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Brief article

Numbers are associated with different types of spatial information depending on the task

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ABSTRACT

In this study, we examined the nature of the spatial–numerical associations underlying the SNARC-effect by imposing a verbal or spatial working memory load during a parity judgment and a magnitude comparison task. The results showed a double dissociation between the type of working memory load and type of task. The SNARC-effect disappeared under verbal load in parity judgment and under spatial load in magnitude comparison. These findings provide the first direct empirical evidence against the view that all behavioral signatures of spatial–numerical associations have their origin in a common spatial code. Instead they show that numbers are associated with different spatial codes which, depending on the task, have a visuospatial or verbally mediated nature.

1. Introduction

It is generally accepted that the mental representation of numerical magnitude is tightly linked to the mental representation of space. Evidence for spatial coding of numbers comes from studies in healthy participants and in brain-lesioned patients.

In a seminal study, Dehaene, Bossini, and Giraux (1993) asked healthy participants to perform a parity judgment task and observed faster left-hand responses to small numbers and faster right-hand responses to large numbers. This *s*patial–*n*umerical *a*ssociation of *r*esponse *c*odes, the SNARC-effect, indicates that small numbers are associated with left and large numbers with right. It is a robust phenomenon that is also observed in tasks other than parity judgment, for example, phoneme monitoring (Fias, Brysbaert, Geypens, & d'Ydewalle, 1996) or magnitude comparison (Brysbaert, 1995). Importantly, it has been shown that the relation between numbers and space is not absolute but context-dependent. For example, Dehaene and colleagues (1993) observed that the SNARC-effect is range-dependent. Numbers 4 and 5 elicited faster left than right responses when the numbers ranged from 4 to 8, but elicited faster right than left responses when numbers ranged from 1 to 5. Bachtold, Baumuller, and Brugger (1998) extended this idea of context-dependency to mental imagery. When asked to imagine numbers on a clock face, the SNARC-effect reversed. This flexible relation between numbers and space suggests that the spatial code is not inherently associated with number representations but that it is constructed during task execution, suggesting the involvement of a mental workspace that is constructed in working memory. The involvement of working memory was recently confirmed by Herrera, Macizo, and Semenza (2008). They measured the SNARC-effect in a magnitude comparison task during the retention interval of a verbal and a spatial working memory task. The SNARC-effect disappeared under spatial, but not under verbal load, indicating the contribution of visuospatial processes to the SNARC-effect.

The idea of a spatially organized number representation is further supported by studies in hemineglect patients suffering from impaired attentional processing of contralesional hemispace. Zorzi, Priftis, and Umilta (2002)

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demonstrated that these patients not only show a bias when bisecting physical lines (Marshall & Halligan, 1989), but also when bisecting numerical intervals. When patients neglecting the left side of perceptual space bisect physical lines, they typically shift the subjective midpoint towards the right. Similarly, when indicating the midpoint of a numerical interval (e.g. what is in the middle between 1 and 9?) they overestimate the midpoint (e.g. 7). The spatial nature of the number bisection bias was further illustrated by the remediating effect of prism adaptation. Spatial remapping of the environment evoked by prism goggles not only reduced the bias in perceptual line bisection (Farne, Rossetti, Toniolo, & Ladavas, 2002), but also in number interval bisection (Rossetti et al., 2004).

The most widely accepted and influential view is that the SNARC-effect and the number bisection bias in neglect both derive from a common numerical–spatial representational system, conceivable as a mental number line, of which the spatial coding overlaps with or at least is very similar to the way perceptual space is represented and processed (Hubbard, Piazza, Pinel, & Dehaene, 2005; Zorzi et al., 2002). The close link with perceptual space representations is supported by a number of additional observations such as the demonstration that numbers can initiate shifts of spatial attention (Fischer, Castel, Dodd, & Pratt, 2003), and by the fact that numbers can influence the kinematics of grasping movements (Andres, Davare, Pesenti, Olivier, & Seron, 2004).

Recent evidence, however, may contradict the hypothesis of a common spatial–number representation underlying both the SNARC-effect and the bisection bias in neglect. Priftis and colleagues (2006) described neglect patients showing a number interval bisection bias with the SNARC-effect in a parity judgment task being unaffected. They suggested that the explicit use of number magnitude information in interval bisection versus its implicit involvement in parity judgment explains the dissociation, but an alternative explanation is equally meaningful and needs to be considered. Even though the bisection bias in neglect, and especially its modulation by prism adaptation, suggests that the type of spatial representation involved in number bisection is analogous to the representations of physical space, such a perceptual representation is not the only way to cognitively represent spatial knowledge. There is substantial evidence that spatial information can also be represented in conceptual form expressing spatial relations using linguistic elements like above, below, left and right (Logan, 1994). Conceptual and perceptual spatial representations have been shown not to correspond (Crawford, Regier, & Huttenlocher, 2000) and to rely on dissociable neural systems (Jager & Postma, 2003).

Proctor and Cho (2006) recently proposed that not perceptual but conceptual spatial representations are the determining factor of the SNARC-effect. They assume that space, like many other cognitive representations, is organized in binary categories (e.g. left/right; small/large; hot/cold). Moreover, such conceptual categories have a polarity (e.g. left is negative and right is positive; small is negative and large is positive, ...) and it is the correspondence between the polarity of the stimulus (viz. the number magnitude) and the response (viz. position of the response) that induces the SNARC-effect. Gevers and colleagues (2006) proposed a computational model that incorporates this idea and show that it captures the behavioral details of the SNARC-effect. Noteworthy, this model shows that the linear relationship between number magnitude and RT difference between right and left hand is consistent with the binary classification that is inherent to the conceptual explanation of the SNARC-effect. This is because in the model, numbers are categorized as small or large in a graded fashion and it is this gradedness that generates the linearity of the SNARC-effect.

In sum, there is currently no agreement on the nature of the spatial codes from which the SNARC-effect originates. While a visuospatial mental number line representation is most commonly seen as the determinant of the SNARC-effect, recently a conceptual spatial representation has been proposed as an alternative. However, this proposal remained exclusively based on theoretical (Proctor & Cho, 2006) and computational (Gevers et al., 2006) arguments that merely illustrate that a conceptual basis of the SNARC-effect is logically possible. So far, however, this idea has not received direct empirical support.

The present study aimed to investigate the idea that multiple types of spatial information are associated with numbers and that they might be engaged differently in different tasks. From the study of Herrera et al. (2008), showing that a visuospatial but not a verbal load eliminates the SNARC-effect in a magnitude comparison task, it can be concluded that magnitude comparison primarily depends on perceptual spatial associations. However, from the patient study of Priftis and colleagues (2006), showing a normal SNARC-effect in parity judgment in the presence of biased number bisection performance, we predict that the SNARC-effect in parity judgment originates from a spatial code that differs from the perceptual spatial representations. Based on Proctor and Cho (2006) we hypothesize this spatial code is of a conceptual nature. Although concepts are not necessarily represented linguistically (see e.g. Quinn (2004) showing that preverbal infants can make left/right distinctions), we assume that the spatial concepts related to numbers are verbally mediated. Given the importance of language and education for the development of numerical cognition in general (Dehaene & Cohen, 1995) and for some specific aspects of numerical knowledge, like parity, in particular (Nuerk, Iversen, & Willmes, 2004), we predict that a verbal but not a visuospatial load will abolish the SNARC-effect in a parity judgment task.

2. Experiment 1

To evaluate the involvement of verbally mediated and visuospatial representations in parity judgment, we asked participants to perform a parity judgment task while keeping verbal or spatial information in working memory.

2.1. Methods

Forty six subjects (age range: 18–33 years) participated in the experiment. To obtain a baseline measure of the SNARC-effect, all participants started with a parity judgment task without working memory load. Afterwards, their memory span was determined. Subsequently, a parity judgment task was performed under working memory load. Half of the subjects were assigned to the spatial, the other half to the verbal load condition.

2.1.1. Parity judgment

During parity judgment, the Arabic numbers from 1 to 9 (except 5) were presented. Participants completed two blocks. In the first, they were instructed to press the left button for odd and the right button for even numbers (or vice versa). The response mapping was reversed in the second block and the order of blocks was counterbalanced across subjects.

Each trial started with a fixation mark (500 ms), immediately followed by the target number (ca.10 × 19 mm) which remained visible until response. After responding, the fixation point reappeared (250 ms). In case of an error, this point was red. Subsequently a blank screen appeared (250 ms). Eight practice trials were delivered prior to each block. Finally, each target number was presented 16× per response mapping block.

2.1.2. Working memory span

To determine the working memory span, sequences of items had to be memorized and recalled in correct order. Sequences were presented with an increasing amount of items (three to eight items; three sequences per length). Within a sequence, the same item was never presented twice. The individual span was defined as the last sequence length for which two of the three sequences were recalled correctly.

For the verbal condition, consonant strings were constructed following Szmalec and Vandierendonck (2007). A trial started with an empty screen (1500 ms) followed by the consonants (1250 ms) which were separated by a blank screen (250 ms). During retention, the screen remained empty (1500 ms) until the request for recall. Participants typed their responses and the letters entered were displayed at the bottom of the screen.

For the spatial condition, a computerized 2D-version of the Corsi-task was administered. Nine grey squares (35 × 35 mm) presented on a white background, were positioned according to Corsi's (1972) original configuration. A trial started with the presentation of the configuration (1500 ms) followed by the successive presentation of the target positions by a color change of those squares (1000 ms each with 500 ms in between). On completion of the sequence, the configuration reappeared after an empty screen (1500 ms) and participants were required to reproduce the memorized sequence by pressing the squares on the touch-screen.

2.1.3. Dual-task

To investigate the effect of load on the SNARC-effect, the parity judgment task was administered in the retention interval of the working memory task. A trial started with the presentation of the memory items (same procedure as above). Sequence length was determined individually (span-1) and remained constant throughout the experiment. For both spatial and verbal conditions, 24 sequences were constructed. For every subject, these sequences were presented randomly. Furthermore, to minimize verbal labeling, six different Corsi-configurations were generated. Each configuration was presented four times, twice in every SNARC response-mapping condition. After the last memory item, the parity judgment task started (same procedure as above). When all digits were presented twice (16 trials), subjects were asked to reproduce the memorized items. For both spatial and verbal conditions, 24 blocks were completed. After 12 blocks, the response mapping of the parity task was reversed. Speed and accuracy were stressed during parity judgment while only accuracy during the memory task. To familiarize with the procedure, participants performed a practice trial.

2.2. Results and discussion

We included subjects recalling at least 25% of the memory blocks in the dual-task condition and with overall parity judgment RTs smaller than four standard deviations from the group median. This resulted in a selection of 40 subjects (20 in each load condition). 95% (SD = 5%) of the memory items in the verbal load condition were correctly recalled in correct order and 76% (SD = 9%) in the spatial load condition. The difference between these tasks was significant [$t(38) = 8.11$, $p < .01$]. Median RTs were computed on correct parity judgment trials.

There was no trade-off between parity judgment and working memory performance in the dual-task condition (the correlation between parity judgment RT and working memory performance for the verbal load condition was −.23, $p = .33$ and for the spatial load condition .27, $p = .24$).

The SNARC-effect was analyzed using the regression approach described in Fias et al. (1996). dRTs (median RT right response–median RT left response) were computed for each number separately. Per subject, dRTs were entered in a regression analysis with magnitude as predictor. The weight of the magnitude predictor expresses the size of the SNARC-effect. Statistical analyses were performed on these regression weights. For the load conditions, the equation for the verbal condition was: *dRT* = −*9.33–0.37(magnitude)* and for the spatial condition: *dRT* = *19.81–6.25(magnitude)*, see Fig. 1. The magnitude predictor differed significantly from zero in the spatial but not in the verbal condition ([$t(19) = -2.72$, $p = .01$] and [$t(19) = 0.18$, $p = .86$], respectively). For the baseline

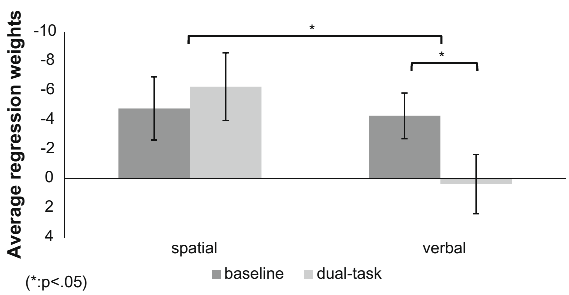

Fig. 1. The average regression weights for the different conditions of the parity judgment task.

conditions the following regression equations were obtained: *dRT = 17.94–4.28(magnitude)* for the verbal and *dRT = 19.52–4.78(magnitude)* for the spatial baseline. The weights of both baselines did not differ [$t(38) = -0.19$, $p = 0.85$] and were both significant from zero (verbal group: [$t(19) = -2.75$, $p = .01$]; spatial group: [$t(19) = -2.23$, $p < .04$]; Fig. 1).

To further substantiate the differential influence of a spatial and verbal memory load on the SNARC-effect, a repeated measure ANOVA was conducted on the regression weights with Condition (baseline or load) as within-subject variable and Memory-modality (spatial or verbal) as between-subject variable. Since it has been shown that the strength of the SNARC-effect is modulated by RT (Gevers, Caessens, & Fias, 2005), any potential influence of differences in RT between the baseline and load condition was ruled out by introducing this difference (overall RT load–overall RT baseline) as a covariate. Only the interaction between Condition and Memory-modality reached significance [$F(1,37) = 4.56$, $p < .04$]. Planned comparisons revealed that the interaction originated from a significant reduction of the SNARC-effect in the verbal condition [$F(1,37) = 5.19$, $p = .03$] (verbal baseline: −4.28 vs. verbal load: 0.37), whereas the SNARC-effect under spatial load did not differ from its baseline [$F(1,37) = 0.56$, $p = .46$] (spatial baseline: −4.78 vs. spatial load: −6.25).

In sum, these results indicate that a verbal but not a spatial working memory load abolished the SNARC-effect.

3. Experiment 2

Our findings combined with the finding of Herrera et al. (2008) (showing that a spatial but not a verbal load abolishes the SNARC-effect in a magnitude comparison task) establish a double dissociation between memory load (verbal or spatial) and task (parity judgment or magnitude comparison). To ensure that the double dissociation is not due to differences in the experimental procedures, we tried to replicate the findings of Herrera et al. (2008) by applying the same procedural details of Experiment 1 to a magnitude comparison instead of parity judgment task.

3.1. Methods

Experimental setup and analyses were identical to Experiment 1 with the exception that the parity judgment task was replaced by the magnitude comparison task in which participants had to indicate whether the target was smaller or larger than 5. Eighty undergraduates (age range: 18–33 years) participated.

3.2. Results and discussion

Using the same selection criteria as in the first experiment, data of 71 subjects were selected (35 in the verbal condition and 36 in the spatial condition). 92% (SD = 7%) of the memory items in the verbal load condition were correctly recalled in correct order and 80% (SD = 11%) of the

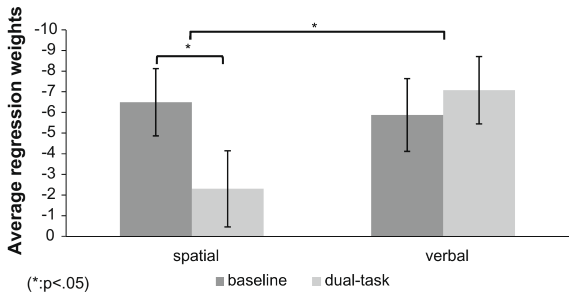

Fig. 2. The average regression weights for the different conditions of the magnitude comparison task.

spatial load condition. The difference between these tasks was significant [$t(69) = 5.62$, $p < .01$].

There was no trade-off between the magnitude comparison RT and the load tasks (all $r > .01$, all $p > .28$). Regression analyses revealed the following equations for the load conditions: verbal load: *dRT = 25.81–7.08 (magnitude)*; spatial load: *dRT = 8.93–2.30(magnitude).* The magnitude-weight differed from zero under verbal load [$t(34) = -4.34$, $p < .01$], but not under spatial load [$t(35) = -1.25$, $p = .22$]. The equation of the verbal baseline was: *dRT = 24.38–5.88(magnitude)* and of the spatial baseline: *dRT = 27.13–6.50(magnitude),* see Fig. 2. The weights of both baselines did not differ [$t(69) = -0.26$, $p = .80$] and were both significantly different from zero (verbal [$t(34) = -3.34$, $p < .01$]; spatial [$t(35) = -4.00$, $p < .01$]).

A repeated measure ANOVA was conducted with Condition (baseline or load) as within-subject variable, Memory-modality (spatial or verbal) as between-subject variable and difference between overall RT load condition and overall RT baseline as a covariate. Only the interaction between Condition and Memory-modality reached significance [$F(1,68) = 4.07$, $p < .05$]. Planned comparisons revealed that this interaction resulted from a significant reduction of the SNARC-effect in the spatial condition [$F(1,68) = 4.31$, $p < .05$].

4. General discussion

We investigated the nature of the spatial–numerical associations underlying the SNARC-effect by imposing a verbal or spatial working memory load during a parity judgment and a magnitude comparison task. In Experiment 1 it was shown that during parity judgment, the SNARC-effect was abolished under verbal load but not under spatial load. This result provides the necessary empirical argument to substantiate the claim that verbally mediated spatial representations can be the critical determinants of the SNARC-effect – a claim that so far was merely based on theoretical (Proctor & Cho, 2006) and computational (Gevers et al., 2006) arguments. In Experiment 2 the opposite pattern was found: during a magnitude comparison task the SNARC-effect was abolished by spatial load but not by verbal load.

Together the results of Experiment 1 and 2 constitute a double dissociation between type of working memory load and type of task, indicating that numbers are associated with multiple spatial codes differentially engaged by magnitude comparison and parity judgment. It is widely accepted that spatial information can be represented separately in verbal and visuospatial format, based on behavioral (e.g. Crawford et al., 2000; Logan, 1994) and neuroscientific evidence (e.g. Jager & Postma, 2003). The distinction between visuospatial and verbal spatial information is also reminiscent to Paivio's (1986) dual-coding theory which claims that information is organized in both visual analogue and verbal symbolic representations. Our results provide an empirical demonstration of these distinct spatial codes being associated with numerical magnitude.

Whether these distinct number–space associations preexist in long-term memory or, alternatively, are only created for short-term purposes (possibly based on one common type of long-term number associations) is a question that cannot be answered based on the present results. Whatever the precise mechanism, the importance of these findings is situated in the fact that it unequivocally runs against the prevailing view that all behavioral signatures of number–space associations derive from a common spatial coding (generally conceived of as a mental number line).

Another question that emerges is why parity judgment and magnitude comparison engage spatial information of a different nature. Previously, relevance of magnitude information for correct task completion has been thought to be the critical difference between both tasks (e.g. Gevers et al., 2005). Obviously, magnitude comparison explicitly draws on magnitude information, whereas this is not the case for parity judgment, where access to magnitude information remains implicit (Priftis et al., 2006). However, the explicit–implicit distinction alone cannot provide an explanation for the dissociation observed. If magnitude information is implicitly and automatically processed in parity judgment, it should be immune to any kind of working memory load or at least be influenced by the same type of load as in magnitude comparison.

A possibility worth considering is that the mapping of numbers to responses is a determining factor for the visuospatial nature of the SNARC-effect in magnitude comparison, where all numbers that are smaller or larger than the referent are associated with the same response. It is therefore not only more obvious, but also helpful to associate numbers with responses in a visuospatial way. Similarly, visuospatial associations may also be beneficial in number bisection, explaining why patients neglecting one part of physical space also neglect one part of the mental number line. These associations are not beneficial in parity judgment because the responses alternate with each number. A plausible mechanism that might be at play during parity judgment is that when a number's parity status is retrieved from the long-term memory store of conceptual knowledge, also other attributes like the conceptual spatial associations are simultaneously retrieved. When a task does not invoke this conceptual number knowledge, like in magnitude comparison, however, the conceptual store is not addressed and these spatial labels are not retrieved either.

The fact that we demonstrated dissociable mechanisms in parity judgment and magnitude comparison and attribute it to different types of spatial information (verbal and visuospatial, respectively), combined with the observations that conceptual spatial information (Kosslyn et al., 1989) and verbal spatial information in particular are processed by the left hemisphere and visuospatial by the right hemisphere (Jager & Postma, 2003; Kemmerer, 2006) provides a coherent explanation for the fact that neglect patients with right hemisphere damage show impairments in number comparison (Vuilleumier, Ortigue, & Brugger, 2004) and number bisection (Zorzi et al., 2002) while their SNARC effect in parity judgment is intact (Priftis et al., 2006).

In conclusion, our results demonstrate that the tight relationship between numbers and space is richer than previously thought: Numbers are not only associated with spatial representations of a visuospatial nature but also to spatial representations of a verbal nature. Existing theories (e.g. Hubbard et al., 2005) and models (e.g. Gevers et al., 2006) need to be extended and must incorporate both types of representations. Future empirical and modeling work is needed to understand the representational details of both representations, how they are related to each other and how they are recruited as a function of task-context.

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