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Temporal order judgment reveals how number magnitude affects visuospatial attention ☆

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Abstract

The existence of spatial components in the mental representation of number magnitude has raised the question regarding the relation between numbers and spatial attention. We present six experiments in which this relation was examined using a temporal order judgment task to index attentional allocation. Results demonstrate that one important consequence of numerical processing is the automatic allocation of spatial attention, which in turn affects the perception of the temporal order of visual events. Given equal onset time, left-side stimuli are perceived to occur before right-side stimuli when a small number (1, 2) is processed, whereas right-side stimuli are perceived to occur before left-side stimuli when a larger number (8, 9) is processed. In addition, we show that this attentional effect is specific to quantity processing and does not generalize to non-numerical ordinal sequences.

Keywords: Numerical cognition; Spatial attention; Numbers and space; Temporal order judgement; Ordered sequences

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1. Introduction

Several studies investigating the mental representation of numbers demonstrated a tight coupling between numbers processing and spatial cognition. Dehaene and collaborators (Dehaene, Bossini, & Giraux, 1993; Dehaene, Dupoux, & Mehler, 1990) first demonstrated an association between number magnitude and response side: small numbers are associated with left-side responses and large numbers with right-side responses. This effect is known as the Spatial-Numerical Association of Response Codes (*SNARC*) effect and suggests that number magnitude is represented along a mental 'number line' that has a spatial orientation. Importantly, the spatial processing of numbers seems to be fast and automatic (Dehaene et al., 1993; Mapelli, Rusconi, & Umiltà, 2003).

More direct evidence for the spatial nature of number representations comes from the study of Zorzi, Priftis, and Umiltà (2002), in which patients with left hemispatial neglect showed a systematic bias in a number bisection task as if they were neglecting the left part (smaller numbers) of the mental number line. Neglect patients in the Zorzi et al. (2002) study systematically misplaced the midpoint of the numerical interval (e.g., responding that 5 is halfway between 2 and 6) and their errors closely resembled the typical pattern found in bisection of true visual lines, including the modulating effect of line length (also see Priftis, Zorzi, Meneghello, Marenzi, & Umiltà, 2006; Zorzi, Priftis, Meneghello, Marenzi, & Umiltà, 2006).

The automatic spatial coding of numbers has raised the question regarding the relation between numbers and spatial attention (Fischer, Castel, Dodd, & Pratt, 2003). Fischer and collaborators have shown that number perception causes a shift in covert attention to one side of visual space depending on number magnitude. Participants were required to detect as fast as possible a peripheral target that was preceded by an irrelevant digit cue. Results indicated that right targets were detected faster when preceded by a large digit (8 or 9), whereas left targets were detected faster when preceded by a small digit (1 or 2).

The orienting of attention in space allows the human visual system to sample sensory information to increase processing efficiency. Spotlight (Posner, Snyder, & Davidson, 1980), zoom lens (Eriksen & St. James, 1986) and gradient (LaBerge & Brown, 1989) models of spatial attention share the assumption that attention influences the speed of processing in the visual system. Stelmach and Herdman (1991) have provided evidence in favor of this assumption showing that the perception of temporal order is influenced by attentional allocation. Attentional effects were measured using a temporal order judgment (TOJ) task in which participants were required to report which of two visual stimuli occurred first. When the stimuli were presented at the same time, attended stimuli were perceived to occur before unattended stimuli (also see Shore, Spence, & Klein, 2001). Thus, the TOJ technique is a sensitive index of attentional allocation allowing one to assess attentional effects without requiring speeded manual responses.

We report a series of six experiments in which we investigated the relation between number processing and spatial attention using the TOJ technique to index attention orienting. Experiment 1 addressed the question of whether presentation of irrelevant numbers affects the perceived temporal order of two visual stimuli. In Experiments 2, 3A and 3B, number processing was engaged by requiring participants to report the identity of the digit after performing the TOJ task. That is, numbers were task-relevant, but unrelated to the temporal order of the visual stimuli. Experiments 4A and 4B examined whether modulation of temporal order depended on number magnitude or on ordinal information. Experiments 5 and 6 were designed to rule out the possibility that the results of the previous experiments depended on a response bias rather than on attention orienting. Moreover, Experiment 6 allowed us to measure the amount of temporal bias induced by the digit cues.

2. Experiment 1

In Experiment 1, we examined whether the simple perception of irrelevant digits may determine an automatic allocation of spatial attention depending on number magnitude. Our aim was to replicate the results of Fischer et al. (2003) using the TOJ technique to index the allocation of attention in space. Participants were required to report which of two brief flashes of light (TOJ stimuli), presented on either side of fixation, occurred first. TOJ stimuli were presented simultaneously or separated by 55 ms. An irrelevant digit appeared centrally before presentation of the TOJ stimuli. In the synchronous condition, temporal order should have been indiscriminable because TOJ stimuli were presented simultaneously. However, if attention is allocated to the left or right hemispace, depending on number magnitude, there should be an effect on perception of temporal order. That is, participants should provide a greater proportion of left-first responses in the small number condition and a greater proportion of right-first responses in the large number condition. If allocation of attention is not affected by number magnitude, right-first and left-first responses should be equally likely.

2.1. Method

2.1.1. Participants

Eleven students of the University of Padua participated in the experiment (4 males and 7 females, mean age: 25.8).

2.1.2. Visual display

Stimuli were presented on a 17 in. color monitor driven by an IBM-compatible Pentium III computer using E-prime (Psychology Software Tools). There were four panels in the display sequence (see Fig. 1). The first panel consisted of a central fixation cross and two lateral markers located at 4° of visual angle on either side of fixation. Each marker subtended 1° of visual angle. In the second panel the fixation cross was replaced by one of four digits (1, 2, 8, 9). The third panel was equal to the first panel and the fourth panel contained the background elements

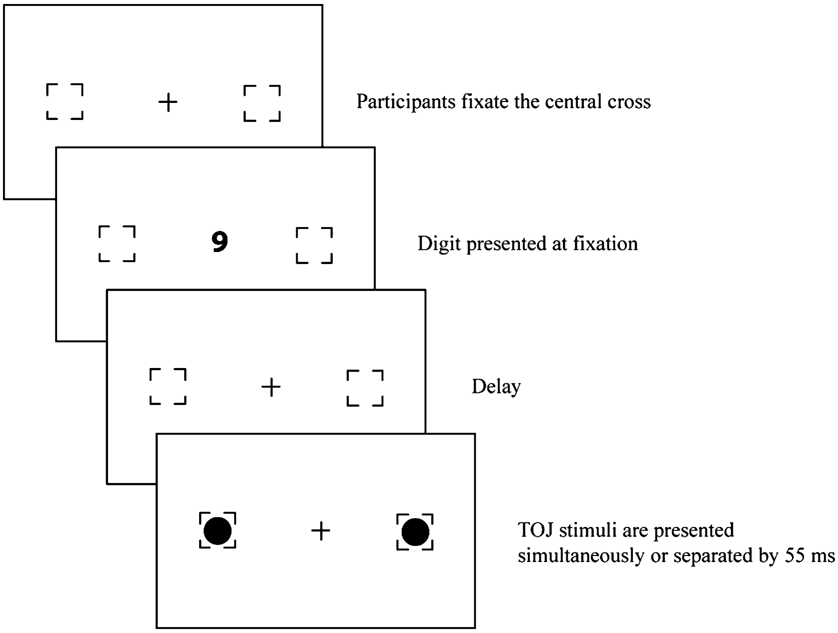

Fig. 1. Display sequence.

plus the two imperative stimuli within the two lateral markers. The stimuli occurred simultaneously or separated by 55 ms and lasted for 10 ms. Because of their short duration, TOJ stimuli were displayed at a higher luminance than background elements.

2.1.3. Design and procedure

Participants were seated at about 60 cm from the screen of the monitor with their heads held by a chin-rest. They were presented with 480 experimental trials in a random sequence. On half of the trials the stimuli occurred simultaneously (SOA = 0) and on the remaining half they occurred asynchronously, 50% left-first (SOA = −55) and 50% right-first (SOA = 55). Synchronous trials allowed us to assess attention orienting, whereas asynchronous trials were used to test whether participants were able to perform temporal order judgments accurately. Each trial started with presentation of the first panel and, after 500 ms, the second one containing the irrelevant digit was presented for 250 ms. After a random delay (250, 500 or 750 ms) the fourth panel with the TOJ stimuli was presented. Participants were required to report which of the two stimuli had occurred first by pressing one of two response keys on the computer keyboard (‘*q*’ or ‘*p*’, operated with the left-hand and the right-hand, respectively) without time pressure. In case of uncertainty, they were told to base their responses only on the available perceptual evidence. Participants were instructed to maintain fixation and were informed that the digit cue was irrelevant for the task.

Table 1
Percentage of left-first responses in Experiment 1

TOJ condition	Number					
	1	2	Mean (small)	8	9	Mean (large)
Delay: 250 ms						
Left-first	86.4	82.7	84.5	80.0	78.2	79.1
Synchronous	41.4	39.1	40.2	33.2	40.5	36.8
Right-first	11.8	18.2	15.0	17.3	18.2	17.7
Delay: 500 ms						
Left-first	89.1	85.5	87.3	83.6	83.6	83.6
Synchronous	44.1	38.6	41.4	31.4	36.8	34.1
Right-first	12.7	14.5	13.6	11.8	20.0	15.9
Delay: 750 ms						
Left-first	85.5	82.7	84.1	87.3	84.5	85.9
Synchronous	45.5	39.1	42.3	35.5	41.8	38.6
Right-first	10.9	14.5	12.7	10.9	17.3	14.1

2.2. Results and discussion

When the stimuli were presented simultaneously, the proportion of left-first responses was nearly equivalent across all conditions (see Table 1). A 3 (delay: 250, 500, 750) × 2 (number magnitude: small vs. large) repeated-measures ANOVA on left-first responses in synchronous trials did not yield any significant effect [main effect of delay: $F(2,20) = .87$; main effect of number magnitude: $F(1,10) = 1.02$; interaction: $F(2,20) = .46$]. That shows that number magnitude did not affect TOJs, suggesting that the simple perception of irrelevant numbers did not cause automatic orienting of visuospatial attention.

On asynchronous trials, participants were 85% accurate in reporting the veridical order of TOJ stimuli. A repeated-measures ANOVA on percentage of errors (error rate) with number magnitude, side (in which the first TOJ stimulus occurred; left vs. right) and delay as factors revealed a significant main effect of delay [$F(2,20) = 5.73$, $p < .05$]. That is, the error rate was slightly higher (17.9%) when the delay was 250 than in the other conditions (14.4%). No other main effect or interaction was significant.

3. Experiment 2

In Experiment 1, the presence of the irrelevant number at fixation did not produce attentional effects, contrary to the findings of Fischer et al. (2003) with a cueing paradigm. One possible explanation of the null result is that irrelevant numbers constitute a weak cue for the automatic triggering of attention shifts, as shown by a recent study that compared different types of irrelevant cues, including numerals (Bonato, Priftis, Marenzi, & Zorzi, 2005). Moreover, Galfano, Rusconi, and Umiltà (in press) have shown that the orienting response induced by number magnitude is not obligatory and that the size of the cueing effect is very small. However, active processing of the number might produce stronger and more reliable attention orienting. In addition, it is possible that the processing of irrelevant numbers was prevented because participants fully allocated attention to the lateral markers in order to increase the processing of TOJ stimuli. As demonstrated by Lavie (1995; also see Lavie & Tsal, 1994), the processing of irrelevant information is prevented when the load of the task is sufficiently high to exceed the available attentional resources. Moreover, Mack and Rock (1998) demonstrated that the distance from the focus of attention plays an important role in the detection of unattended stimuli.

In Experiment 2, we required participants to report the digit after performing the TOJ task. Therefore, even though it was unrelated to the TOJ task, the number needed to be processed.

3.1. Method

Eight students of the University of Padova participated (4 males and 4 females, mean age: 27). The procedure and design were identical to Experiment 1, except that participants were required to report the number after judging which of the TOJ stimuli occurred first.

3.2. Results and discussion

We analyzed temporal judgments only in the trials in which participants were accurate in reporting the identity of the number (3.8% of errors). A repeated-measures ANOVA on left-first responses in synchronous trials revealed that the main effect of number magnitude [$F(1,7) = 6.41$, $p < .05$] and delay [$F(2,14) = 5.25$, $p < .05$],

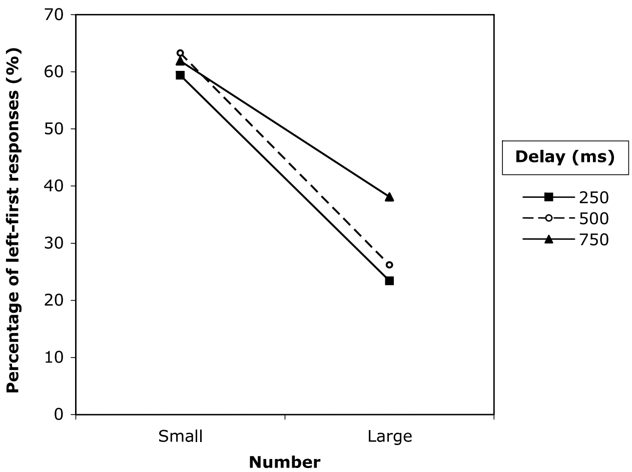

Fig. 2. Mean percentage of left-first responses in Experiment 2 as a function of number magnitude (small vs. large) and delay (250, 500 and 750) in the synchronous condition.

Table 2
Percentage of left-first responses in Experiment 2

TOJ condition	Number					
	1	2	Mean (small)	8	9	Mean (large)
Delay: 250 ms						
Left-first	93.6	93.7	93.6	91.0	88.8	89.9
Synchronous	58.0	60.8	59.4	21.8	25.0	23.4
Right-first	11.5	11.7	11.6	9.0	9.0	9.0
Delay: 500 ms						
Left-first	96.2	92.2	94.2	93.6	91.1	92.4
Synchronous	68.8	57.7	63.3	27.2	25.2	26.2
Right-first	14.3	7.8	11.0	7.6	6.6	7.1
Delay: 750 ms						
Left-first	96.1	94.8	95.5	91.0	90.4	90.7
Synchronous	63.8	60.0	61.9	43.0	33.3	38.1
Right-first	2.6	10.5	6.6	5.4	10.3	7.8

as well as their interaction were significant [$F(2,14) = 4.41$, $p < .05$]. That is, left-first responses were more frequent in the small number condition than in the large number condition, but this effect decreased at the longer delay (see Fig. 2 and Table 2). That clearly indicates that number processing caused an automatic shift of attention that depended on number magnitude.

On asynchronous trials, participants were 91.7% accurate in reporting the veridical order of TOJ stimuli. A repeated-measures ANOVA on error rate yielded a significant interaction [$F(1,7) = 6.24$, $p < .05$] between number (small vs. large) and side (left vs. right). Planned comparisons revealed that in the small number condition participants were less accurate when the first stimulus was presented to the right side than when it was presented to the left-side (see Fig. 3), $F(1,7) = 8.24$, $p < .05$; the effect was not significant for the large number condition. Thus, processing a small number affected the perceived temporal order of visual events even when they had a veridical

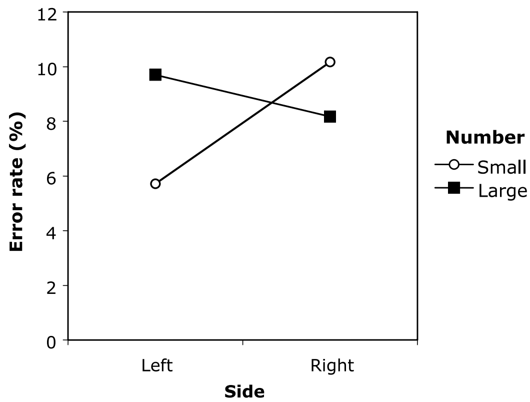

Fig. 3. Error rate in Experiment 2 as a function of number magnitude (small vs. large) and side in which the first TOJ stimulus occurred (left vs. right) in the asynchronous condition.

temporal order and occurred separate in time by 55 ms. This suggest that small numbers produce a stronger orienting effect than larger numbers. One tentative explanation for this result is that spatial coding for larger numbers is dynamic because it depends on the range of numbers employed throughout the task. For instance, Dehaene et al. (1993, Experiment 3) showed that when the range was either 0–5 or 4–9 in separate conditions, the numbers 4 and 5 were associated with the right responses or the left responses, respectively. Flexible, task-dependent coding of spatial associations is thought to be mediated by short-term memory links (Tagliabue, Zorzi, Umiltà, & Bassignani, 2000). In contrast, spatial coding for the smallest integer numbers such as 1 and 2 is likely to be mediated by long-term associations (in addition to task-dependent links) because they occupy a fixed position on the left-side of the mental number line.

4. Experiments 3A and B

In Experiment 2 we demonstrated that number processing affects perception of temporal order. The purpose of Experiment 3 was to replicate this finding using a simplified experimental design. Therefore, only two numbers were used (digits 1 and 9 in Experiment 3A; digits 2 and 8 in Experiment 3B), whereas the delay between the digit and the TOJ stimuli was of about 250 ms (note that this delay was most effective in Experiment 2).

4.1. Experiment 3A

4.1.1. Method

Nineteen students of the University of Padova participated (9 males and 10 females, mean age: 27). The procedure and design were as in Experiment 2, except that only the digits 1 and 9 were presented and the cue-to-stimulus delay was randomly selected for each trial in the range between 220 and 280 ms. The total number of trials was 320 for each participant.

4.1.2. Results and discussion

We analyzed temporal order judgments only in the trials in which participants were accurate in reporting the identity of the number (5.5% of errors). Results showed that on synchronous trials number magnitude had a reliable effect on TOJs. As shown in Table 3, left-first responses were more frequent in the small number con-

Table 3
Percentage of left-first responses in Experiments 3A (digits 1 and 9) and 3B (digits 2 and 8)

TOJ condition	Number			
	1	2	8	9
Left-first	81.1	87.8	74.5	82.2
Synchronous	61.0	68.6	48.3	45.0
Right-first	20.8	31.6	24.4	19.7

dition than in the large number condition (61% vs. 45%). A repeated-measures ANOVA with number magnitude (1 vs. 9) as factor on left-first responses in synchronous trials, $F(1,18) = 11.81$, $p < .005$, produced a significant effect. On asynchronous trials, participants were 80.7% accurate in reporting the order of TOJ stimuli. A repeated-measures ANOVA on error rate with number magnitude (small vs. large) and side (left vs. right) as factors did not reveal any significant effect [interaction: $F(1,18) = .004$].

4.2. Experiment 3B

Digits 1 and 9 may cause an automatic shift of attention to the left or right hemispace because they represent the extreme values within the class of one-digit numerals (i.e., units). Therefore, participants were presented only with digits 2 and 8 in Experiment 3B.

4.2.1. Method

Nine students of the University of Padova participated (2 males and 7 females, mean age: 26.4). Stimulus presentation and design were the same as in Experiment 3A, except that the digits 2 and 8 were used instead of the digits 1 and 9.

4.2.2. Results and discussion

Only trials in which participants were accurate in reporting the identity of the number were analyzed (3.9% of errors). Results replicated those of Experiment 3A showing an effect of number magnitude on temporal order judgment on synchronous trials (see Table 3). A repeated-measures ANOVA on left-first responses yielded a significant effect of number magnitude [$F(1,8) = 6.34$, $p < .05$], indicating that the modulation of the perceived temporal order does also occur for the digits 2 and 8. On asynchronous trials, participants were 76.5% accurate in reporting the order of TOJ stimuli. A repeated-measures ANOVA on error rate with number magnitude (small vs. large) and side (left vs. right) as factors did not reveal any significant effect [interaction: $F(1,8) = 1.84$].

5. Experiments 4A and B

The results of Experiments 2 and 3 demonstrate that number processing affects the perceived temporal order of simultaneous events by causing an automatic shift of attention in space. However, attentional allocation might be linked to the ordinal character of numbers rather than to quantity information. Gevers, Reynvoet, and Fias (2003) have investigated the mental representation of non-numerical ordinal sequences such as letters and months, which share ordinality with numbers but not quantity. They demonstrated an association between ordinal position and spatial response preference, even when ordinal information was irrelevant to the task, suggesting that the *SNARC* effect may depend on ordinality. However, Zorzi et al. (2006) have recently demonstrated that hemispatial neglect exerts qualitatively

Table 4
Percentage of left-first responses in Experiments 4A (letters *a* and *i*) and 4B (letters *a* and *z*)

TOJ condition	Letter			
	a	*i*	*a*	*z*
Left-first	92.4	88.9	79.1	76.9
Synchronous	56.0	50.8	46.6	41.2
Right-first	15.7	12.0	22.6	26.8

different effects on the mental bisection of numerical vs. non-numerical intervals. That is, the pattern of errors shown by neglect patients when asked to bisect letter intervals and month intervals was found to be inconsistent with a continuous, left-to-right oriented spatial layout (which, instead, was fully compatible with the error pattern in the bisection of number intervals and of visual lines).

Thus, Experiment 4 examined whether letters of the alphabet would cause an automatic shift of attention, influencing perception of temporal order. Letters *a* and *i* were used in Experiment 4A, whereas letters *a* and *z* were used in Experiment 4B. Participants had to report the identity of the letter after performing the TOJ task.

5.1. Experiment 4A

5.1.1. Method

Eight students of the University of Padova participated (3 males and 5 females, mean age: 28.4). Stimulus presentation and design were the same as in Experiments 3, except that the digits were replaced with the letters *a* and *i*, which hold positions 1 and 9 in the Italian alphabet.

5.1.2. Results and discussion

Only trials in which participants were accurate in reporting the identity of the letter were analyzed (4.5% of errors). In the synchronous condition, the proportion of left-first responses did not change reliably depending on the letter (Table 4). The effect of letter identity (*a* vs. *i*) was not significant [$F(1,7) = .78$] in a repeated-measures ANOVA on left-first responses, indicating that processing these letters did not affect temporal order judgments. During asynchronous trials, participants were 88.4% accurate in reporting the veridical order of the TOJ stimuli. An ANOVA on error rate with letter identity (*a* vs. *i*) and side (left vs. right) as factors did not reveal any significant effect [interaction: $F\,(1,7) = 3.77$].

5.2. Experiment 4B

One possible explanation for the null effect in Experiment 3A is that the letter *i* was perceived as belonging to the beginning of the alphabet. Thus, in Experiment 4B participants were presented with letters *a* and *z*, which hold the first and the last position in the alphabet.

5.2.1. Method

Ten students of the University of Padova participated (5 males and 5 females, mean age: 28.8). Stimulus presentation and design were the same as in Experiments 4A, except that the letter *z* was presented instead of the letter *i*.

5.2.2. Results and discussion

Only trials in which participants were accurate in reporting the identity of the letter were analyzed (4.9% of errors).The effect of letter identity (*a* vs. *z*) was not significant [$F(1,9) = 1.64$] in a repeated-measures ANOVA on left-first responses in the synchronous condition. During asynchronous trials, participants were 76.6% accurate in reporting the veridical order of TOJ stimuli. An ANOVA on error rate with letter identity (*a* vs. *z*) and side (left vs. right) as factors did not reveal any significant effect [interaction: $F(1,9) = 0.36$].

The results of Experiments 4A and B indicate that ordinality does not affect temporal order judgments. That suggests that only magnitude causes an automatic shift of attention.

6. Experiment 5

Our previous experiments indicate an automatic orienting of attention during number processing, the direction of which depends on number magnitude. However, one might argue that these results did not arise from attention orienting, but from the association between number processing and response side – that is, a SNARC effect (Dehaene et al., 1993). Specifically, it is possible that when TOJ stimuli were perceived simultaneously, participants were biased to respond with the left hand in the small number condition (1 or 2) and with the right-hand in the large number condition (8 or 9). To investigate the possibility of a SNARC-like biasing of the manual responses in Experiments 2 and 3, in Experiment 5 participants were required to respond vocally in the TOJ task.

6.1. Method

Nineteen students of the University of Padova participated (8 males and 11 females, mean age: 27.6). Design and procedure were identical to those of Experiment 3, except that participants were presented with the digits 1, 2, 8 and 9, and they were instructed to report vocally which stimulus they perceived to occur first and the identity of the digit. The total number of trials was 240 for each participant.

6.2. Results and discussion

Only trials in which participants were accurate in reporting the identity of the number were analyzed (3.1% errors). A repeated-measures ANOVA on left-first responses with number magnitude (small vs. large) as factor yielded a significant main effect, $F(1,18) = 14.78$, $p < .005$. As in Experiments 2 and 3, in the synchronous

Table 5
Percentage of left-first responses in Experiment 5

TOJ condition	Number					
	1	2	Mean (small)	8	9	Mean (large)
Left-first	89.5	88.8	89.1	82.5	86.6	84.5
Synchronous	64.9	57.1	61.0	41.4	42.0	41.7
Right-first	18.7	17.4	18.0	18.0	13.8	15.9

condition the percentage of left-first responses (see Table 5) was higher when a small number was presented than when a large number was presented (61% vs. 42%). This result replicates those of Experiments 2 and 3 allowing one to rule out the possibility that the differences in the distribution of left-first responses as a function of number magnitude were simply caused by the association between numbers and response side.

On asynchronous trials, participants were 84.9% accurate in reporting the order of TOJ stimuli. Interestingly, an ANOVA on error rate during asynchronous trials with number magnitude (small vs. large) and side (left vs. right) as factors revealed a significant interaction, $F(1,18) = 5.49$, $p < .05$. Participants were less accurate in reporting the veridical temporal order when the first stimulus was presented to the left after a large number than after a small number, whereas the opposite occurred when the first stimulus was presented to the right. That is, number processing caused an attentional allocation depending on number magnitude, which affected the perceived temporal order of visual events even though they occurred separate in time.

7. Experiment 6

In Experiment 5, we showed that temporal order judgments are affected by number magnitude even when participants are required to indicate vocally which stimulus appeared first, using the Italian words corresponding to ”*left*” and ”*right*”. Even thought these results indicate that the observed effects did not depend on a bias of manual responses, they may be attributed to a response bias depending on an association between number and space at a conceptual level. In order to rule out this possibility, in Experiment 6 participants were required to perform the TOJ task with arbitrary vocal responses that cannot be associated with any spatial dimension. Moreover, we manipulated the interval between TOJ stimuli in asynchronous trials. This allows to determine the point of subjective simultaneity for each type of cue and thus the amount of temporal order bias incurred by participants.

7.1. Method

Ten students of the University of Padova participated (3 males and 7 females, mean age: 32.4). The procedure and design were as in Experiment 3A, except that in asynchronous trials TOJ stimuli occurred separated by an interstimulus interval (ISI) of 5, 10, 15, 20, 30 or 50 ms (see Table 6) and participants performed vocally both

Table 6
Number of trials for each condition in Experiment 6

TOJ condition (ISI in ms)	Number		*n* trials
	1	9	
−50	15	15	30
−30	15	15	30
−20	15	15	30
−15	15	15	30
−10	15	15	30
−5	15	15	30
0	30	30	60
5	15	15	30
10	15	15	30
15	15	15	30
20	15	15	30
30	15	15	30
50	15	15	30
Total	210	210	420

experimental tasks. They were instructed to report which of the TOJ stimuli appeared first using two arbitrary pseudo-words. Half of the participants (group A) responded "*fulpo*" instead of "*left*" and "*pingo*" instead of "*right*", while the other half (group B) received the opposite instructions. The total number of trials was 420 for each participant.

7.2. Results and discussion

Only trials in which participants were accurate in reporting the identity of the number were analyzed (1.8% of errors). A repeated-measures ANOVA with group (A

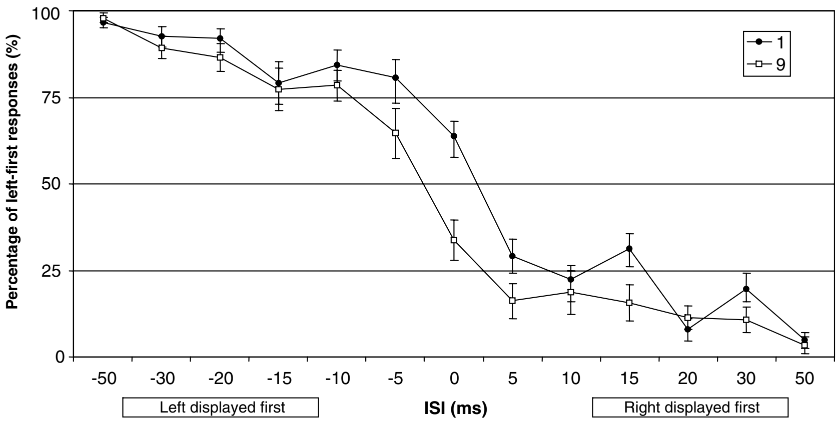

Fig. 4. Mean percentage of left-first responses in Experiment 6 as a function of number magnitude (1 vs. 9) and ISI between the TOJ stimuli. Negative and positive values of ISI refer to left- and right-side stimulus precedence, respectively. Error bars show the standard error of mean.

vs. B), number magnitude (1 vs. 9) and ISI (−50, −30, −20, −15, −10, −5, 0, 5, 10, 15, 20, 30, 50 ms) as factors was performed on left-first responses (see Fig. 4 and Table 7). The factor group was manipulated between-subjects and the remaining factors within-subjects. The ANOVA revealed that the main effect of number magnitude [$F(1,8) = 6.44$, $p < .05$] and ISI [$F(12,96) = 116.86$, $p < .0001$], as well as their interaction [$F(12,96) = 3.84$, $p < .0001$] were significant. No other effect was significant. Neumann-Keuls post-hoc tests ($p < .05$) indicated that the percentage of left-first responses was higher in the small number condition than in the large number condition when the ISI was −5, 0, 5 and 15 ms.

In order to measure the amount of temporal bias induced by each number, the individual frequencies of left-first responses were converted into probabilities and a logistic model was fitted to the data of each participant as a function of the interval between the onset of TOJ stimuli, separately for digit 1 and digit 9. This allows to determine the point of subjective simultaneity (PSS) for each type of digit cue. The PSS represents the interval for which the observer perceives the stimuli as simultaneous and is computed as the interval at which left-first and right-first responses are reported equally often (more specifically, when $p(\text{left-first}) = .5$). A shift in the PSS in either direction indicates that the cue induced a temporal bias. A paired samples two-tailed t test was then performed on the individual PSS to compare the temporal biases induced by each digit. The statistical comparison was significant, $t(9) = 2.79$, $p < .05$, with digit 1 inducing a mean bias of 5.7 ms and digit 9 of −4.6 ms (see Fig. 5).

Table 7
Percentage of left-first responses in Experiment 6

Number	TOJ condition (ISI in ms)												
	−50	−30	−20	−15	−10	−5	0	5	10	15	20	30	50
1	96,6	92,6	91,9	79,2	84,4	80,7	63,7	29,1	22,3	31,3	8,1	19,6	4,9
9	98,0	89,3	86,5	77,4	78,4	64,6	33,8	16,1	18,7	15,6	11,3	10,7	3,4

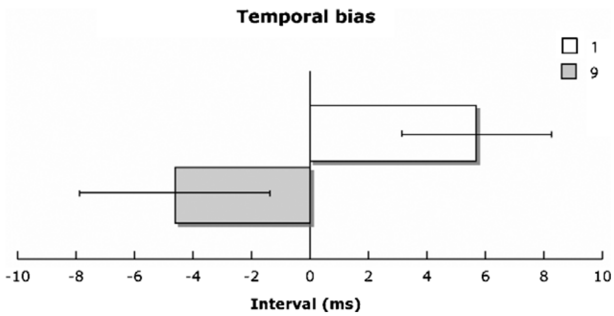

Fig. 5. Mean temporal biases induced by digits 1 and 9 in Experiment 6 as a function of the interval for which the observer perceives the TOJ stimuli as simultaneous (point of subjective simultaneity, PSS). The PSS was determined for each type of digit cue by fitting a logistic model to the individual probabilities of left-first responses. Error bars show the standard error of mean.

These findings demonstrate that the effect of number magnitude on TOJs depend on an attentional bias that occurs at an early visual level and cannot be attributed to a response bias. The results suggest that digit 1 determined a shift of attention to the left hemifield, which in turn increased by 6 ms the speed with which left-side stimuli were processed. Conversely, digit 9 produced attention orienting to the right hemifield, increasing by 5 ms the speed with which right-side stimuli were processed.

8. General discussion

The relation between number processing and orienting of visuospatial attention was examined in six experiments using the TOJ technique to index attentional allocation. Our results clearly demonstrate that number processing determines an automatic shift of visuospatial attention, which in turn modulates the speed with which information is processed in the visual system and affects the perceived temporal order of visual events (e.g., Shore et al., 2001; Stelmach & Herdman, 1991). We also determined that processing a small number increases by about 6 ms the speed with which stimuli in the left hemifield are processed, whereas processing a large number induces a temporal bias of about 5 ms in favor of right-side stimuli.

Fischer and collaborators (2003) suggested that merely looking at numbers determines a shift of attention in space, whereas we obtained attentional effects that depended on number magnitude only when the task required to process the digit cue. The results of Experiments 1 and 2 suggest that merely looking at numbers is not sufficient to activate automatic attention orienting. In contrast, processing a number determines a shift of spatial attention, which in turn affects the perception of temporal order. One possible explanation of the contrasting results is that irrelevant numbers constitute a weak cue for the automatic triggering of attention shifts. Galfano et al. (in press) have recently shown that the effect of number magnitude in the cued detection paradigm is rather small (6.5 ms) and that the orienting response is not obligatory. The latter result implies that the automaticity criterion is not met. In the same vein, Bonato et al. (2005) have shown that the automatic orienting induced by irrelevant digits is weak or absent in comparison to that induced by other types of irrelevant cues such as eye gaze and arrows.

One alternative, or even complementary, explanation for the discrepancy between Experiment 1 and 2 is that processing of irrelevant numbers may have been prevented in Experiment 1, because participants fully allocated attention to the lateral markers in order to enhance processing of TOJ stimuli. It has been shown that allocation of attention may influence the degree to which irrelevant information is processed (Kahneman & Chajczyk, 1983; Kahneman & Henik, 1981; Lavie, 2005; Lavie & Tsal, 1994; Mack & Rock, 1998). For example, Kahneman and Chajczyk (1983), in a color-naming task, demonstrated that Stroop-like interference from an irrelevant color-word can be diluted simply by adding one neutral stimulus to the visual display. This finding is consistent with the proposition by Lavie and Tsal (1994) that attentional resources are automatically allocated to irrelevant information only when relevant processing is not sufficiently demanding. Lavie (1995) used a variation of the response competition paradigm to measure irrelevant processing when different processing for identical displays was required and demonstrated that the distractors' interference was prevented under the high-load detection task. It has to be noted that even though the perceptual load in the TOJ paradigm is low, the load of the task is high as on half of the trials TOJ stimuli were presented simultaneously. Note, however, that irrelevant gaze cues produced reliable orienting effects in a TOJ task identical to that employed in the present study (Zorzi, Casarotti, & Michielin, submitted).

Importantly, we also demonstrated that attentional effects do not arise from the processing of ordinal sequences, such as letters, which do not convey quantity information. This result is consistent with recent electrophysiological evidence demonstrating differential processing of numerical quantity and order (Turconi, Jemel, Rossion, & Seron, 2004) and with the finding of Zorzi et al. (2006) that neglect patients show qualitatively different behavior when asked to mentally bisect numerical vs. non-numerical (i.e., letters or months) intervals.

Finally, the replication of the attentional effect when participants used arbitrary vocal responses to judge the temporal order of the stimuli rules out one alternative explanation in terms of a response bias, demonstrating that the observed effect occurs at an early visual level.

In summary, the experiments presented here demonstrate that one important consequence of processing number magnitude is the allocation of spatial attention, which in turn determines a modulation of the speed with which information is processed in the visual system. When a small number is processed there is a shift of spatial attention that causes a faster processing of sensory signals coming from the left-side, whereas the processing of large numbers produces a shift of attention that speeds up processing of sensory signals coming from the right-side.

The TOJ technique is a useful tool to further investigate the relation between number processing, space and attention because it does not hinge upon small RT differences, as with typical cued detection paradigms. As shown in the present study, the attentional orienting induced by number processing is very reliable and it is sufficiently strong to bias the perception of the veridical temporal order of two visual events.

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