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Visuospatial priming of the mental number line

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Abstract

It has been argued that numbers are spatially organized along a "mental number line" that facilitates left-hand responses to small numbers, and right-hand responses to large numbers. We hypothesized that whenever the representations of visual and numerical space are concurrently activated, interactions can occur between them, before response selection. A spatial prime is processed faster than a numerical target, and consistent with our hypothesis, we found that such a spatial prime affects non-spatial, verbal responses more when the prime follows a numerical target (backward priming) then when it precedes it (forward priming). This finding emerged both in a number-comparison and a parity judgment task, and cannot be ascribed to a "Spatial–Numerical Association of Response Codes" (SNARC). Contrary to some earlier claims, we therefore conclude that visuospatial–numerical interactions do occur, even before response selection.

Keywords: Number line; SNARC; Magnitude; Backward priming; Attentional shift

1. Introduction

A few decades ago, it was suggested that the representation of numbers could be spatially organized along a *mental number line* (Restle, 1970). That this mental num-

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ber line is more than a metaphor has been shown by Zorzi, Priftis, and Umiltà (2002), who found that the pattern of errors of neglect patients in a mental-number-line-bisection task are remarkably similar to those in a physical-line bisection task (see also Priftis, Zorzi, Meneghello, Marenzi, & Umiltà, 2006; Zorzi, Priftis, Meneghello, Marenzi, & Umiltà, 2006).

Since Dehaene, Bossini, and Giraux (1993), it has often been assumed that the mental number line affects spatial aspects of response selection. Dehaene et al. presented single digits at fixation, asked subjects to indicate their parity (odd or even), and found that small numbers lead to faster left-hand responses than right-hand responses, and that large numbers lead to faster right-hand responses than left-hand responses. Dehaene et al. interpreted the effect as due to a *Spatial–Numerical Association of Response Codes* (*SNARC*), an association between the spatially organized "mental number line" and a response preparation that is also spatial in nature and could, for example, involve left and right hands (Fias, 2001), saccades (Schwarz & Keus, 2004), or the left and right fingers of one single hand (Priftis et al., 2006).

However, Fischer et al. (2003; see also Caessens et al., 2004), provided some evidence suggesting that the mental number line could affect processing before response selection. They presented subjects with a dot, either to the right or left of fixation, and asked them to detect it as quickly as possible, but always with the same hand. The dot was preceded by one of four digits (1, 2, 8, or 9) and, although the digit was uninformative about the location of the dot (and subjects knew this), it nevertheless led to faster target detection on the left when it represented a number that was small, and to faster detection on the right when it represented a number that was large. Response selection was irrelevant, and the authors attributed their result to a lateral shift of attention, induced upon number perception by the activation of the mental number line.

Ristic, Wright, and Kingstone (2006) and Galfano, Rusconi, and Umilta (2006) replicated the result, but also found that the attentional shift is not obligatory, and reflects top–down rather than bottom–up processes. Nevertheless, using temporal order judgments rather than detection, Casarotti, Michielin, Zorzi, and Umiltà (2007) corroborated Fischer et al.'s conjecture that attention might play a mediating role. Casarotti et al. found that when two dots, that are presented at the same time, are preceded by a small number, the left dot is judged to appear sooner, and when they are preceded by a large number, the right dot is judged to appear sooner. The effects did require active processing of the cue as a number, and only appeared when it had to be reported, but with that condition fulfilled, the attentional temporal order effect could offset an opposite physical temporal order difference of about 5–6 ms.

In the current article, as in the studies we just mentioned, we investigate visuospatial–numerical interactions that precede response selection. However, whereas Fischer, Castel, Dodd, and Pratt (2003) investigated whether a number can affect the processing of a non-number, we do the opposite, and explore whether a non-number can affect the processing of a number. Given that the representations of visual and numerical space are homeomorphic (Zorzi et al., 2002; but cf. Doricchi, Guariglia, Gasparini, & Tomaiuolo, 2005), we hypothesize that the two representations interact when they are concurrently activated and that, in particular, a concurrently processed visuospatial cue and a numerical target can affect each other in this way.

Keus and Schwarz (2005) also investigated whether non-numerical information can affect numerical processing. Their subjects had to indicate the parity of a number that could appear either to the right or left of fixation. The task ensured the numbers were processed – shown to be important by Casarotti et al. (2007) – but nevertheless they only obtained an effect of the position of the numbers on lateralized manual responses, and not on (non-lateralized) voice key responses. Keus and Schwarz concluded that visuospatial–numerical effects can only occur at, and not before, response selection.

However, spatial information is coded fast and automatically (e.g., Lu & Proctor, 1995) and could decay or be inhibited (e.g., Zorzi & Umiltà, 1995) before concurrently presented numerical information is processed, especially when this spatial information is task-irrelevant. Consequently, it is possible that the concurrently presented visuospatial and numerical information in the stimuli of Keus and Schwarz (2005) did not activate their respective representations at the same time, and that this is why they did not find an interaction in their verbal task. In Fischer et al. (2003), in contrast, a numerical prime was presented well in advance of a spatial target, and with the processing of the numerical prime being slower than of the spatial target, it is consistent with our conjecture that Fischer et al. did, and Keus and Schwarz did not, find visuospatial–numerical interactions before response selection.

In two experiments, we test our conjecture that there are visuospatial effects on numerical processing, even before response selection, provided the representations of visual space and numerical space are activated concurrently. More specifically, we predict that a spatial prime does affect the processing of a numerical target, but that this effect emerges when the prime *follows* rather than precedes the target. That is, we predict that *backward priming* is more effective than *forward priming*. By employing a verbal task, we avoid the use of lateralized effectors, and control a SNARC effect that could otherwise confound our results. Moreover, in order to collect converging evidence for our claim, we use two different tasks: a number comparison task (Experiment 1), and a parity judgment task (Experiment 2).

2. Method

2.1. Participants

Twenty naïve undergraduates of the Università di Padova participated in Experiment 1 (for course credit) and twenty different ones in Experiment 2 (for a small fee).

2.2. Apparatus

We used an IBM-compatible computer with a 17 in. flat-screen monitor (85 Hz refresh rate), and recorded responses with the help of a voice key, with a Sigma Tel soundcard, that had a sensitivity of −59 dBm, and 80–12,000 Hz. With the help of a custom made MATLAB program, the onset of the voice key responses was detected with millisecond precision using a method similar to the word-boundary detection algorithm of Rabiner and Sambur (1975; similar results were obtained using an alternative method by James, 1996), and subsequently those responses were fully automatically classified as "Ti" or "To" (Stoianov & Kramer, in preparation). Voice key errors occurred in only 0.2% and 1.2% of the trials of, respectively, Experiments 1 and 2, and consisted in missing, multiple, or non-classifiable responses.

2.3. Stimuli

A dot-shaped fixation point, dot-shaped cue, and a number that was the target were used as stimuli (Fig. 1). All were white on a black background. The fixation point and cue had diameters of, respectively, 0.2° and 1° of visual angle. The target was one of the numbers 2, 4, 6, or 8 in Experiment 1, and one of the numbers 1, 2, 3, 4, 6, 7, 8, 9 in Experiment 2. All numbers were presented in Arial font, with a height of 0.8°. The stimuli were created, and presented in pseudo-random order within each block, with the help of Matlab 7 and the Cogent toolbox. Viewing distance was 50 cm.

2.4. Procedure

After the 495-ms presentation of the fixation point, either a 118-ms cue, or a 518-ms target, was presented first. When the cue was presented first (*forward priming*), it

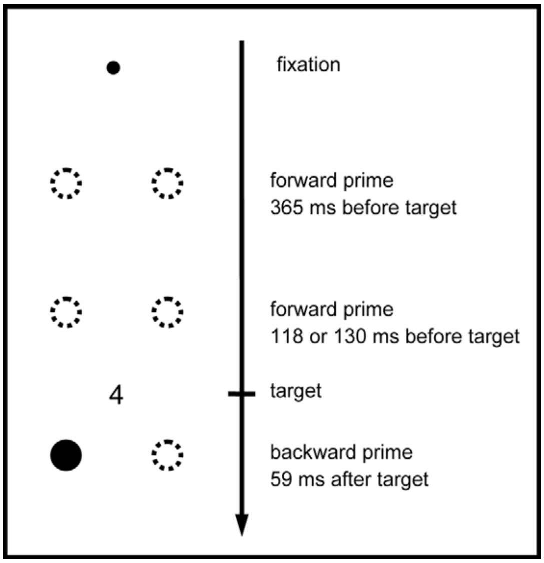

Fig. 1. Stimulus presentation: a forward prime was presented either well before (−365 ms SOA) or shortly before (−118 or −130 ms SOA) the onset of the target, or a backward prime was presented shortly after the onset of the target (+59 ms SOA). Prime duration was always 118 ms. The arrow represents time. The visuospatial prime could occur at any location and time indicated by the disks. The filled disk shows a backward prime on the left.

appeared either well before target onset (365 ms SOA), or shortly before it (118 ms SOA in Experiment 1, and 130 ms SOA in Experiment 2). When the target was presented first (*backward priming*), the cue appeared shortly after target onset (59 ms SOA).

In Experiment 1, the subjects were asked to respond as accurately and fast as possible, as soon as they saw the target, by saying either "Ti" when the target was smaller than 5, or "To" when it was larger than 5 (or vice versa, counterbalanced between subjects). In Experiment 2, the subjects were asked to respond as accurately and fast as possible, as soon as they saw the target, by saying either "Ti" when the target was odd, or "To" when it was even (or vice versa, counterbalanced between subjects). Finally, after the offset of the target, an intertrial interval was presented with a pseudo-random duration between 1.8 and 2.2 s, to prevent the development of a response rhythm.

The trials were presented in pseudo-random order, with short self-paced breaks between blocks. Experiment 1 contained 384 trials, divided into four blocks of four repetitions of each condition. Experiment 2 contained 432 trials, divided into three blocks of three repetitions of each condition. Experiment 1 was preceded by a practice block with one repetition per condition. Experiment 2 was preceded by a practice block in which each number was presented three times, and cue position and SOA were chosen pseudo-randomly. In both experiments, feedback was only provided in the practice blocks, after incorrect or missing responses.

3. Results

We averaged across the counterbalanced voice key responses of "Ti" and "To", and submitted the reaction time (RT) data to an ANOVA. Only correct trials were considered with RTs no smaller than 200 ms, no larger than 1000 ms, and no larger than two standard deviations above the mean of the condition in which the trial occurred (Miller, 1988; Ratcliff, 1993), leading to the exclusion of 4.0% and 3.9% of the data as outliers in, respectively, Experiments 1 and 2. Results were similar when outliers were not removed.

In separate ANOVAs on the RT and accuracy results of only Experiment 2, we did not find any effects of parity. After averaging across this factor, and after averaging across the data for small numbers and the data for large numbers, we submitted the RT results of both Experiments 1 and 2 to one single ANOVA, and the accuracy results to another one. Both ANOVAs contained the between-subjects factor of *Experiment* (number comparison vs. parity), and the within-subjects factors of *Cue-Position* (left vs. right), *Target-Magnitude* (smaller or larger than 5), and *SOA* (forward priming well before, or just before, the target vs. backward priming).

Fewer errors were made in Experiment 1 (1.3%) than in Experiment 2 (2.8%; $F(1,38) = 5.6$, $p < .05$), and the pattern of errors was affected slightly differently by target-magnitude in Experiment 1 (0.9% for small, and 1.6% for large, magnitudes) than in Experiment 2 (3.0% for small, and 2.5% for large, magnitudes; $F(1,38) = 5.8$, $p < .05$). No other accuracy effects were found.

For our current study, the RT results are more important than the accuracy results, and we found that Experiments 1 and 2 produced similar ones, with none of the differences between them reaching significance (Fig. 2 shows the backward-priming results). Most important are the interactions between cue position and target magnitude ($F(1,38) = 5.1$, $p < .05$), and cue position, target magnitude, and SOA ($F(2,76) = 9.0$, $p < .001$). As predicted, these results suggest that spatial–numerical interactions occurred before response selection that depended on SOA.

In addition, we found a main effect of target magnitude ($F(1,38) = 7.6$, $p < .01$; see also Moyer & Landauer, 1967). Responses were faster when targets were smaller, than when they were larger, than 5 (respectively, 549 and 555 ms). In Fig. 2, priming on the left appears more effective than on the right. However, most of the asymmetry is due to this non-spatial target magnitude effect that, unlike the spatial–numerical effect, did not interact with SOA, and did not depend on backward priming. There was also an effect of SOA (mean RTs were 549 ms for the long forward-priming SOA, 547 ms for the short forward-priming SOA, and 560 ms for the backward-priming SOA; $F(2,76) = 22.1$, $p < .001$), but no other effects were significant.

Besides these analyses, we performed ANOVAs for each SOA separately (Table 1 shows all means). For the backward priming, we found an interaction between cue position and target magnitude ($F(1,38) = 16.6$, $p < .001$) and a main effect of target magnitude ($F(1,38) = 4.0$, $p < .05$). When the target magnitude was small, RTs were faster when the cue appeared on the left than when it appeared on the right. When the target magnitude was large, RTs were slower when the cue appeared on the left than when it appeared on the right. There was also a main effect of cue position. Responses were faster to a cue on the right than on the left ($F(1,38) = 6.5$, $p < .05$).

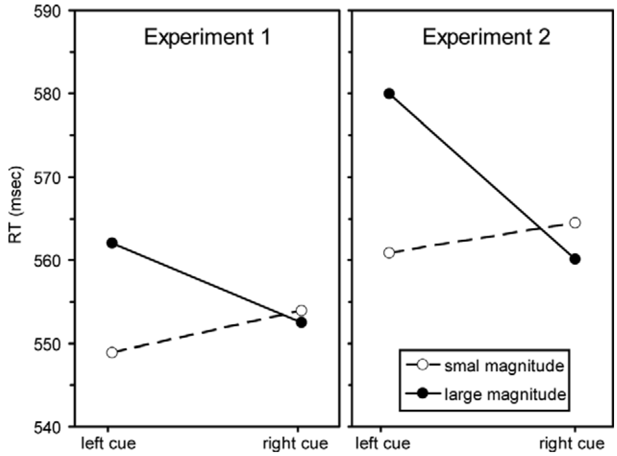

Fig. 2. Mean RTs of Experiments 1 (number comparison) and 2 (parity judgment) after backward priming, revealing interactions between number magnitude and prime location: faster responses to small numbers when followed by a prime on the left than when followed by a prime on the right, and the opposite pattern for large numbers.

Table 1
Mean reaction time in Experiments 1 and 2 (ms)

Experiment	Magnitude	Cue onset relative to target					
		Well-before		Shortly-before		After	
		Left	Right	Left	Right	Left	Right
1. Number-comparison	Small	535	539	537	534	549	554
	Large	541	542	540	541	562	552
2. Parity-judgment	Small	554	555	552	548	561	564
	Large	564	560	556	564	580	560

For forward-priming with a prime shortly before target onset, we found an effect of target magnitude ($F(1,38) = 8.3$, $p < .01$), but only a marginally significant spatial–numerical interaction between cue position and target magnitude ($F(1,38) = 3.4$, $p < .07$) that had a direction opposite to that in the backward-priming condition. For forward-priming with a prime well before target onset, we found neither a significant nor marginally significant spatial–numerical interaction. However, there was a marginally significant main effect of target magnitude ($F(1,38) = 3.7$, $p = .06$) and responses were faster when targets were smaller, than when they were larger, than 5.

Finally, we performed analyses for Experiments 1 and 2 separately. In both experiments, we obtained spatial-numerical interactions that depended on SOA, and effects of target magnitude (in accuracy in Experiment 1 and in RT in Experiment 2) that did not depend on SOA. Most importantly, the spatial–numerical interactions between cue position and target magnitude were once again significant in the backward-priming condition, and neither significant nor marginally significant in the forward-priming conditions.

For Experiment 1, although not of primary concern, we analyzed the effect of the numerical distance between the target (either 2, 4, 6, or 8) and the reference number (always 5). As expected, RTs were slower for target numbers close to the reference number than for those further away (*distance effect*; Moyer & Landauer, 1967). That is, the mean RT for the target numbers 4 and 6 (that differ from the reference of 5 by only 1) was 557 ms, whereas the mean RT for the target numbers 2 and 8 was faster and was 535 ms ($t(19) = 3.66$, $p < .005$). In a separate number comparison experiment, with 20 different subjects, we replicated our current backward-priming result with an SOA of 59 ms, found similar backward-priming results with SOAs of 106 and 177 ms, and replicated the distance effect.

4. Discussion

Based on neuropsychological evidence that the representations of visual and numerical space are homeomorphic (Zorzi et al., 2002), we hypothesized that interactions between a spatial prime and a numerical target should be possible. However, semantic processing of a target digit must be preceded by its perceptual processing, whereas a non-numerical visuospatial prime does not require any more than just perceptual processing. For this reason, the spatial coding of a number (activation of the mental number line) is delayed relative to the spatial coding of a visuospatial prime. We hypothesized that in order for a spatial prime and a numerical target to interact, they need to activate their representations concurrently. The physical delay of the prime, during backward priming, compensates for the processing delay of the target and ensures that the prime and target can indeed activate their respective spatial representations concurrently. In two experiments, we corroborated our hypothesis, and found that backward priming is, and forward priming is not, effective. The effects we obtained were similar or larger in size than those obtained in related studies (Casarotti et al., 2007; Fischer et al., 2003; Galfano et al., 2006).

The subjects' responses were verbal and non-spatial, our results could therefore not have involved a SNARC, which requires lateralized responses. In Experiment 1, subjects were asked to respond differently to small numbers than to large ones. If small number magnitudes activate the left of a response-related spatial reference frame and large ones the right of that frame, then the task could perhaps still lead to response selection effects. However, in Experiment 2, subjects were asked to respond differently to odd than to even numbers. The parity of the numbers is orthogonal to their magnitude, and we did not find interactions of parity judgments with cue location. Instead, we observed similar interactions between target-magnitude and cue position in both our experiments. Thus, the visuospatial–numerical interaction that we found cannot be explained in terms of a task-induced spatial reference frame. We therefore conclude that (a) during the semantic processing of target numbers, a left-to-right oriented mental number line is accessed and (b) this mental number line can be primed by a visuospatial stimulus. The results are complementary to those of Fischer et al. (2003), and the studies that replicated and extended their results.

The exact mechanism behind our new priming effect, and whether it involves direct interactions between the representations of visual and numerical space, or whether attention plays a mediating role (Casarotti et al., 2007; Fischer et al., 2003) remains to be investigated. Although we found evidence for a spationumerical association before response selection, it is possible that the association is more general and not limited to numerical information. For instance, it may apply to other ordered sequences that are spatially organized, such as the letters of the alphabet or the months of the year (Gevers, Reynvoet, & Fias, 2003; Zorzi et al., 2006). This possibility remains to be investigated, but it is worth noting that important differences between numbers and other ordered sequences have been shown in relation to both spatial coding and spatial attention (Casarotti et al., 2007; Zorzi et al., 2006). Finally, the neurophysiological underpinnings of our visuospatial priming effect should be explored. A promising starting point for this could be the intraparietal sulcus, in which spatial and numerical processing has been found to occur in directly adjacent and partially overlapping areas (Cohen-Kadosh et al., 2005; Pinel, Piazza, Le Bihan, & Dehaene, 2004; and for reviews see Hubbard, Piazza, Pinel, & Dehaene, 2005; Walsh, 2003).

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