Journal of Experimental Psychology: General
2010, Vol. 139, No. 1, 180–190

0096-3445/10/$12.00 DOI: 10.1037/a0017688

Verbal-Spatial and Visuospatial Coding of Number–Space Interactions

Wim Gevers
Université Libre de Bruxelles

Seppe Santens, Elisah Dhooge, Qi Chen,
Lisa Van den Bossche, Wim Fias, and Tom Verguts
Ghent University

A tight correspondence has been postulated between the representations of number and space. The spatial numerical association of response codes (SNARC) effect, which reflects the observation that people respond faster with the left-hand side to small numbers and with the right-hand side to large numbers, is regarded as strong evidence for this correspondence. The dominant explanation of the SNARC effect is that it results from visuospatial coding of magnitude (e.g., the mental number line hypothesis). In a series of experiments, we demonstrated that this is only part of the story and that verbal-spatial coding influences processes and representations that have been believed to be purely visuospatial. Additionally, when both accounts were directly contrasted, verbal-spatial coding was observed in absence of visuospatial coding. Relations to other number–space interactions and implications for other tasks are discussed.

Keywords: SNARC effect, numerical cognition

The idea that higher level cognition is grounded on sensorimotor foundations has recently received much interest (Barsalou, 1999, 2008; Dehaene & Cohen, 2007; Lakoff & Núñez, 2000). One instance of this trend concerns the idea that the abstract dimension of number is deeply rooted in the concrete dimensions of space. For instance, it has been assumed that numerical–spatial interactions originate from neural circuits that are commonly involved in attending to external space and in representing numerical information (Hubbard, Piazza, Pinel, & Dehaene, 2005). This is reflected in the popular metaphor of the *mental number line,* which assumes a tight correspondence between the left–right coordinates of external space and the representation of numbers (Dehaene, 1997; Restle, 1970).

Good evidence does exist for such a spatial organization of numbers. One important source of evidence comes from patients with left neglect following a right hemisphere lesion. These patients fail to report, orient to, or verbally describe stimuli in the contralesional left hemispace (for a review, see Halligan, Fink, Marshall, & Vallar, 2003). When these patients are asked to bisect a visually presented physical line, the line is typically bisected toward the ipsilesional, not-neglected hemispace. Similar observations were made in representational space (Bisiach & Luzzatti, 1978). When asked to describe familiar places (e.g., the Piazza del Duomo), these patients omitted details about what would have been their left-hand side. Zorzi, Priftis, and Umiltà (2002) extended these observations of physical and representational neglect to the numerical domain. When left-neglect patients bisected numerical intervals, a significant displacement toward large numbers, corresponding to the right side of the mental number line, was observed. For instance, when a patient was asked to indicate, without calculating, the midpoint of an orally presented number interval (e.g., "What number lies in the middle between 1 and 9?"), the patient would typically answer, "7." This result could reasonably be explained by assuming an isomorphism between physical lines and the mental number line. A further illustration of this tight link between the processing of numerical information and physical space was provided by Rossetti and colleagues (2004). Neglect patients were asked to point to visual targets while wearing prisms that induce a rightward optical shift. It was observed that such an adaptation task improved performance not only in bisection of physical lines but also in bisecting numerical intervals.

Another observation that is regarded as strong evidence for a tight correspondence between the representation of numbers and physical space is the spatial numerical association of response codes (SNARC) effect. The SNARC effect reflects the observation that responses are faster for relatively small numbers with the left-hand side and faster for relatively large numbers with the right-hand side (Dehaene, Dupoux, & Mehler, 1990). The existence of this spatial association between numbers and space was first observed in an experiment where magnitude information was relevant and responses were lateralized. Dehaene et al. (1990) made participants classify numbers as larger or smaller than 65 by pressing a left or right response key. Large numbers were classified faster with the right hand, and small numbers were classified faster with the left hand. Other experiments have shown that magnitude information does not need to be relevant to obtain the

Wim Gevers, Unité de Recherché en Neurosciences Cognitives, Université Libre de Bruxelles, Brussels, Belgium; Seppe Santens, Elisah Dhooge, Qi Chen, Lisa Van den Bossche, Wim Fias, and Tom Verguts, Department of Experimental Psychology, Ghent University, Ghent, Belgium.

Part of this work was conducted while Wim Gevers was supported as a postdoctoral researcher by the FWO-Flanders. The contribution of Tom Verguts and Wim Fias was supported by Grant BOF08/GOA/011 from Ghent University. The contribution of Seppe Santens was supported by Grant BOF 01J01406 from Ghent University. The contribution of Elisah Dhooge was supported by Grant FWO B/09670/01. The contribution of Qi Chen was supported by Grant BOF 01D02106 from Ghent University.

Correspondence concerning this article should be addressed to Wim Gevers, Unescog: Unité de Recherche en Neurosciences Cognitives, Université Libre de Bruxelles, Avenue F. D. Roosevelt 50, 1050 Brussels, Belgium. E-mail: Wim.Gevers@ulb.ac.be

SNARC effect. For instance, it has been observed in parity (i.e., odd–even status) judgment tasks (Dehaene, Bossini, & Giraux, 1993) and in tasks where the number itself is totally irrelevant to the task (Fias, Lauwereyns, & Lammertyn, 2001). Although participants merely had to judge the orientation of a triangle superimposed on a centrally presented Arabic number in the Fias et al. (2001) study, small (large) numbers were responded to faster with the left (right) hand.

The dominant explanation for the SNARC effect is, just as for the number interval bisection tasks, that it results from a tight correspondence between the position of a number on a continuous left-to-right-oriented representational medium (the mental number line) and the spatial position of the response (or the stimulus; Fischer, Castel, Dodd, & Pratt, 2003; e.g., Bächtold, Baumüller, & Brügger, 1998; Casarotti, Michielin, Zorzi, & Umiltà, 2007; Dehaene et al., 1993; Fias et al., 2001; Fischer, 2003; Gevers, Reynvoet, & Fias, 2003; Hubbard et al., 2005; Mapelli, Rusconi, & Umiltà, 2003; Song & Nakayama, 2008; Stoianov, Kramer, Umiltà, & Zorzi, 2008). We refer to this explanation as a visuospatial coding account. This account further assumes that the positions of numbers on a number line are associated with extracorporal space and not with the effectors operating in that space. More generally, numerical–spatial interactions arise at a central level, independent of input modality or output effector (Hubbard et al., 2005). Indeed, the SNARC effect still appears when participants perform the task with hands crossed (Dehaene et al., 1993), with foot responses (Schwarz & Müller, 2006), with saccade responses (Fischer, Warlop, Hill, & Fias, 2004; Schwarz & Keus, 2004), and with unimanual pointing responses. (e.g., Fischer, 2003; Gevers, Lammertyn, Notebaert, Verguts, & Fias, 2006). Besides numerical cognition, visuospatial coding was also the dominant framework in studies on the SNARC effect in other dimensions or domains, such as music (Lidji, Kolinksky, Lochy, & Morais, 2007; Rusconi, Kwan, Giordano, Umiltà, & Butterworth, 2006), time (Santiago, Lupianez, Perez, & Funes, 2007), and language (De Brauwer, Duyck, & Brysbaert, 2007).

This body of research has clearly indicated that number and space exhibit dimensional overlap (Kornblum, Hasbroucq, & Osman, 1990). However, recent theories have questioned whether this dimensional overlap is of a visuospatial nature. Gevers, Verguts, Reynvoet, Caessens, and Fias (2006); Proctor and Cho (2006); and Santens and Gevers (2008) pointed to the importance of conceptual similarity between dimensions. In particular, they proposed that the SNARC effect does not result from internal left-to-right-oriented continuous number representations (visuospatial coding) but instead from an association between verbal concepts such as "small" and "left" and "large" and "right." For instance, the polarity coding account proposed by Proctor and Cho starts from the fact that opposite concepts such as "small" and "large" together determine a category. Other similar categories are formed by pairs of concepts such as "odd"–"even," "left"–"right," "up"–"down," and so on. Each of these concepts is associated with either a positive or a negative polarity. According to this view, a SNARC effect is observed because the concepts "small" and "left" refer to the same negative (−) polarity whereas the concepts "large" and "right" refer to the same positive (+) polarity. In a similar vein, the dual route account proposed by Gevers, Verguts, et al. argues that the SNARC effect results from learned connections between magnitude labels (small–large) on the one hand and spatial representational labels (left–right) on the other. In the neural network model presented by these authors, it is assumed that small (large) numbers automatically activate the small (large) label. These magnitude labels in turn activate the spatial left and right labels. Hence, if the task requires a left (right) response for a small (large) number, responding will be facilitated. Regardless of the specific functional details, both Proctor and Cho and Gevers et al. assumed that the SNARC effect results from verbal coding of space, so we refer to this interpretation as the *verbal-spatial account.*

This contrast between visuospatial and verbal-spatial accounts relates more broadly to Paivio's (1986) dual coding theory. According to this framework, objects are coded both in an analogue and in a verbal-symbolic system. In the analogue system, properties of the object (e.g., length, color) are represented in an analogue way; in the simplest case, one might imagine that a larger number of neurons are recruited for a larger object, so that the length property is thus analogously encoded. In the verbal-symbolic system, on the other hand, the coding does not retain analogue properties but instead substitutes an essentially symbol for the object at hand. An example is the (verbal) word *dog* for representing a dog. Because language constitutes the prototypical symbolic system, this coding system is called *verbal-symbolic* in Paivio's terminology.

When applied to the numerical cognition literature, the visuospatial system is an instance of the analogue system of Paivio (1986). Indeed, the defining characteristic of the visuospatial number system is that an analogue representation of number (in spatial coordinates) is generated. On the other hand, the verbal-spatial system proposed by Proctor and Cho (2006) and by Gevers, Verguts, et al. (2006) is an instance of Paivio's verbal-symbolic system. Given that objects generally can be represented in both systems (e.g., Lupker, 1979; Rosinski, 1977), it seems plausible also that numbers can be represented in both ways. Hence, we argue that there are both visuospatial and verbal-spatial representational frames for number and that the SNARC effect can result from both. With respect to the visuospatial frame, the SNARC effect can result from a congruency between the position of the effector or the stimulus itself and the number's position in the visuospatial frame. With respect to the verbal-spatial frame, the SNARC effect results from a congruency between verbally coding numbers as small or large and verbally coding responses as left or right. Indeed, it is exactly this categorization of external space through verbal concepts such as "left," "right," "above," or "below" that defines our conceptual coding of space.

Despite both frameworks having appeared recently in the literature, they have not been systematically compared. The purpose of the present article is to do exactly this. In Experiment 1, we investigated whether verbal-spatial coding is sufficient to generate a SNARC effect; in Experiment 2, we investigated whether visuospatial coding is sufficient. These two experiments already establish an important aim because the two coding systems have never been clearly distinguished in the numerical cognition literature and are therefore typically confounded in experimental designs. To compare the relative strengths of the two coding systems, in Experiments 3 and 4, we pitted both directly against each another, in a parity judgment and a magnitude comparison task, respectively.

Experiment 1

In previous studies, the association between numbers and space has been observed when either the target stimuli (Fischer et al., 2003; Galfano, Rusconi, & Umiltà, 2006; Ristic, Wright, & Kingstone, 2006; Tlauka, 2002) or the responses (e.g., Dehaene et al., 1993) were physically lateralized. In the present experiment, we tested the SNARC effect without any physical lateralization. Target numbers were presented at the center of the screen, and participants had to respond verbally, by saying "left" or "right" in response to the parity of the target number (e.g., if the presented number is odd, say "left"; if it is even, say "right"). Hence there is verbal-spatial coding at the level of the responses, but visuospatial congruency is not possible because there is no physical lateralization of either stimuli or responses. As a control condition, the same participants performed the same task with physically lateralized manual responses (press left or right in response to number parity). Note that in this control condition, there is the typical confound between the two coding systems: Pressing a left button to a small number, for example, could be faster either because the response is located left in physical space (visuospatial coding) or because the label *small* associated to the small number evokes the concept "left" (verbal-spatial coding).

Method

Participants. 16 Dutch-speaking volunteers (4 female, 12 male) with a mean age of 22 years participated in the experiment. All participants took part in this experiment only. All participants were naive with respect to the objective of the study and had normal or corrected to normal vision.

Apparatus and stimuli. The experiment was run on a PC running Tscope (Stevens, Lammertyn, Verbruggen, & Vandierendonck, 2006). Responses were registered with a response box or a voice key, depending on the task. All stimuli were presented in a white lowercase Arial font (14-pt. type) on a black background. A hash mark (#) served as the fixation mark. Stimuli were the Arabic numbers from 1 to 9 with the exception of 5. Target numbers and the fixation mark were viewed from a distance of approximately 60 cm.

Procedure. All participants performed the parity judgment task both with a spoken and a manual response modality. Within each task, each participant completed two blocks. Order of task and blocks was counterbalanced across participants. In the manual task, even numbers had to be responded to with the right-hand (left-hand) button and odd numbers with the left-hand (right-hand) button. In the subsequent block, this response assignment was reversed. Similarly, during the verbal task, participants had to say "left" ("right") to even numbers and "right" ("left") to odd numbers. In the subsequent block, this response assignment was reversed. Before the experimental session, a practice block was run in which each target number was presented twice. During the experimental session, each block consisted of 24 presentations per target number, leading to a total of 192 trials. Between blocks, participants were allowed to take a break.

Each target number was preceded by a fixation mark (#) in the center of the screen for 500 ms and was then replaced by the target number. This target remained on the screen until response or until 3,000 ms had elapsed. In the verbal task, after the participant responded, the experimenter noted the answer and initiated a new trial. For the manual task, the intertrial interval was set to 1,000 ms.

Results and Discussion

In the verbal condition, the mean percentage of unreliable measurements due to coughs or noise was 5.96%, and these were discarded from further analysis. The mean percentage of errors was 2.12% and 1.81% for the verbal and the manual conditions, respectively. Correct median reaction times (RTs) were subjected to a $2 \times 2 \times 2$ repeated measures analysis of variance (ANOVA) with three within-subject factors: task (2: manual, verbal), magnitude (2: small, large), and response (2: left, right). A significant main effect was observed for magnitude, $F(1, 15) = 6.07$, $p < .05$. Small numbers were responded to faster than large numbers. An overall SNARC effect was observed as indicated by the significant interaction between magnitude and response, $F(1, 15) = 15.38$, $p < .01$. The SNARC effect did not interact with task, $F(1, 15) = 1.76$, $p = .20$. The interactions between magnitude and response were significant for both the manual, $F(1, 15) = 15.42$, $p < .01$, and the verbal, $F(1, 15) = 7.29$, $p < .05$, tasks. (A detailed overview of median RT and standard errors of measurement for all experiments for all conditions can be found in the Appendix.)

Error rates were first subjected to an arcsin transformation (Bishop, Fienberg, & Holland, 1975, pp. 376ff), followed by an ANOVA with the same factors as the RTs. Again, a significant main effect for magnitude was obtained, $F(1, 15) = 5,89$, $p < .05$. There was also a SNARC effect in the error rates: interaction between magnitude and response, $F(1, 15) = 17.66$, $p < .001$. Again, the SNARC effect did not interact with task, $F(1, 15) < 1$.

There is a different method that is often used to test the SNARC effect; here, for each number, the difference in RT (response right minus response left) is entered in a regression analysis for each participant separately with magnitude as predictor (e.g. Fias, Brysbaert, Geypens, & d'Ydewalle, 1996; Lorch & Myers, 1990). The regression weight of the magnitude predictor (Levels 1–9, omitting Level 5) is used as an index of the SNARC effect. The results showed a highly significant SNARC effect both in the manual, $t(15) = -4.40$, $p < .001$, and the verbal, $t(15) = -4.79$, $p < .001$, conditions. Importantly, a dependent samples *t* test showed that the SNARC slopes did not differ, $t(15) = -1,46$, $p = .13$, confidence intervals (e.g., 95%) $[-11.60, -4.61]$ and $[-8.3, -3.6]$ for the manual and the verbal conditions, respectively. The regression plots are shown in Figure 1A.

A SNARC effect was observed of approximately the same size in the manual and the verbal tasks. In the verbal task, target and responses were central in physical space (hence, coded centrally in a visuospatial frame), but they were lateralized in a verbal-spatial frame (i.e., say "left" or "right"). The observation of a regular SNARC effect in this condition shows that verbal-spatial coding is sufficient to obtain an association between numbers and space.

Experiment 2

The previous experiment established that verbal-spatial coding is sufficient to generate a SNARC effect. In Experiment 2, we checked whether visuospatial coding is sufficient. For this purpose, lateralized responses were used—participants were required to press laterally presented response labels on a touch screen in

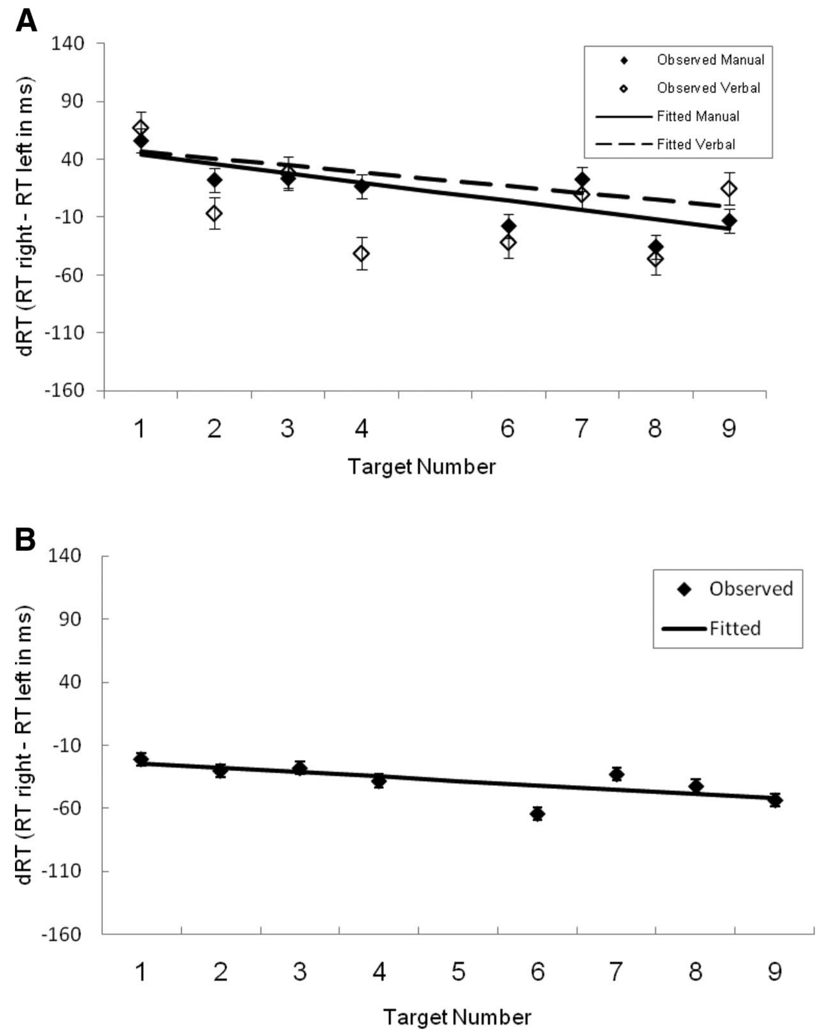

Figure 1. A: The results of Experiment 1. The solid regression line represents reaction time (RT) differences between right-handed minus left-handed responses as a function of magnitude in a manual parity judgment task. The dashed regression line represents RT differences between the verbal response "right" minus the verbal response "left" as a function of magnitude in a verbal parity judgment task. B: The regression line represents RT differences between right-handed minus left-handed responses as a function of magnitude in Experiment 2. Error bars indicate one standard error of measurement.

response to the parity of a centrally presented target. The response label *ODD* had to be pressed if the presented target number was odd, and the response label *EVEN* had to be pressed if the presented target number was even. To prevent verbal-spatial coding of the responses (e.g., "even is left, odd is right"), we varied the lateral position of the response labels on the touch screen randomly from trial to trial (i.e., the response labels *ODD* and *EVEN* could appear in the left and right positions or the right and the left positions on the screen, respectively). If simply performing a response to the left or to the right side of the screen (visuospatial coding) is sufficient, a SNARC effect should be observed.

Method

Participants. 23 Dutch-speaking undergraduates (all right-handed; age range: 17–24 years) participated in the experiment. All participants were undergraduate students of Ghent University (Ghent, Belgium) who participated in the experiment for course credit. All participants took part in this experiment only. None of the participants were familiar with the purpose of the study.

Apparatus and stimuli. Stimulus delivery and millisecond-accurate response registration were achieved by means of the Tscope software package (Stevens et al., 2006). Responses were registered using a touch screen. Targets were the Arabic numbers from 1 to 9 (except 5). Numbers extended 0.8° in height and 0.5° in width and were presented centrally on screen. Three buttons were presented on the lower half of the screen: one central button to initiate the trial and two lateral response buttons. Within the borders of each response button (3.5° × 1.5°), a response label was presented. One response label consisted of the Dutch word *ONEVEN* (odd; 12-pt. Arial font) presented in the center of a response button. The other response label consisted of the word

EVEN presented in the center of an equally sized response button. The distance between the two response labels was 10.2 cm.

Procedure. Each trial started with the presentation of two response buttons at a lower left and a lower right position on the touch screen. On each trial, the words *ONEVEN* and *EVEN* appeared in the response labels. In half of the trials, the response label *ONEVEN* appeared on the left side of the fixation point, and the response label *EVEN* appeared on the right side of the fixation point. In the other half of the trials, these positions were reversed. The position of the response labels varied randomly from trial to trial. This information remained on screen for 1,500 ms, after which a central start button appeared between the left and right buttons. As soon as the participant pressed this central button with the index finger of the dominant hand, a number was presented at the top center of the screen. Participants had to respond to the parity of this number. The participant had to press the correct response button with the index finger of the dominant hand. Each target number was presented 20 times: 10 trials with the word *ONEVEN* in the left position and *EVEN* in the right position, and 10 times with the word *ONEVEN* in the right position and *EVEN* in the left position. Hence, each number was responded to 10 times toward the left location and 10 times toward the right location. Because the position of the response labels *ONEVEN* and *EVEN* varied randomly from trial to trial, participant were forced to code the responses as a function of the labels *ONEVEN* and *EVEN*. Participants had to indicate the parity status of the target number by moving from the central start button and pressing with the index finger on the *ONEVEN* or the *EVEN* button. Both speed and accuracy were emphasized.

Results and Discussion

Correct median RTs were subjected to a 2 × 2 repeated measures ANOVA. Within-subject factors were magnitude (small, large) and response side (left, right). Only 0.6 % of the trials were responded to erroneously. Therefore, errors were not analyzed separately.

No main effect was observed for magnitude ($F < 1$). A significant main effect of response side was observed, $F(1, 22) = 8{,}80$, $p < .01$. Responses toward the right square (703 ms) were faster than responses toward the left square (738 ms). The interaction between response side and magnitude, indicative of the SNARC effect, was not significant, $F(1, 22) = 1.16$, $p = .29$.

As for the previous experiment, a magnitude predictor was taken into a regression analysis with difference in RT for each number (right-hand response minus left-hand response) as dependent variable. Using this more sensitive method (for a more elaborate discussion, see Fias et al., 1996), although small in effect size, a SNARC effect was reliably observed, indicated by a significant negative slope, slope value: −3.37, $t(22) = -2.72$, $p < .05$, confidence interval (e.g., 95%) [−5.8, −0.9] (see Figure 1B). The results of this experiment suggest that visuospatial lateralization of the responses, although relatively weak, can be sufficient to obtain the spatial association with numbers.

Experiment 3

Given that both verbal-spatial and visuospatial coding systems appear to exist for numbers (Experiments 1 and 2, respectively), it is of interest to pit them directly against one another to compare their relative strength. This was done in Experiments 3 and 4. To this end, a design highly similar to Experiment 2 was used. Visuospatial coding was made possible because left- and right-hand sided responses were used. Verbal-spatial coding was made possible by replacing the response labels *ONEVEN* and *EVEN* from Experiment 2 with the verbal response labels *LINKS* (meaning left) and *RECHTS* (meaning right).

By randomly varying the positions of the response labels *LINKS* and *RECHTS,* it was possible to see whether the SNARC effect resulted from a congruency between the number and the physical position of the response (visuospatial coding) or from a congruency between the number and the conceptual meaning of the response (verbal-spatial coding). A graphical illustration of our design is provided in Figure 2.

Word congruency refers to whether the verbal labels are in their canonical position (left right) or not (right left). The hands in Figure 2 indicate the preferred direction of responses. According to the visuospatial account (see the left column of Figure 2), a congruency is expected between the magnitude of the number and the response side. Therefore, responses to the left are expected to be faster for small numbers and faster to the right for large numbers. This is expected regardless of the spatial words presented in the response labels. Therefore, a negative SNARC slope is expected for both the word-position-congruent and the word-position-incongruent conditions. According to the verbal-spatial account (see the right column of Figure 2), a congruency is expected between the number and the response label. Therefore, if word position is congruent, we expect again a negative regression slope. However, if word position is incongruent, we expect faster responses to the left-hand side for large numbers (to the word *right*) and faster responses to the right-hand side for small numbers (to the word *left*). Therefore, this account predicts a positive regression slope when word position is incongruent but a negative regression slope when word position is congruent. Stated otherwise, the visuospatial account predicts a main effect of physical

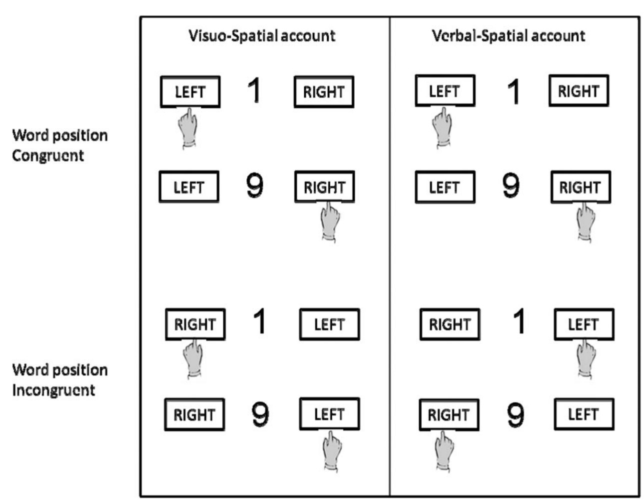

Figure 2. Illustration of predictions for both the visuospatial account and the verbal-spatial account when word positions are congruent (upper half) or incongruent (lower half). Hand positions indicate the side of response that is preferred according to the two respective accounts.

congruency (i.e., a SNARC effect, or effect of pressing on the physically congruent side), but no interaction with word congruency, whereas the verbal-spatial account predicts an interaction between physical congruency and word congruency.

In directly contrasting the verbal-spatial and visuospatial accounts, it is useful to consider the possibility that each exerts its effect in a different time window. More generally, it has been proposed that different task components in conflict tasks may be influential at different time points after stimulus presentation (Ridderinkhof, 2002). For this reason, we manipulated stimulus onset asynchrony (SOA) between presentation of the labels and the target number to allow the verbal-spatial and visuospatial components to exert their effects in different time windows.

Method

Participants. Nineteen Dutch-speaking undergraduates of Ghent University (age range: 17–23 years) participated in the experiment for a monetary reward (€5 [$7.40 U.S.]). All participants took part in this experiment only. None of the participants were familiar with the purpose of the study.

Apparatus and stimuli. Apparatus was the same as for Experiments 1 and 2. A hash mark (#; 10-pt. Arial font) served as fixation mark. Targets were the numbers 1, 2, 8, and 9 (12-pt. Arial font). Two response labels were used. One response label consisted of the word *LINKS* (left) presented in the center of a square (3.5° × 1.5°). The other response label consisted of the word *RECHTS* (right; 12-pt Arial font) presented in the center of an equally sized square. The distance between the two response labels was 3.5° such that one response label was presented on the left and one response label was presented on the right side of the screen.

Procedure. Each trial started with the presentation of the fixation mark at the center of the screen for 750 ms. Subsequently, the response labels appeared to the left and to the right of the fixation point. In half of the trials, the response label *LEFT* appeared on the left side of the fixation point and the response label *RIGHT* appeared on the right side of the fixation point. In the other half of the trials, this position was reversed. The position of the response labels varied randomly from trial to trial. Four different SOAs were used (0, 200, 800, and 1,500 ms) between the onset of the response labels and the onset of the target number. For each SOA, each target number was presented 40 times: 20 times with the word *LEFT* on the left position and the word *RIGHT* on the right position, and 20 times with the word *LEFT* on the right position and the word *RIGHT* on the left position. Half of the participants had to respond on a response box by pushing a button corresponding to the side of the response label *LEFT* if the number was odd and to the side of the response label *RIGHT* if the number was even. The other half of the participants received the reversed mapping. After the response, the screen remained blank for 1,000 ms before a new trial started.

Results

Median RT and errors were subjected to a 4 × 2 × 2 repeated measures ANOVA. Within-subject factors were SOA (0, 200, 800, and 1,500 ms), word congruency (word congruent: word *LEFT* presented left on screen and word *RIGHT* presented right on screen; word incongruent: word *LEFT* presented right on screen and word *LEFT* presented right on screen), and physical congruency (physically congruent: small number responded with left-hand side and large number responded with right-hand side; physically incongruent: small number responded with right-hand side and large number responded with left-hand side).

One participant made more than 40% errors and was therefore discarded from the analysis. On average, errors were made on 7.24% of the trials. No main effects or interactions on the arcsin-transformed errors reached significance. Median correct RTs were 747, 744, 735, and 773 ms for the target numbers 1, 2, 8, and 9, respectively. There was a significant main effect of SOA, $F(3, 51) = 105.70$, $p < .0001$: RTs decreased with increasing SOA. Planned comparisons showed that this was true for SOA 0 (872 ms) compared to SOA 200 (758 ms), $F(1, 17) = 110.37$, $p < .0001$; for SOA 200 compared to SOA 800 (678 ms), $F(1, 17) = 32.30$, $p < .0001$; and for SOA 800 compared to SOA 1,500 (643 ms), $F(1, 17) = 22.30$, $p < .001$.

Word-congruent trials were responded to 22 ms faster than word-Incongruent trials, $F(1, 17) = 8.37$, $p < .05$, and physically congruent trials were responded to 11 ms faster than physically incongruent trials, $F(1, 17) = 7.79$, $p < .05$. Most importantly, the interaction between word congruency and physical congruency was highly significant, $F(1, 17) = 29.53$, $p < .0001$. This interaction between word congruency and physical congruency was significant for each SOA (all *p*s < .05). In the word-congruent condition, physically congruent trials were responded to 51 ms faster than physically incongruent trials, $F(1, 17) = 35.49$, $p < .0001$. However, in the word-incongruent condition, the effect was reversed: Physically congruent trials were responded to 29 ms slower than physically incongruent trials, $F(1, 17) = 12{,}64$, $p < .01$. The three-way interaction between SOA, word congruency, and physical congruency was not significant ($F < 1$), meaning that this pattern was similar across SOAs.

As with the previous experiments, the SNARC predictors were taken into the regression analysis (see Figure 3A). For each SOA, slope values were calculated for the word-congruent and the word-incongruent conditions separately. These slope values were entered in an ANOVA with word congruency (congruent, incongruent) and SOA (0, 200, 800, and 1,500 ms) as factors. Consistent with the Word Congruency × Physical Congruency interaction observed in the previous analysis, a significant main effect was obtained for word congruency, $F(1, 17) = 15.17$, $p < .01$.

In particular, a significant SNARC effect was observed in the word-congruent condition (i.e., left right), average slope: −13.78 ms, confidence interval (e.g., 95%) [−19, −8.6], $t(17) = -5.19$, $p < .0001$. In the word-incongruent condition (i.e., right left), the slope value was marginally significant and positive (indicative of a reversed SNARC effect), average slope: 5.51 ms, confidence interval (e.g., 95%) [0.19, 10.8], $t(17) = 2.03$, $p < .06$. Importantly, a dependent samples *t* test showed that these SNARC slopes (−13.78 ms and 5.51 ms for the word-congruent and the word-incongruent conditions, respectively) were different, $t(17) = -4.14$, $p < .001$. The main effect for SOA was not significant; neither was its interaction with word position (both *p*s > .11).

To sum up, in line with the verbal-spatial coding account, an interaction between word congruency and physical congruency was observed. A regular SNARC effect was obtained in the word-congruent condition and a reversed one in the word-incongruent condition. This was true irrespective of the SOA between the onset

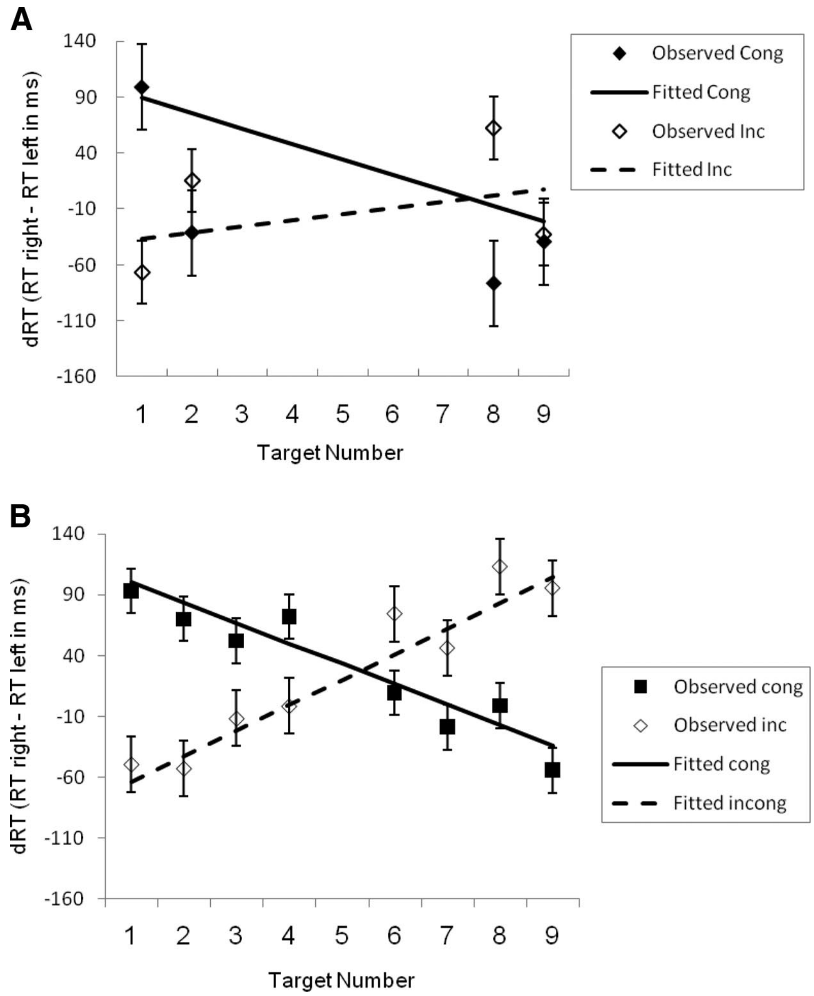

Figure 3. The solid regression line represents reaction time (RT) differences between right-handed minus left-handed responses as a function of magnitude in the word-congruent condition (Experiments 3 and 4). The dashed line represents the word-incongruent condition. A: The results for a parity judgment task (Experiment 3). B: The results for a magnitude comparison task (Experiment 4). Error bars indicate one standard error of measurement. cong = congruency; inc = incongruency.

of the response labels and the onset of the target number. The regression analysis confirmed the results of the ANOVA with a more positive slope for the word-incongruent compared to the word-congruent condition.

Experiment 4

In Experiment 3, a SNARC effect was observed in line with verbal-spatial coding. However, it might be argued that the task we used favored verbal-spatial coding. First, parity is uncorrelated with number magnitude, and second, labeling a number as odd versus even is a typically verbal task. On the other hand, in a magnitude comparison task, target numbers can easily be categorized spatially as left (smaller than 5 to the left side of the representation) and right (larger than 5 to the right side of the representation). Also, in the literature, a magnitude comparison task is thought to address a visuospatial representation (Bächtold et al., 1998; Herrera, Macizo, & Semenza, 2008). For this reason, we used a magnitude comparison task in Experiment 4 to see whether visuospatial coding would be stronger than verbal-spatial coding in this particular setup.

Method

Participants. Twenty-six Dutch speaking undergraduates of Ghent University (age range: 18–23 years) participated in the experiment for course credit. All participants took part in this experiment only. None of the participants were familiar with the purpose of the study.

Apparatus and stimuli. The apparatus and stimuli were exactly the same as in Experiment 3.

Procedure. Participants were required to respond to the magnitude of the numbers by pressing at the side of the word *LINKS* (left) if the target number was smaller than 5 and pressing at the side of the word *RECHTS* (right) if the target number was larger than 5. In a second block, this response mapping was reversed: Now, participants had to press at the side of the word *RIGHT* if the number was smaller than 5 and to the side of the word *LEFT* if the number was larger than 5. The order of these blocks was counterbalanced across subjects. Apart from the task instructions, a small change in the design was introduced. In Experiment 3, we observed that the SOA manipulation did not influence the results but that it did lengthen the experiment considerably (making it 4 times as long). Therefore, in this experiment, we chose to use a fixed SOA between the onset of the response labels and the onset of the target number (SOA = 800 ms). This had the extra advantage that all numbers in the range from 1 to 9 (except 5) could be used. Otherwise, the design of the experiment was exactly the same as in Experiment 3.

Results

As in Experiment 3, median RT and errors were submitted to a 2×2 repeated measures ANOVA with word congruency (word congruent: word *LEFT* presented left on screen and word *RIGHT* presented right on screen; word incongruent: word *LEFT* presented right on screen and word *LEFT* presented right on screen) and physical congruency (physically congruent: small number responded with left-hand side and large number responded with right-hand side; physically incongruent: small number responded with right-hand side and large number responded with left-hand side) as within-subjects factors. Two subjects were removed from the analysis because their RTs were more than two standard deviations slower than the mean in either the word-congruent or the word-incongruent condition. For the remaining 24 participants, we observed an average of 6.23% errors. No main effect or interaction in the error analysis reached significance (all $ps > .10$). For the RTs, the main effect for word congruency just failed to reach significance, $F(1, 23) = 3.29$, $p = .08$. Word-congruent responses were initiated 10 ms faster than word-incongruent responses. The main effect for physical congruency was not significant, $F(1, 23) = 0.17$, $p = .69$. Importantly, in line with the verbal-spatial account, the interaction between word congruency and physical congruency was significant, $F(1, 23) = 6.68$, $p < .05$. To evaluate this interaction in more detail, in line with the previous experiment, we performed the regression analysis for both the word-congruent and the word-incongruent conditions (see Figure 3B). The results showed a marginally significant SNARC effect in the word-congruent condition, $t(23) = -2.03$, $p < .06$, and a significant reversed SNARC effect in the word-incongruent condition, $t(23) = 3.02$, $p < .001$. Importantly, a dependent samples t test showed that the SNARC slopes, −19.85 ms, confidence interval (e.g., 95%) [−33.1, −0.5], and 24.89, confidence interval (e.g., 95%) [7.4, 34.8], for the word-congruent and the word-incongruent conditions, respectively, differed, $t(23) = -2.93$, $p < .01$.

General Discussion

Experiment 1 showed that verbal-spatial coding was sufficient to obtain the SNARC effect. In Experiment 2, it was observed that visuospatial coding was sufficient also, although the effect in this case was more subtle. In Experiments 3 and 4, we directly pitted the two accounts against one another. The present design does not allow the complete rejection of the possibility that visuospatial coding contributes to the SNARC effect when the verbal-spatial account is emphasized. However, both in a parity judgment task (Experiment 3) and in a magnitude comparison task (Experiment 4), it was observed that verbal-spatial coding was the dominant factor in driving the SNARC effect. A detailed overview of all median RTs (and standard errors) can be found in the Appendix.

The proposed verbal-spatial coding scheme can be applied to a variety of studies on the SNARC effect. For instance, in a recent study, it was observed that the SNARC effect does not necessarily imply the existence of a mental number line (Santens & Gevers, 2008). In this study, participants made responses to close and far response locations while performing a magnitude comparison task (e.g., "Is the presented number larger or smaller than 5?"). From a direct isomorphism between the mental number line and the position of the response (a visuospatial coding account), one would predict that numbers close (e.g., 4 and 6 are close to 5) on the mental number line should be associated with "close" responses, whereas numbers far on the mental number line (e.g., 1 and 9 are far from 5) should be associated with "far" responses. This was not observed. Small numbers (1 and 4) were associated with "close" responses, and large numbers (6 and 9) were associated with "far" responses. We argue that numbers are verbally coded as relatively small or large, and because small and large are themselves associated with different concepts, different SNARC-like congruency effects may appear. In the Santens and Gevers (2008) study, the congruency effect then results from an association between concepts "small" and "close"; and between concepts "large" and "far." A similar observation was made in another recent study where participants performed both a horizontal (left or right response alternatives) and a vertical (top and bottom response alternatives) SNARC task (Müller & Schwarz, 2007). Crucially, the instructions emphasized either the hand for responding (press with your left hand/press with your right hand) or the location of the response button (in the vertical condition, press on the top location/press on the bottom location; in the horizontal condition, press on the left location/press on the right location). In the vertical dimension, the SNARC effect was congruent with the instruction (e.g., hand-based or location-based). However, in the horizontal dimension, a location-based SNARC effect was observed regardless of whether the instruction emphasized the location of the response button or the location of the response hand. These results seem to suggest that the SNARC effect in the vertical dimension results from verbal-spatial coding while the same effect in the horizontal dimension results from visuospatial coding. This explanation agrees with the claim that the Simon (1969) effect also has a different origin for the horizontal and the vertical dimensions (e.g., Vallesi, Mapelli, Schiff, Amodio, & Umiltà, 2005; Wiegand & Wascher, 2005). However, interpretation of the Müller and Schwarz (2007) experiment must be done with some caution because, regardless of the instruction, participants were able to internally recode their response in terms of the location. Additionally, this recoding was more likely in the horizontal dimension because, in the horizontal dimension, both location-based and hand-based instructions referred to the same left–right dimension.

Similar reasoning can be applied to other studies where the SNARC effect was reversed. Bächtold et al. (1998; see also Ristic et al., 2006) specifically instructed participants to imagine a reversed mental representation of numbers. Participants had to imagine numbers in the range from 1 to 11 either as numbers on a ruler or as hours on a clock face. Whereas a ruler has the same left-to-right orientation as a mental number line, numbers on a clock are oriented such that large numbers (7–11) are on the left and small numbers (1–5) are on the right. A typical SNARC effect resulted in the ruler condition, but a reversed SNARC effect was found in the clock condition. Bächtold et al. adopted the visuospatial coding account and concluded that the reversal resulted from an interaction between lateralized mental representations and lateralized motor outputs. Another explanation is that, in the clock face condition, the reversed SNARC effect is obtained because participants associated small with right and large with left. In line with this explanation, Notebaert, Gevers, Verguts, and Fias (2006) observed that the SNARC effect can be modulated by specifically instructing participants to associate small with right and large with left. On half of the trials, participants had to respond to the magnitude of a number (e.g., "Is the presented number larger or smaller than 5?"). On the other half of the trials, subjects had to respond to the orientation of the number (e.g., "Is the number presented upright or tilted?"). The data showed that the mapping rule of the magnitude task influences the SNARC effect in the orientation task. Participants responding in a compatible way in the magnitude task (press *left* on small numbers and *right* on large numbers) showed a regular SNARC effect in the orientation task. However, participants responding in an incompatible way in the magnitude task (press *right* on small numbers and *left* on large numbers) showed a reversed SNARC effect in the orientation task.

Relations to Other Number–Space Interactions

As outlined in the introduction, patients with left neglect extend physical bisection displacement to the representational domain (Zorzi, Priftis, & Umiltà, 2002). In a more recent study, Priftis, Zorzi, Meneghello, Marenzi, and Umiltà (2006) compared the performance of left-neglect patients in a number interval bisection task with the SNARC effect in a parity judgment task. A dissociation was observed: The performance of the patients was impaired in the number bisection task, but the SNARC effect was intact. This dissociation was explained by assuming that the SNARC effect in parity judgment results from implicit access to the mental number line, whereas, in the number bisection task, this access is explicit. Therefore, neglect patients may have a problem with explicitly accessing an otherwise intact mental number line. The implicit access to this number line, however, remains intact.

The verbal-spatial coding account also predicts that a dissociation is possible between performance on the interval bisection task and the SNARC effect, but for other reasons. According to the verbal-spatial coding account, neglect patients have a preserved SNARC effect because it results from an association between verbal concepts such as "small" and "left" and between "large" and "right." These associations are believed to be preserved in neglect patients. This interpretation, based on a dissociation between the SNARC effect and the location of numbers on a mental number representation, is in line with observations on a participant with number-form synesthesia (Galton, 1880a, 1880b). Piazza, Pinel, and Dehaene (2006) investigated a synesthetic subject, S. W., who had a vivid mental image of a number line. Its form deviated from the standard left-to-right representation; when asked to draw his number form, a number line was drawn oriented from right to left. In another task, he was asked to compare pairs of Arabic numbers presented horizontally around a fixation point. Control subjects perform the task faster if the numbers are presented congruently (e.g., 2 5) than incongruently (e.g., 5 2). Although this effect is also sometimes called a SNARC effect (e.g., Brysbaert, 1995; Zebian, 2005), we call it a SNARC-like effect here to distinguish it from the regular SNARC effect (e.g., as calculated in Dehaene et al., 1993, or in the experiments reported above). S.W. was faster in judging these number pairs if the spatial layout of the stimuli was compatible with his number line form (e.g., small numbers presented on the right, large numbers presented on the left); hence, he exhibited a reverse SNARC-like effect as compared to the control subjects. In contrast, the SNARC effect was not modulated by S.W.'s number line form. A normal SNARC effect was observed with small numbers responded to faster with the left-hand side and larger numbers responded to faster with the right-hand side. A testable explanation is that the SNARC effect results from verbal-spatial coding, whereas the SNARC-like effect results from visuospatial coding.

Our observation that both visuospatial coding and verbal-spatial coding can be manipulated independently is not restricted to the number domain. For instance, Hommel and Müsseler (2006) also showed that manual or verbal actions differently influence the identification of left- or right-pointing arrowheads. A broader framework is needed to frame our results. We used the dual coding framework of Paivio (1986). A related theory which emphasized a qualitative distinction between different types of spatial representations, was proposed by Kosslyn and colleagues (Kosslyn, 2006; Kosslyn et al., 1989). In their framework, a distinction is made between categorical and coordinate spatial representations. The coordinate system codes for precise distance, magnitude, and orientation, whereas the categorical system codes for relative location. For example, when holding one hand next to the other, the first will remain left or right of the second (categorical coding) no matter how high, low, or far away it is from the other hand (coordinate coding). Whereas categorical coding of space is not necessarily verbal, the opposite is true: Verbal-spatial labels (such as left, right, up, down, etc.) are by definition categorical. Additionally, visuospatial coding cannot be expressed using verbal labels. Interestingly, Kosslyn (2006) also argued that the two systems are relatively independent.

A tight correspondence has been postulated between processes responsible for attending to external space and processes responsible for representing numerical information (e.g., Zorzi et al., 2002). However, the present study demonstrates that the nature of this interaction is not exclusively of a visuospatial nature, as was previously assumed. This observation provides new opportunities for investigating how spatial information is encoded in numerical and other (e.g., Simon) tasks. In doing so, special interest should be given to the role of language or verbal labeling of spatial information.

References

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

Barsalou, L. W. (1999). Perceptual symbol systems. *Behavioral and Brain Sciences, 22,* 577–609.

Barsalou, L. W. (2008). Grounded cognition. *Annual Review of Psychology, 59,* 617–645.

Bishop, Y. M. M., Fienberg, S. E., & Holland, P. W. (1975). *Discrete multivariate analysis: Theory and practice.* Cambridge, MA: MIT Press.

Bisiach, E., & Luzzatti, C. (1978). Unilateral neglect of representational space. *Cortex, 14,* 129–133.

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.

Casarotti, M., Michielin, M., Zorzi, M., & Umiltà, C. (2007). Temporal order judgment reveals how number magnitude affects visuospatial attention. *Cognition, 1,* 101–117.

De Brauwer, J., Duyck, J., & Brysbaert, M. (2007). The SNARC effect in the processing of second-language number words: Further evidence for strong lexico-semantic connections. *Quarterly Journal of Experimental Psychology, 61,* 444–458.

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

Dehaene, S., Bossini, S., & Giraux, P. (1993). The mental representation of parity and number magnitude. *Journal of Experimental Psychology: General, 122,* 31–396.

Dehaene, S., & Cohen, L. (2007). Cultural recycling of cortical maps. *Neuron, 56,* 384–398.

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 and Performance, 16,* 626–641.

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.

Fischer, M. H. (2003). Spatial representations in number processing: Evidence from a pointing task. *Visual Cognition, 10,* 493–508.

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

Fischer, M. H., Warlop, N., Hill, R. L., & Fias, W. (2004). Oculomotor bias induced by number perception. *Experimental Psychology, 51,* 91–97.

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

Galton, F. (1880a, January 15). Visualised numerals. *Nature, 21,* 252–256.

Galton, F. (1880b, March 25). Visualised numerals. *Nature, 21,* 494–495.

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.

Gevers, W., Reynvoet, B., & Fias, W. (2003). The mental representation of ordinal sequences is spatially organized. *Cognition, 87,* B87–B95.

Gevers, W., Verguts, T., Reynvoet, B., Caessens, B., & Fias, W. (2006). Numbers and space: A computational model of the SNARC effect. *Journal of Experimental Psychology: Human Perception and Performance, 32,* 32–44.

Halligan, P. W., Fink, G. R., Marshall, J. C., & Vallar, G. (2003). Spatial cognition: Evidence from visual neglect. *Trends in Cognitive Sciences, 7,* 125–133.

Herrera, A., Macizo, P., & Semenza, C. (2008). The role of working memory in the association between number magnitude and space. *Acta Psychologica, 128,* 225–237.

Hommel, B., & Müsseler, J. (2006). Action-feature integration blinds to feature-overlapping perceptual events: Evidence from manual and vocal actions. *Quarterly Journal of Experimental Psychology, 59,* 509–523.

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

Kornblum, S., Hasbroucq, T., & Osman, A. (1990). Dimensional overlap: Cognitive basis for stimulus–response compatibility—A model and taxonomy. *Psychological Review, 97,* 253–270.

Kosslyn, S. M. (2006). You can play 20 questions with nature and win: Categorical versus coordinate spatial relations as a case study. *Neuropsychologia, 44,* 1519–1523.

Kosslyn, S. M., Koenig, O., Barrett, A., Cave, C. B., Tang, J., & Gabrieli, J. D. E. (1989). Evidence for two types of spatial representations: Hemispheric specialization for categorical and coordinate relations. *Journal of Experimental Psychology: Human Perception and Performance, 15,* 723–735.

Lakoff, G., & Núñez, R. E. (2000). *Where mathematics comes from: How the embodied mind brings mathematics into being.* New York, NY: Basic Books.

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

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

Lupker, S. J. (1979). The semantic nature of response competition in the picture-word interference task. *Memory & Cognition, 7,* 485–495.

Mapelli, D., Rusconi, E., & Umiltà, C. (2003). The SNARC effect: An instance of the Simon effect? *Cognition, 88,* B1–B10.

Müller, D., & Schwarz, W. (2007). Is there an internal association of numbers to hands? The task set influences the nature of the SNARC effect. *Memory & Cognition, 35,* 1151–1161.

Notebaert, W., Gevers, W., Verguts, T., & Fias, W. (2006). Shared spatial representations for numbers and space: The reversal of the SNARC and the Simon effects. *Journal of Experimental Psychology: Human Perception and Performance, 32,* 1197–1207.

Paivio, A. (1986). *Mental representations: A dual-coding approach.* New York, NY: Oxford University Press.

Piazza, M., Pinel, P., & Dehaene, S. (2006). Objective correlates of an unusual subjective experience: A single-case study of number-form synaesthesia. *Cognitive Neuropsychology, 23,* 1162–1173.

Priftis, K., Zorzi, M., Meneghello, F., Marenzi, R., & Umiltà, C. (2006). Explicit versus implicit processing of representational space in neglect: Dissociations in accessing the mental number line. *Journal of Cognitive Neuroscience, 16,* 680–688.

Proctor, R. W., & Cho, Y. S. (2006). Polarity correspondence: A general principle for performance of speeded binary classification tasks. *Psychological Bulletin, 132,* 416–442.

Restle, F. (1970). Speed of adding and comparing numbers. *Journal of Experimental Psychology, 83,* 32–45.

Ridderinkhof, K. R. (2002). Activation and suppression in conflict tasks: Empirical clarification through distributional analyses. In W. Prinz & B. Hommel (Eds.), *Common mechanisms in perception and action: Attention and performance XIX* (pp. 494–519). Oxford, England: Oxford University Press.

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

Rosinski, R. R. (1977). Picture-word interference is semantically based. *Child Development, 48,* 643–647.

Rossetti, Y., Jacquin-Courtois, S., Rode, G., Ota, H., Michel, C., & Boisson, D. (2004). Does action make the link between number and space representation? Visuo-manual adaptation improves number bisection in unilateral neglect. *Psychological Science, 15,* 426–430.

Rusconi, E., Kwan, B., Giordano, B. L., Umiltà, C., & Butterworth, B. (2006). Spatial representation of pitch height: The SMARC effect. *Cognition, 99,* 113–129.

Santens, S., & Gevers, W. (2008). The SNARC effect does not imply a mental number line. *Cognition, 108,* 263–270.

Santiago, J., Lupianez, J., Perez, E., & Funes, M. J. (2007). Time (also) flies from left to right. *Psychonomic Bulletin & Review, 14,* 512–516.

Schwarz, W., & Keus, I. M. (2004). Moving the eyes along the mental number line: Comparing SNARC effects with saccadic and manual responses. *Perception & Psychophysics, 4,* 651–664.

Schwarz, W., & Müller, D. (2006). Spatial associations in number-related tasks: A comparison of manual and pedal responses. *Experimental Psychology, 53,* 4–15.

Simon, J. R. (1969). Reaction toward the source of stimulation. *Journal of Experimental Psychology, 81,* 1974–1976.

Song, J. H., & Nakayama, K. (2008). Numeric comparison in a visually-guided manual reaching task. *Cognition, 106,* 994–1003.

Stevens, M., Lammertyn, J., Verbruggen, F., & Vandierendonck, A. (2006). Tscope: A C library for programming cognitive experiments on the MS Windows platform. *Behavior Research Methods, 38,* 280–286.

Stoianov, I., Kramer, P., Umiltà, C., & Zorzi, M. (2008). Visuospatial priming of the mental number line. *Cognition, 2,* 770–779.

Tlauka, M. (2002). The processing of numbers in choice-reaction tasks. *Australian Journal of Psychology, 54,* 94–98.

Vallesi, A., Mapelli, D., Schiff, S., Amodio, P., & Umiltà, C. (2005). Horizontal and vertical Simon effect: Different underlying mechanisms? *Cognition, 96,* B33–B43.

Wiegand, K., & Wascher, E. (2005). Dynamic aspects of stimulus-response correspondence: Evidence for two mechanisms involved in the Simon effect. *Journal of Experimental Psychology: Human Perception and Performance, 31,* 453–464.

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.

Zorzi, M., Priftis, K., & Umiltà, C. (2002, May 9). Brain damage: Neglect disrupts the mental number line. *Nature, 417,* 138–139.

Appendix

Overview of Experiments

Experiment and condition	SNARC-congruent RT (*SE*)	SNARC-incongruent RT (*SE*)
Experiment 1		
Manual condition		
Basic SNARC experiment	534 (16.8)	554 (15.7)
Verbal condition		
Only verbal-spatial coding	534 (17.0)	546 (17.0)
Experiment 2		
Only visuospatial coding	720 (27.0)	722 (26.0)
Experiment 3		
SOA 0 ms		
Verbal-spatial congruent	847 (38.4)	914 (44.2)
Verbal-spatial incongruent	903 (38.3)	877 (35.6)
SOA 200 ms		
Verbal-spatial congruent	724 (27.4)	785 (37.7)
Verbal-spatial incongruent	801 (36.5)	772 (39.6)
SOA 800 ms		
Verbal-spatial congruent	663 (41.0)	693 (35.2)
Verbal-spatial incongruent	715 (44.8)	692 (42.8)
SOA 1,500 ms		
Verbal-spatial congruent	620 (34.4)	663 (41.6)
Verbal-spatial incongruent	680 (57.0)	644 (37.3)
Experiment 4		
Verbal-spatial congruent	600 (24.9)	650 (29.6)
Verbal-spatial incongruent	664 (31.3)	605 (21.5)

Note. RT = reaction time; SNARC = spatial numerical assoication of response codes; SOA = stimulus onset asynchrony.

Received August 7, 2008
Revision received September 11, 2009
Accepted September 14, 2009 ■