon the effect size for the three-way interaction and the correlation between the measures of Experiment 1. The power calculations were performed using the program G*Power 3 (Faul, Erdfelder, Lang, & Buchner, 2007).

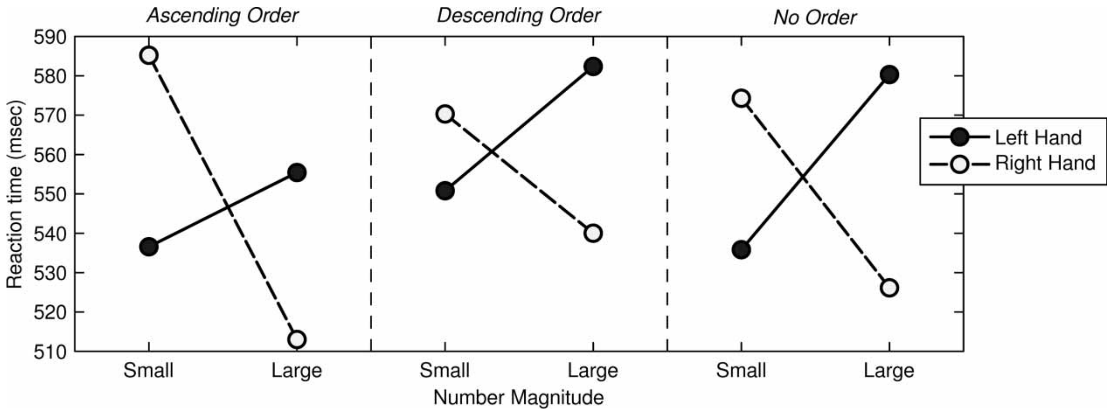

Figure 3. *Mean reaction times in the parity judgement task of Experiment 2 as a function of the factors number magnitude, response side, and sequence type.*

Discussion

Experiment 2 revealed that if digit ordering varied randomly, the SNARC effect was not affected by the coding of number locations between trials and was now also present when participants memorized digits in a descending order. It can therefore be concluded that the mere coding of a digit sequence in the memory task was not sufficient to affect the spatial representation of numbers in the parity task. This argues against the explanation that the findings in Experiment 1 were the result of an automatic activation of two oppositely oriented mental number lines. Rather, Experiment 2 suggests that participants were unable to adopt a strong spatial coding strategy for sequences. Apparently, participants represent the sequences under these circumstances as three independent numbers without their inner structure and did not activate the concept of a mental number line. Thus, the results of Experiment 2 support the account that it was the cognitive strategy in the memory task of Experiment 1 that influenced the spatial representation of numbers in the parity task.

GENERAL DISCUSSION

The present study demonstrates that the cognitive association of numbers and space is influenced by current task demands. We observed that the SNARC effect in a parity task is mediated by the specific sequential order involved in a simultaneously performed unrelated numerical task. This finding is inconsistent with the assumption of an automatic obligatory spatial representation of numbers along the mental number line. Since a SNARC effect was found under dual-task conditions when the memorized number sequences had no internal monotonic order (Experiment 1), as well as when the number ordering was unpredictable (Experiment 2), the observed interference with the descending sequences in the first experiment cannot be due to an increased task difficulty or a higher cognitive load in general. Moreover, this mediation of the SNARC effect was not due to any sequence-specific speed–accuracy trade-off. We argue consequently that the specific requirement to maintain a short-term memory representation of numbers in a descending order was responsible for the lack of spatial–numerical associations in the parity judgement task.

Interestingly, the SNARC effect was only sensitive to the sequential order of the memory representations if all number sequences within one experimental block were identically ordered (Experiment 1), but not if the sequence type was fully randomized (Experiment 2). This dissociation in the SNARC effect can be explained by the use of different coding strategies when sequences types were blocked or completely randomized. That is, if numbers are repetitively arranged in a descending order, participants seem to use the information about the right-to-left digit ordering to simplify the processing of the number locations. This activated spatial–numerical frame of reference, however, is in conflict with the representation of magnitude along a left-to-right oriented mental number line and seems to result in an absence of spatial–numerical associations. In other words, we interpret that the use of spatial strategies in the memory task modulated the spatial coding of numbers for parity judgements. The outcome of the present study is therefore consistent with the notion that the SNARC effect is driven by top-down processes and provides direct empirical support for the idea of a strategic origin of the mental number line (Fischer, 2006).

In contrast to our interpretation that the SNARC effect depends on the concurrent task requirements, several authors have argued that spatial numerical associations are driven by an automatic activation of the mental number line. This idea has so far received support from studies showing that numerical magnitude information activates spatial codes even under conditions in which number processing is irrelevant for the task performance (Fias et al., 2001; Gevers et al., 2006). However, the notion of an automatic SNARC effect implies not only that spatial codes are evoked by task-irrelevant magnitude information. It is also important to notice that the assumption of automaticity entails by definition the presence of an obligatory cognitive process, which is immune against the influence of any other task concurrently executed (Palmeri, 2002). With the present paradigm, we now provide a direct behavioural test of this prediction and demonstrate for the first time that SNARC effects are strongly affected under certain dual-task conditions. This outcome clearly argues against the idea that spatial–numerical associations are the result of an automatic and obligatory cognitive process.

An interesting aspect of the current data is that the SNARC effect disappeared, but did not reverse, when descending number sequences were memorized. A reason for this might be that the two tasks were functionally unrelated and independent from each other. Apparently, participants do not employ a preexisting spatial structure that has been activated for one task to process numbers for another task. Instead, they seem to refrain from spatial number processing if it is under dual-task conditions that are in conflict with concurrently activated and to-be-maintained memory representations. Thus, together with the finding of a SNARC effect for disordered sequences, which demonstrate the participants' preference for a left-to-right mapping of numbers with space, our data indicate that this highly overlearned spatial coding strategy can be ignored in certain situations. The lack of a reversed SNARC effect further suggests that the coding of numbers along a mental continuum oriented differently than the default mental number line is a more effortful process that will not be performed if it is not required or beneficial for solving the task (see Bächthold et al., 1998).

Our report that the spatial coding of numbers is affected by the memory requirements of a second unrelated task substantially extends previous research demonstrating that the SNARC effect is sensitive to contextual task-related information (Dehaene et al., 1993) and affected if participants are explicitly instructed to use a different frame of reference for the spatial mapping of numbers (Bächthold et al., 1998; Galfano et al., 2006; Ristic et al., 2006; Vuilleumier et al., 2004). In line with these studies, we demonstrate that left-to-right orientation of the mental number line is not obligatory and can be easily adapted or inhibited if the current task requires conceiving of numbers differently. Moreover, our findings demonstrate that the SNARC effect is modulated by the sequential order of task-irrelevant memory representations and by the activation of spatial–numerical reference frames in another simultaneously performed task.

Taken together, the present study provides support for the idea that the spatial coding of numbers is the result of a cognitive coding strategy of how to deal with numerical magnitude information.

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REFERENCES

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

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

Di Luca, S., Grana, A., Semenza, C., Seron, X., & Pesenti, M. (2006). Finger-digit compatibility in Arabic numeral processing. *Quarterly Journal of Experimental Psychology*, *59*, 1648–1663.

Faul, F., Erdfelder, E., Lang, A.-G., & Buchner, A. (2007). G*Power 3: A flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behavior Research Methods*, *9*, 175–191.

Fias, W., Brysbaert, M., Geypens, F., & d'Ydewalle, G. (1996). The importance of magnitude information in numeric processing: Evidence from the SNARC effect. *Mathematical Cognition*, *2*, 95–100.

Fias, W., & Fischer, M. (2005). Spatial representation of numbers. In J. I. D. Campbell (Ed.), *Handbook of mathematical cognition* (pp. 43–54). Hove, UK: Psychology Press.

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.

Fischer, M. H. (2006). The future for SNARC could be stark. *Cortex*, *42*, 1066–1068.

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

Galfano, G., Rusconi, E., & Umiltà, C. (2006). Number magnitude orients attention, but not against one's will. *Psychonomic Bulletin and Review*, *13*, 869–874.

Ganor-Stern, D., Tzelgov, J., & Ellenbogen, R. (2007). Automaticity of two-digit numbers. *Journal of Experimental Psychology: Human Perception and Performance*, *33*, 483–496.

Gevers, W., Lammertyn, J., Notebaert, W., Verguts, T., & Fias, W. (2006). Automatic response activation of implicit spatial information: Evidence from the SNARC effect. *Acta Psychologica*, *122*, 221–233.

Hommel, B., Pratt, J., Colzato, L., & Godijn, R. (2001). Symbolic control of visual attention. *Psychological Science*, *12*, 360–365.

Hubbard, E. M., Piazza, M., Pinel, P., & Dehaene, S. (2005). Interactions between number and space in parietal cortex. *Nature Reviews Neuroscience*, *6*, 435–448.

Ito, Y., & Hatta, T. (2004). Spatial structure of quantitative representation of numbers: Evidence from the SNARC effect. *Memory and Cognition*, *32*, 662–673.

Palmeri, T. J. (2002). Automaticity. In L. Nadel (Ed.), *Encyclopedia of cognitive science* (pp. 390–401). London: Nature Publishing Group.

Ristic, J., Wright, A., & Kingstone, A. (2006). The number line effect reflects top-down control. *Psychonomic Bulletin and Review*, *13*, 862–868.

Smithson, M. (2001). Correct confidence intervals for various regression effect sizes and parameters: The importance of noncentral distributions in computing intervals. *Educational and Psychological Measurement*, *61*, 605–632.

Vuilleumier, P., Ortigue, S., & Brugger, P. (2004). The number space and neglect. *Cortex*, *40*, 399–410.

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