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Processing numerosity, length and duration in a three-dimensional Stroop-like task: towards a gradient of processing automaticity?

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Abstract The existence of a possible continuum of automaticity for numerosity, length and duration processing was tested with a three-dimensional Stroop-like paradigm. Participants had to compare the numerosity, the length or the duration of two successive linear arrays of sequentially flashed dots in which the three dimensions were manipulated independently to create congruent, incongruent or neutral pairs. The results show that numerosity and length both affected duration processing separately and cumulatively, whereas temporal cues did not influence judgements of numerosity or length. Moreover, length and numerosity influenced each other, with numerical cues having a stronger influence on length processing than the reverse. These findings support the idea that, in sequentially presented stimuli, numerosity, length and duration are processed with different levels of automaticity, with numerosity being processed most, and duration least automatically.

Introduction

The idea of a single representational mechanism supporting magnitude processing was first developed for time and numerosity in the Accumulator model (Meck & Church, 1983) and later extended by A Theory Of Magnitude (ATOM; Bueti & Walsh, 2009; Walsh, 2003). In the last 10 years it has led to a profusion of behavioural studies looking for possible interactions between various magnitude dimensions, most generally between numerical, spatial and temporal magnitudes.

Firstly, a robust interference effect of numerosity (i.e., the number of elements in a set) on duration processing was observed, using either symbolic or nonsymbolic stimuli, both in children (Droit-Volet, Clément, & Fayol, 2003) and in adults (Brown, 1997; Dormal, Seron, & Pesenti, 2006; Oliveri et al., 2008; Xuan, Zhang, He, & Chen, 2007). The reverse influence of duration on numerosity processing has been less frequently explored, and appears weaker (only reported by Brown, 1997; see Table 1). For instance, although irrelevant to the task, the magnitude of Arabic digits was shown to interfere with duration judgements: when asked to estimate the duration of presentation of Arabic digits, participants underestimated the duration of small digits whereas they overestimated the duration of large digits (Oliveri et al., 2008; Vicario et al., 2008; Xuan et al., 2007). Moreover, the numerosity of rapidly flashed dot sequences or simultaneously presented dot arrays interacted with duration comparison: numerical cues facilitated duration processing when numerosity and duration were congruent and interfered with it when they were incongruent, whereas duration cues did not affect numerosity judgements (Dormal et al., 2006; Xuan et al., 2007).

Secondly, the interaction between space and time has been investigated through the concept of speed in many psychophysical studies over the past century, revealing the existence of two main effects. In a classical paradigm in which three horizontally aligned visual signals were flashed successively, forming two distinct spatio-temporal intervals, participants had to compare either the spatial or the temporal extents of these intervals. The results showed that duration comparison was influenced by the spatial distance between the flashed signals (the *kappa* effect; Cohen, Hansel, & Sylvester, 1953) and, conversely, that the temporal intervals between stimuli

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Table 1 Studies investigating interactions between numbers and durations and durations and lengths

Dimensions	Studies	Explored links	Tasks	Materials	Results
Numerosity-Duration	Xuan et al. (2007)	Unilateral $N \rightarrow D$	Duration comparison	N = Arabic digits: 1, 2, 8 or 9 N = dot arrays: 1, 2, 8 or 9 dots, D = between 600 and 937 ms	Unilateral interference of N on D
	Oliveri et al. (2008)	Unilateral $N \rightarrow D$	Duration estimation	N = Arabic digits: 1, 5 and 9, D = 250, 300 or 350 ms	Unilateral interference of N on D
	Vicario et al. (2008)	Unilateral $N \rightarrow D$	Duration comparison	N = Arabic digits: 1 or 9, D = between 150 and 450 ms	Unilateral interference of N on D
	Brown (1997)	Bilateral $N \Leftrightarrow D$	Dual-task paradigm: duration production and mental arithmetic	N = substraction: between 2 and 99, D = 2 or 5 s	Mutual interference between N and L
	Droit-Volet et al. (2003)	Bilateral $N \Leftrightarrow D$	Duration and numerical bisection	Sequences of dots in which time and numerosity co-varied N = between 2 and 8, D = between 2 and 8 s	Unilateral interference of N on D
	Dormal et al. (2006)	Bilateral $N \Leftrightarrow D$	Stroop-like paradigm: duration and numerosity comparison	Visual flashed dots series N = between 5 and 9 dots, D = between 1,200 and 2,100 ms	Unilateral interference of N on D
Duration-Length	Xuan et al. (2007)	Unilateral $L \rightarrow D$	Duration comparison	D = between 600 and 937 ms L = open square: 0.8°, 1.2°, 3.0° or 3.4°	Unilateral interference of L on D
	Casasanto & Boroditsky (2008)	Bilateral $D \Leftrightarrow L$	Length and duration reproduction	D = between 1,000 and 5,000 ms, L = between 200 and 800 pixels	Unilateral interference of L on D

interfered with length comparison (the *tau* effect; Helson, 1930). More recently, the kappa effect was also observed in other experimental contexts, through the presence of compatibility between temporal estimation and the available spatial cues (Table 1): the duration of exposure of small squares was perceived to be shorter than the duration of exposure of large squares (Xuan et al., 2007), and the duration of stimuli presented in the left hemispace was underestimated, whereas the duration of stimuli presented in the right hemispace was overestimated (Vicario et al., 2008). Similarly, spatial extent interfered with judgements on the duration of presentation of growing lines or moving dots (Casasanto & Boroditsky, 2008). This latter study did not replicate the tau effect in that only an asymmetric interaction between spatial extent and duration was found, duration never interfering with space.

Finally, the idea of an association between numbers and space is supported by various pieces of evidence (Table 2). It is worth noting that the term "space" encompasses a large variety of cognitive and motor processes; here, we only consider studies investigating space operationalized as a length. Length interference in numerosity judgements is frequent in children who numerically overestimate the longer of two arrays of elements, demonstrating the dominant influence of length over numerosity, and this strong perceptual bias is still present in educated adults (e.g., Houdé, 1997; Houdé & Guichart, 2001; Piaget, 1952; Pufall & Shaw, 1972). Reciprocally, numerosity influences performance on visuo-spatial cognitive tasks even when the numerical information is irrelevant. Indeed, participants show systematic spatial biases towards the larger magnitude when they have to bisect a horizontal line flanked by Arabic digits (Fischer, 2001) or dot arrays (de Hevia & Spelke, 2009), and they under-estimate the space between two small Arabic numbers while they over-estimate the space between two large numbers (de Hevia, Girelli, Bricolo, & Vallar, 2008). Until now, only one study (Dormal & Pesenti, 2007) has explored simultaneously the impact of numerosity on length processing and, conversely, the influence of length cues on numerosity processing with non-symbolic numerosities (Table 2). This mutual influence of length and numerosity processing was investigated in a Stroop-like experiment in which participants had to compare the length or the numerosity of arrays of dots in which the two dimensions were manipulated independently: whereas length cues strongly interfered with numerosity processing, numerical cues interfered only moderately with length judgements.[1]

[1] The size-congruity paradigm also investigates the bilateral influence between numerical and spatial dimensions but with stimuli in symbolic notation. In this paradigm, the numerical magnitude and the physical size of Arabic digits are varied independently and participants have to judge either the physical size of the digits while ignoring their numerical magnitude, or the numerical magnitude while ignoring their physical size. Typically, physical size interferes with numerical processing and vice versa, showing that the participants are unable to ignore the irrelevant dimension and implicitly process this dimension (e.g., Henik & Tzelgov, 1982).

Table 2 Studies investigating interactions between numbers and lengths and numbers, lengths and durations

Dimensions	Studies	Explored links	Tasks	Materials	Results
Numerosity-Length	Pufall & Shaw (1972)	Unilateral $L \rightarrow N$	Numerosity comparison	Two arrays of dots $N = 5$, 7 or 9 dots	Unilateral interference of L on N
	Fischer (2001)	Unilateral $N \rightarrow L$	Length bisection	Arabic digits composing the line or placing in the extremities of an horizontal line $N = 1$, 2, 8 or 9	Unilateral interference of N on L
	de Hevia et al. (2008)	Unilateral $N \rightarrow L$	Length reproduction	Extend delimited by two Arabic digits $N = 1$, 2, 8 or 9	Unilateral interference of N on L
	de Hevia & Spelke (2009)	Unilateral $N \rightarrow L$	Length bisection	Pattern of dots in the extremities of an horizontal line $N = 2$ or 9 dots	Unilateral interference of N on L
	Dormal & Pesenti 2007	Bilateral $N \Leftrightarrow L$	Stroop-like paradigm: numerosity and length comparison	Linear array of dots $N = 5$, 6 or 9 dots, $L =$ between 80 and 120 mm	Mutual interference between N and L
Numerosity-Duration-Space	Vicario et al. 2008	Unilateral N and $S \rightarrow D$	Duration comparison	$D =$ between 150 and 450 ms, $S =$ left or right spatial position, $N =$ Arabic digits 1 or 9	Joint interference of N and S on D

To our knowledge, only one study (Vicario et al., 2008) has investigated these three dimensions in the same experiment by exploring the influence of numerical magnitude and spatial cues on duration perception (Table 2). The participants had to estimate the duration of an Arabic digit presented either in the left or in the right visual hemifield. The results showed that the duration of a small digit (i.e., 1) was underestimated more when it was presented in the left hemispace and, conversely, that the duration of a large digit (i.e., 9) was more overestimated when it was presented in the right hemispace. This was interpreted as suggesting that time could be mentally represented by spatial coordinates within a left-to-right oriented linear representation similar to the one postulated for numbers (Dehaene, 1992). It is worth noting that, in this interpretation, the space–duration interaction stems from the relative position in space influencing duration processing, and not from the extent in space (e.g., length).

Thus, most of the previous studies have tried to show how the dimensions interact by only exploring unidirectional interfering effects (e.g., effect of length on numerosity but not the reverse), and many of them only used symbolic numerical stimuli. Moreover, as can be seen from Tables 1 and 2, the range of numerical magnitudes, length and duration, the tasks, the designs and general procedures greatly varied across studies, which makes it difficult to compare them and to draw firm conclusions. Taken together, the particular pattern of asymmetric results we observed in our two previous Stroop-like studies has led to the suggestion that there might be a continuum of automaticity in processing length, numerosity and duration. We tentatively explained the asymmetric effect of numerosity on duration by different levels of mandatory processing, the observed unilateral effect possibly reflecting a more automatic processing of numerosity than duration (Dormal et al., 2006). Similarly, with simultaneously presented arrays of dots, length appeared to be more automatically processed than numerosity (Dormal & Pesenti, 2007). However, although we used the same rational and method in these two studies, the mutual and bidirectional interactions of numerosity, length and duration have to date not been investigated within the same experimental design, and it is thus hard to exclude the possibility that differences in materials or experimental set-up could have induced these asymmetries. For example, the mode of presentation of the dots (sequential in Dormal et al., 2006; simultaneous in Dormal & Pesenti, 2007) may have a critical impact on how each dimension was individually processed and affected the processing of the other one. Indeed, a sequential presentation of the dots requires a dynamic attentional processing of the accumulated information in a way similar to the processing of duration, which may increase the similarity in the sensitivity to numerosity, length and duration (Droit-Volet, 2010; Droit-Volet, Clément, & Fayol, 2008). To date, an integrated view of how numerosity, length and duration are processed and influence each other is thus still lacking. In the present study, we directly tested the proposal of a gradient of processing automaticity in a Stroop-like task with stimuli in which the three dimensions were manipulated simultaneously. The participants had to compare the numerosity, the length or the total duration of two successively presented linear arrays of dots. We tested (1) whether there was any direct facilitating or interfering effect of each irrelevant dimension on the relevant dimension, and the nature of any such interference (i.e., symmetric or asymmetric effect), and (2) whether there was any joint effect of the manipulation of the two irrelevant dimensions and the nature of any such effect (i.e., cumulative effect or interaction, facilitation or interference). If processing each of these three dimensions enjoys a different degree of automaticity, then the least automatically processed dimension should not influence the processing of the two other dimensions, the most automatically processed dimension should influence the two others, and the intermediate dimension should influence one but not the other. Based on our previous results, we predicted that duration should be the least automatically processed dimension and should thus not influence numerosity and length processing. Predictions are more difficult concerning length and numerosity: numerosity processing was not automatic enough to interfere with length processing when the stimuli were presented simultaneously, but a sequential presentation of the stimuli may change the degree of automaticity with which numerosity and length are processed.

Materials and methods

Participants

A total of 54 volunteers (4 left-handed, 37 females, mean age: 21 ± 5.02 years) took part in this experiment; 18 participants were randomly assigned to each comparison task (i.e., numerosity, length or duration comparison, see below). All the participants had normal or corrected-to-normal vision, and were unaware of the purpose of the study. All the procedures were non-invasive and were performed in accordance with the ethical standards laid down in the 1964 Helsinki Declaration.

Tasks and stimuli

The experiment was composed of three distinct tasks: a numerosity comparison, a length comparison and a duration comparison of two successive linear arrays of flashed dots. In the numerosity comparison task, the participants had to decide which array contained more dots by pressing one of two 13-cm distant keys on a keyboard with the left index finger for the first array, and the right index finger for the second array. In the length comparison task, they had to decide which array was longer, and in the duration comparison task, which array lasted longer from the appearance of the first dot to the disappearance of the array, using the same key presses. In each task, the participants had to compare the relevant dimension of the first presented array with that of the second array. Unbeknown to the participants, the first array was always a standard array for which the value of the three dimensions never changed (i.e., 7 dots, 16 cm and 1,000 ms). In the second array, the two irrelevant dimensions were manipulated in three different ways, so creating nine different experimental conditions. In the neutral conditions (N–N), only the relevant dimension, was manipulated while the two irrelevant dimensions were kept constant across stimuli (i.e., same values as the standard array) and could thus neither facilitate nor interfere with the judgement: the number of dots varied, but the duration and length were fixed (1,000 ms and 16 cm) in the numerosity comparison; the length of the array varied but the numerosity and duration were fixed (7 dots and 1,000 ms) in the length task; finally, the duration of the series varied but numerosity and length were fixed (7 dots and 16 cm) in the duration comparison. Next, the relevant dimension and one irrelevant dimension (say, Irrelevant dimension 1) were manipulated simultaneously, whereas the third dimension (say, Irrelevant dimension 2) was kept fixed to the neutral value. In this case, Irrelevant dimension 1 could be congruent (condition C–N) or incongruent (condition I–N) to the relevant dimension. Then, the relevant dimension and Irrelevant dimension 2 were manipulated simultaneously in the same way, whereas Irrelevant dimension 1 was fixed to the neutral value (conditions N–C and N–I). Finally, the last four conditions were obtained by manipulating the three dimensions simultaneously. Stimuli in which the two irrelevant dimensions were congruent with the relevant dimension gave the congruent condition (C–C) and stimuli in which the two irrelevant dimensions were incongruent gave the incongruent condition (I–I). The two irrelevant dimensions could also have opposite values: one could be congruent and the other incongruent, and vice versa (giving conditions C–I and I–C).

The participants had to compare a 7-dot standard array with arrays containing 5, 6, 8 or 9 dots in the numerosity comparison task, a 16-cm standard array with arrays of 12, 14, 18 or 20 cm length in the length task, and a 1,000-ms standard array with arrays lasting 700, 800, 1,200 or 1,300 ms in the duration comparison. Pairs of arrays were made up of each of the two distances used for each relevant dimension: a small distance (1 dot for numerosity, that is, pairs 6–7 and 7–8; 2 cm for length, that is pairs 14–16 and 16–18 cm; and 200 ms for duration, that is, pairs 800–1,000 ms and 1,000–1,200 ms) and a large distance (2 dots for numerosity, that is, pairs 5–7 and 7–9; 4 cm for

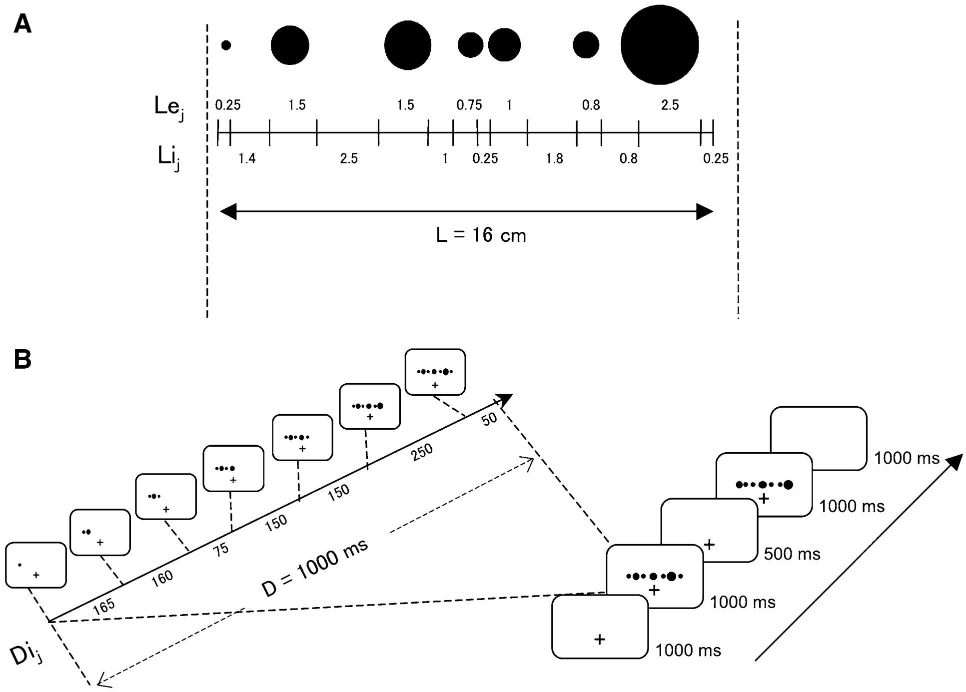


Fig. 1 **a** Spatial attributes of a typical non-periodic standard series with 7 dots, a total duration of 1,000 ms and a total length of 16 cm (*L* total length, *Le*$_j$ dot size, *Li*$_j$ interdot spacing; for details, see Dormal & Pesenti, 2007). **b** Temporal structure of a trial (here, one from the neutral condition of the numerosity task); each trial begins with a fixation cross for 1,000 ms, followed by two series of dots flashed one by one. After the removal of the second series, the participants had 1,000 ms to decide which series contained more dots, or was longer, or was presented for a longer duration as a function of the task. The *left part* of the figure shows the temporal attributes of a typical non-periodic standard series (*D* total signal duration, *D*i$_j$ interdot duration; for details, see Dormal et al., 2006)

length, that is pairs 12–16 and 16–20 cm; and 300 ms for duration, that is, pairs 700–1,000 ms and 1,000–1,300 ms). For the irrelevant dimensions, only the large distance was used (2 dots for numerosity: pairs 5–7 and 7–9; 4 cm for length: pairs 12–16 and 16–20 cm; 300 ms for duration: pairs 700–1,000 ms and 1,000–1,300 ms).

The stimuli were black dots of variable diameters and spacing, flashed one after another from left to right on a virtual horizontal line to constitute two different arrays for each trial. All the pairs of arrays were constructed using non-periodic signals so that temporal ratios did not constitute a potential confounding variable and rhythm biases and temporal pattern recognition were avoided (Breukelaar & Dalrymple-Alford, 1998; Dormal et al., 2006). The duration of each interdot (*D*i$_j$) varied between 75 and 320 ms; to avoid pattern recognition, each array involved at least one *D*i$_j$ of 75 ms and one longer than 250 ms, and each array ended with a *D*i$_j$ of 50 ms (Fig. 1a). To avoid spatial regularity biases, the spatial ratios were also controlled by applying similar principles (Dormal & Pesenti, 2007). The diameter of each dot (*Le*$_j$) and the interdot spacing (*Li*$_j$) varied from 0.25 to 2.5 cm; to avoid pattern recognition, each series involved at least one *Le*$_j$ and one *Li*$_j$ of 0.25 cm, and one *Le*$_j$ and one *Li*$_j$ greater than 2 cm (Fig. 1b).

To avoid as far as possible the use of explicit or implicit counting or enumeration strategies for the numerosity comparison task, nonsubitizable numerosities (i.e., between 5 and 9) and short durations (i.e., less or around 1 s, which has been shown to make a counting strategy little efficient; Grondin, Meilleur-Wells, & Lachance, 1999) were used. To avoid comparisons based only on the distance from the edge of the screen for the length comparison task, the arrays occupied five different positions on the screen: a central position (30% from the left or the right edge of the screen), two intermediate positions (15% from the left or the right edge of the screen) and two extreme positions (7% from the left or the right edge of the screen).

Experimental procedure

Stimuli presentation and data collection were controlled by a Toshiba laptop using a customised E-prime programme (Schneider, Eschman, & Zuccoloto, 2002). The viewing distance was approximately 50 cm. The instructions requested the participants to focus on one of the dimensions and did not mention the other ones. At the beginning of each trial, a black fixation cross was presented horizontally in the centre and 5 cm below the vertical centre on a white background. This fixation cross was present during the whole trial and the participants were told to look at it throughout the task; it disappeared after the presentation of the second series. After 1,000 ms, the first array (i.e., the standard series) appeared, followed by a white background for 500 ms. Then, the second array was presented and was again followed by a white screen for a maximum of 1,000 ms during which the participants could answer (Fig. 1c). As soon as an answer was given, the next trial started. Each task was composed of 10 blocks of 54 randomized items; a practice block of 20 items was administered first but not analysed. The whole experiment lasted about 50 min. It is worth noting that, during the post-experiment debriefing, none of the participants reported having used counting strategies or strategies using the edges of the screen as landmarks.

Results

Comparison of task performance and distance effects

To compare performance across the three tasks and assess the presence of the relevant distance effects, an analysis of variance (ANOVA) was performed on the error rates in the three neutral conditions with tasks (numerosity, length or duration) as a between-subject variable and relevant distance (small or large) as a within-subject variable. There was no difference between the tasks (mean % of errors for numerosity: 13.3 ± 13.4, for length: 17.2 ± 13.3, for duration: 22.1 ± 9.1), $F(2, 51) = 2.388$, $p > 0.1$, but a significant main effect of the relevant distance (mean % of errors for small distances: 21.5 ± 11.4, for large distances: 13.6 ± 15.3), $F(1, 51) = 31.9$, $p < 0.001$. No interaction was observed, $F(1, 51) = 2.041$, $p > 0.1$.

A similar ANOVA on the response latencies (RLs) of the correct answers revealed no difference between the tasks (mean RLs for numerosity: 407 ± 91 ms, for length: 471 ± 129 ms, for duration: 439 ± 157 ms), $F(2, 51) = 1.128$, $p > 0.3$. A significant main effect was found for the relevant distance (mean RLs for small distances: 450 ± 136 ms, for large distances: 428 ± 128 ms), $F(1, 51) = 7.447$, $p < 0.01$. No interaction was observed, $F(2, 51) = 0.035$, ns.

Interference and facilitation effects

For each condition of each task, the percentage of errors was significantly different from 0 (all *p*s at least <0.05) (Fig. 2). To investigate the influence of the irrelevant dimensions on the relevant one, an ANOVA was carried out on the mean percentage of errors with tasks (numerosity, length or duration) as a between-subject variable, and Irrelevant dimension 1 (congruent, incongruent or neutral) and Irrelevant dimension 2 (congruent, incongruent or neutral) as within-subject variables.[2] This revealed a significant three-way interaction between Irrelevant dimension 1, Irrelevant dimension 2 and tasks, $F(8, 204) = 2.503$, $p < 0.02$. Separate ANOVAs for the three tasks were carried out with Irrelevant dimension 1 and Irrelevant dimension 2 as within-subject variables.

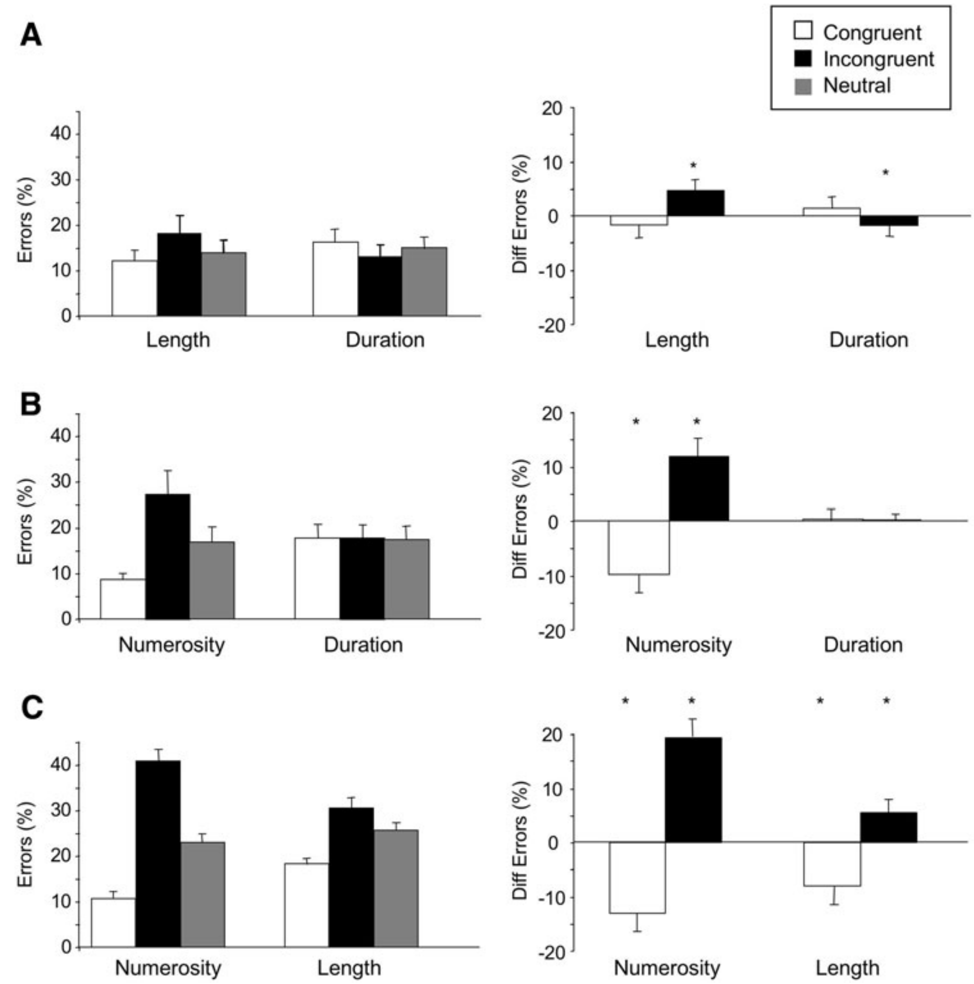
In the numerosity task, there was a marginally significant effect of length (mean % of errors for congruent: 12.1 ± 9.8, for incongruent: 18.3 ± 16.0, for neutral: 13.8 ± 12.3), $F(2, 34) = 3.16$, $p < 0.06$ (Fig. 2a). The incongruent condition differed significantly from the neutral condition, $t(17) = 2.428$, $p < 0.03$, and marginally from the congruent condition, $t(17) = 1.810$, $p < 0.09$, whereas no difference was observed between the neutral and congruent conditions, $t(17) = 0.816$, ns. There was also a main effect of duration (mean % of errors for congruent: 16.3 ± 12.6, for incongruent: 13.1 ± 12.6, for neutral: 14.8 ± 12.9), $F(2, 34) = 10.138$, $p < 0.001$. The congruent condition was more prone to errors than the incongruent condition, $t(17) = 4.523$, $p < 0.001$; the incongruent and neutral conditions also differed significantly, $t(17) = 3.103$, $p < 0.007$. No significant interaction was observed between length and duration, $F(4, 68) = 0.914$, ns. Next, within each irrelevant dimension, we subtracted the percentage of errors of the neutral conditions from the congruent and incongruent conditions, which gives positive or negative differences in case of interference or facilitation, respectively; these differences were then compared to 0 with *t*-tests. This showed that the incongruent condition produced significantly more errors for length, $t(17) = 2.428$, $p < 0.03$, and significantly less errors for durations, $t(17) = 3.103$, $p < 0.007$, whereas the error differences did not differ from 0 for the congruent conditions, both *p*s > 0.1 (Fig. 2a).[3]

In the length task, a significant main effect of numerosity was found (mean % of errors for congruent: 8.7 ± 6.3,

[2] In separate analyses, the relevant distance (small or large) was introduced as an additional within-subject variable. A main effect was found on latencies (mean RLs for small: 450 ± 119 ms, for large: 436 ± 115 ms), $F(1, 51) = 8.601$, $p < 0.01$, and on error rate (% of errors for small: 22.7 ± 9.7, for large: 14.9 ± 11.8), $F(1, 51) = 184.996$, $p < 0.001$. In the error rate analysis, the relevant distance entered into some interactions but, as it never changed the direction of the main effect of other factors, it was not included in the main analysis. It is also worth noting that irrelevant dimensions 1 and 2 changed depending on the task (e.g., for the numerosity task, the irrelevant dimensions were length and duration; for the length task, the irrelevant dimensions were numerosity and duration, etc.)

[3] To ensure that the presentation duration was not a confounded variable possibly affecting the error rate (for example, it could be globally more difficult to process 700-ms than 1,300-ms stimuli), a post-hoc analysis was carried out on the mean percentage of errors as a function of presentation duration. This analysis revealed no significant difference (mean % of errors for 700 ms: 15.3 ± 11.6, for 1,300 ms: 14.1 ± 10.8), $t(17) = 1.969$, $p > 0.07$.

Fig. 2 Mean percentage of errors (±SE; *left panels*), and mean difference of error percentage when subtracting the neutral conditions from the congruent and incongruent conditions (±SE; *right panels*) for numerosity (**a**), length (**b**) and duration (**c**) tasks as a function of irrelevant dimensions. For the *right panels*, positive and negative differences show interference and facilitation, respectively; *asterisks* indicate significant differences compared to 0



incongruent: 27.3 ± 22.1, neutral: 17.1 ± 12.8), $F(2, 34) = 13.171$, $p < 0.001$, with all the conditions differing significantly from each other, all $ps < 0.005$. Duration had no main effect and did not interact with numerosity, all $ps > 0.7$. The analysis on the differences of error percentages showed that the congruent condition produced significantly less, $t(17) = 3.278$, $p < 0.005$, and the incongruent condition significantly more errors, $t(17) = 3.669$, $p < 0.003$, for numerosity, whereas the error differences did not differ from 0 for duration, both $ps > 0.5$ (Fig. 2b).[4]

In the duration task, there were significant main effects of numerosity (mean % of errors for congruent: 10.3 ± 6.3, for incongruent: 39.8 ± 12.2, for neutral: 22.3 ± 9.0), $F(2, 34) = 96.563$, $p < 0.001$, and length (mean % of errors for congruent: 17.7 ± 6.5, for incongruent: 29.8 ± 11.2, for neutral: 24.9 ± 9.9), $F(2, 34) = 29.049$, $p < 0.001$. For both main effects, post-hoc paired sampled *t*-tests showed that all conditions differed significantly from each others, all $ps < 0.001$. The analysis on the differences of error percentages showed that the congruent conditions produced significantly less, $t(17) = 9.445$, $p < 0.001$, and the incongruent condition significantly more errors, $t(17) = 8.864$, $p < 0.001$, for numerosity. This pattern also held for length, congruent: $t(17) = 4.809$, $p < 0.001$, incongruent: $t(17) = 4.68$, $p < 0.001$ (Fig. 2c). Moreover, a significant interaction between numerosity and length was found, $F(4, 68) = 3.812$, $p < 0.008$ (Fig. 3a). For all the comparisons between N–N and the conditions in which only one irrelevant dimension was manipulated, significant differences were observed: whatever the manipulated dimension, participants made fewer errors for congruent manipulation (i.e., C–N and N–C) and more errors for incongruent ones (i.e., I–N and N–I), all ps at least <0.007, but the facilitating and interfering effects of numerosity were stronger than those of length (mean differences of % of errors for [C–N]–[N–N]: −7.12 ± 9.5, for [N–C]–[N–N]: −10.8 ± 8.6), $t(17) = 2.74$, $p < 0.02$, (mean differences of % of errors for [I–N]–[N–N]: 7.6 ± 8.7, for [N–I]–[N–N]: 19.2 ± 11.6), $t(17) = 5.13$, $p < 0.001$ (Fig. 3b).

[4] Again, a post-hoc paired *t*-test showed no difference between stimuli lasting 700 ms and those lasting 1,300 ms (mean % of errors for 700 ms: 17.4 ± 11.5, for 1,300 ms: 18.1 ± 12), $t(17) = 1.205$, $p > 0.2$.

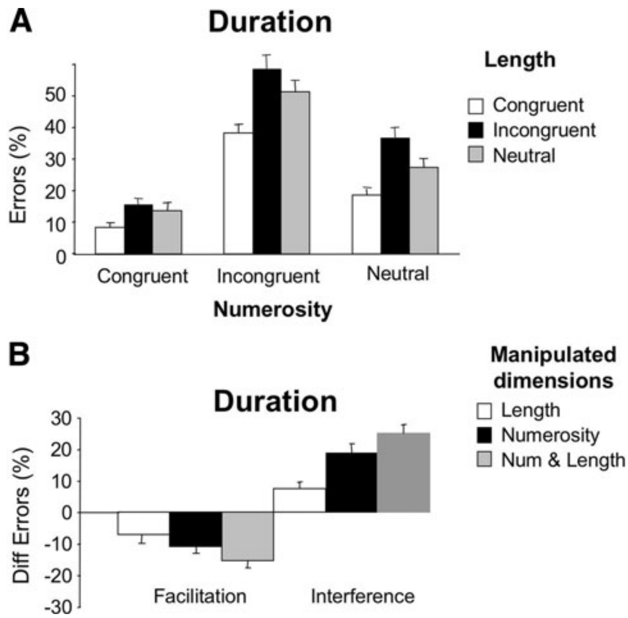


Fig. 3 **a** Mean percentage of errors (±SE) for the duration task as a function of numerosity and length (congruent, incongruent and neutral). **b** Difference in the mean percentage of errors (±SE) for each condition relative to the neutral condition (i.e., NN) for duration task as a function of the direction of the effect (facilitation or interference) and the manipulated dimensions (numerosity, length, or both in the same way)

When the two irrelevant dimensions corresponded to opposite manipulations, numerosity had a stronger effect than length: compared to N–N, more errors were produced when numerosity was incongruent (C–I) and fewer when it was congruent (I–C), (mean % of errors for N–N: 22.1 ± 9.1, for C–I: 31 ± 8.2, for I–C: 12.6 ± 6.6), $t(17) = 4.864$, $p < 0.001$ and $t(17) = 5.498$, $p < 0.001$, respectively. Finally, conditions in which the two irrelevant dimensions were similarly manipulated (i.e., C–C and I–I) produced significantly less and more errors than N–N (mean % of errors for C–C: 6.9 ± 4.9, for I–I: 47.2 ± 15.5), $t(17) = 6.609$, $p < 0.001$, and $t(17) = 7.494$, $p < 0.001$, respectively (Fig. 3b). The joint facilitating and interfering effects of the two irrelevant dimensions were significantly stronger than those observed after the manipulation of one dimension alone (mean differences of % of errors for [N–C]–[C–C]: 4.4 ± 4.6, $t(17) = 3.972$, $p < 0.002$; for [C–N]–[C–C]: 8.1 ± 4.7, $t(17) = 7.291$, $p < 0.001$; for [N–I]–[I–I]: −5.9 ± 9.7, $t(17) = 10.744$, $p < 0.02$; for [I–N]–[I–I]: −17.5 ± 14.3, $t(17) = 5.182$, $p < 0.001$) (Fig. 3b).

The same ANOVA was performed on the RLs of the correct answers. A main effect of Irrelevant dimension 2 was observed (mean RLs for congruent: 436 ± 122 ms, for incongruent: 453 ± 110 ms, for neutral: 439 ± 123 ms), $F(2, 102) = 4.899$, $p < 0.01$. The incongruent condition differed significantly from the congruent and neutral conditions, both $p < 0.03$, that did not differ from each other, $t(53) = 0.525$, ns. As a significant interaction between Irrelevant dimension 2 and task was observed, $F(4, 102) = 6.549$, $p < 0.001$, we report here the results of separate ANOVAs for the three tasks with Irrelevant dimension 2 as within-subject variable. In the numerosity task, there was no main effect of duration, $F(2, 34) = 1.231$, $p > 0.3$. In the length task, there was no main effect of numerosity, $F(2, 34) = 0.462$, ns. In the duration task, a significant main effect of the numerical cues was observed (mean RLs for congruent: 415 ± 142 ms, incongruent: 470 ± 133 ms, neutral: 428 ± 152 ms), $F(2, 34) = 16.203$, $p < 0.001$: the incongruent condition was processed more slowly than the congruent and neutral conditions, both $p < 0.001$, that did not differ from each other, $t(17) = 1.392$, ns. No other significant main effect or interaction were revealed, all $ps > 0.1$.

Discussion

In this study, we investigated for the first time the reciprocal facilitation and interference effects between numerosity, length and duration taken alone or simultaneously. We will first discuss the effect of varying each irrelevant dimension individually and we will then comment on the joint influence of the two irrelevant dimensions and their interactions with the relevant one. Finally, we will formulate an integrative proposal suggesting the existence of a continuum of automaticity in processing these three magnitudes. It is worth noting that, in the selected range of numerosities, lengths and durations, the participants were equally fast and accurate in the neutral conditions[5] of the three comparison tasks, that is when only the relevant dimension was manipulated while the two irrelevant dimensions were kept constant and could thus not affect the decision to make. Therefore, the observed differences cannot be due to mere differences in the relative speed of processing each dimension individually or difficulty demands across tasks. Moreover, a classic effect of the relevant distance (Moyer & Landauer, 1967) was observed in all tasks, ensuring that the participants actually performed the comparisons using the appropriate dimension (i.e., numerosity in the numerosity

[5] Even if there was no reliable statistical difference in the latencies between the three tasks in the neutral conditions, participants were slightly faster for numerosity processing and slower for the length comparison. However, these weak differences in the relative speed of processing cannot account for the observed effects of interference. Indeed, classical "Horse Race" models (Dyer, 1973; Schwarz & Ischebeck, 2003) predict an interference of the fastest processed dimension on the slowest one, but not the reverse. Yet, here, although length was processed more slowly than numerosity and duration, it interfered with these two dimensions. (Note that whatever be the task, participants had to wait till the end of the presentation of the array to be able to answer; anticipated responses were discarded from the analyses.)

comparison, length in the length comparison, and duration in the duration comparison).

Unidimensional and bidimensional effects

First, the independent manipulation of the irrelevant dimensions allowed us to explore the distinct influence of each dimension on the others. In the numerosity comparison task, varying duration had no direct effect on the performance, both for response latencies or error rates,[6] whereas manipulating length interfered moderately with numerosity processing as illustrated by the marginally significant effect of this dimension on error rate. In the length comparison task, error rates were affected only by numerical variations: incongruent cues strongly interfered with length judgements whereas congruent cues facilitated them. Finally, in the duration comparison task, both numerosity and length interfered with duration processing on error rates. Independent interference and facilitation effects of numerical and length cues were observed in duration comparison, with participants making fewer errors in the congruent conditions and making more errors in the incongruent conditions than in the neutral ones. These effects were more strongly influenced by numerosity than by length variations. Moreover, the duration task was affected by numerical cues for the response latencies: the incongruent manipulation of numerosity alone, length remaining neutral, slowed duration comparison. Whereas only one-dimensional interference was observed in numerosity and length tasks, respectively (i.e., moderate influence of length in the numerosity comparison and strong numerical influence in length judgement), the duration comparison task was highly affected by the joint manipulation of numerical and spatial cues. The facilitating and interfering influences of both dimensions were significantly more important than those observed after the manipulation of one dimension alone, suggesting a cumulative interference effect. Moreover, when the two dimensions held opposite values, the numerical influence was predominant and overcame the effect of length cues (Fig. 3b).

The present study thus shows a unilateral interaction between numerosity and duration, similar to the one reported in previous studies (Dormal et al., 2006; Droit-Volet et al., 2003): numerical cues interfered strongly with duration processing, whereas temporal cues did not affect numerosity processing. It also shows, for the first time with this kind of non-symbolic stimuli, an asymmetric pattern of interaction between length and duration. In the duration comparison, there were both facilitation and interference effects of length on error rates (fewer errors when length was congruent, and more errors when length was incongruent, compared to the neutral condition). By contrast, no influence of duration was observed on length judgement. Like the kappa effect described in psychophysical studies (Cohen et al., 1953), this interference of length on duration processing reflects an implicit and automatic processing of this dimension, in a context where it does not need to be processed to carry out the task. This asymmetric interference was also highlighted by behavioural studies in children (Casasanto, Fotakopoulou, & Boroditsky, 2010; Levin, 1979, 1982; Piaget, 1946; Stavy & Tirosh, 2000) and in human adults (Casasanto & Boroditsky, 2008; Merritt, Casasanto, & Brannon, 2010). For example, the judgement of the speed of a train was influenced by its size (Stavy & Tirosh, 2000) or the duration estimation of a light signal depends on its size or its brightness (Levin, 1979, 1982; Piaget, 1946). The results of these experiments in which participants had to judge either the distances or the durations covered by two animals (Casasanto et al., 2010) or by fixed or growing lines (Casasanto & Boroditsky, 2008; Merritt et al., 2010) showed that they were unable to ignore an irrelevant spatial information when making judgements about duration, but they could ignore duration when making a spatial judgement. Theses findings are consistent with the idea that human beings use spatial schemas to think about time, as proposed by theories of metaphorical mental representation (e.g., Clark, 1973; Lakoff & Johnson, 1980). Numerosity and length demonstrated a reciprocal influence, confirming the results reported in various other studies of interference (e.g., Pufall & Shaw, 1972; Henik & Tzelgov, 1982; Dormal & Pesenti, 2007) and being in line with recent findings of an early predisposition to relate representations of numerical magnitude to length in children (de Hevia & Spelke, 2010). However, unlike previous studies (e.g., Dormal & Pesenti, 2007), we found that the numerical influence on length judgements was stronger than the influence of length on numerosity comparisons. Differences in the presentation modes may explain this discrepancy. In the present study, the sequential presentation of the dots forced the participants to focus on each individual dot in order to judge the total length of the arrays. This individuation process may have activated an accumulation mechanism leading to greater salience of the numerical cues. Indeed, a similar sensitivity was observed between numerosity, length and duration judgements, only when the elements were presented sequentially (i.e., when the events had to be aggregated; Droit-Volet, 2010; Droit-Volet et al., 2008). Conversely, individual processing of each element is not necessary to grasp the total length when the elements are presented simultaneously. In

[6] A statistically significant main effect of duration was observed on error rates in the numerosity task, but it is worth noting that this effect did not correspond to a regular pattern of facilitation and interference. It was only due to the congruent condition leading to more errors, which in fact stemmed from the incongruency effect of length.

this case, numerosity does not interfere strongly with length judgements, whereas length is necessarily processed when judging the total numerosity of an array of dots. This may explain why length cues strongly interfere with simultaneous numerosity judgements.

Towards a gradient of processing automaticity?

What do the asymmetrical interference patterns observed in this study tell us about a processing system possibly shared across magnitudes? The presence of facilitation and interference effects between magnitudes clearly runs against the proposal of totally distinct processing systems (e.g., several independent accumulators working in parallel, as proposed in connectionist timing models; Church & Broadbent, 1990). Moreover, it does not easily fit with the idea of a unique mechanism processing several types of magnitude (e.g., a single accumulator processing numerosity and duration thanks to two operative modes; Meck & Church, 1983), either simultaneously, in which case totally symmetric facilitation and interference effects should be observed, or sequentially, in which case the least automatically processed dimension should never overcome the most automatically processed one, and correct judgements should not be possible in case of interference from the latter. This was not the case in this study, duration judgements remaining possible even under length or numerosity interference (about 70 and 60% correct, respectively).

Rather, the presence of asymmetric facilitation and interference effects supports the proposal of partially shared magnitude representations (e.g., Bueti & Walsh, 2009; Walsh, 2003). However, as the overall performance did not differ across tasks, these asymmetrical effects show that this proposal must be further elaborated by integrating the idea of a gradient of automaticity in processing numerosity, length and duration. Such a gradient of automaticity has already been proposed to account for asymmetries in Stroop-like paradigms without resorting to relative speed differences in processing the relevant and irrelevant dimensions (Kahneman & Chajczyk, 1983; MacLeod & Dunbar, 1988; Tzelgov, Meyer, & Henik, 1992). Indeed, automaticity is not necessarily an all-or-none process, but rather may be a matter of degree, may develop gradually with practice, and may be context or task dependent (Besner, Stolz, & Boutilier, 1997; Cohen, Dunbar, & McClelland, 1990; Naparstek & Henik, 2010). Our results thus show that, with sequentially presented stimuli, numerosity is the most and duration the least automatically processed. On the one hand, numerosity is highly automatically processed, as shown by its strong interference effect on duration and length judgements. This fits with previous results using both symbolic (e.g., Arabic or verbal numerals; Algom, Dekel, & Pansky, 1996; Henik & Tzelgov, 1982) and non-symbolic (Dormal et al., 2006; Koechlin, Naccache, Block, & Dehaene, 1999; Piazza, Izard, Pinel, Le Bihan, & Dehaene, 2004) stimuli. On the other hand, duration processing is not sufficiently automatic to interfere with the processing of numerosity and length, but duration judgements are highly sensitive to the influence of both numerosity and length. Importantly, this gradient of automaticity may depend on the range, the modality (e.g., visual or auditory) and mode (e.g., sequential or simultaneous) of presentation of the stimuli, and the experimental design chosen (e.g., comparison in a Stroop-like paradigm). Changing stimulus properties or the tasks could possibly change some automatic relationships between dimensions, making each magnitude more or less salient and facilitation and interference effects more or less prone to appear. For example, with simultaneously presented arrays of dots, length may be more automatically processed than numerosity (e.g., Dormal & Pesenti, 2007); other paradigms, tasks or stimulus properties may make duration more salient hence more automatically processed than numerosity or length.

One may wonder to what extend our proposal of an automaticity gradient differs from an interpretation in terms of attentional requirements, as attention is known to be a key component in processing separately numerosity, space and duration. Indeed, several models of numerosity processing postulate different (pre)attentive mechanisms to account for the ability to quantify collections of objects (e.g., Dehaene & Changeux, 1993; Duncan & Humphreys, 1992) or to account for the differences observed when subitizing (i.e., quantifying quickly and accurately; Kaufman, Lord, Reese, & Volkmann, 1949) versus counting small sets of objects (e.g., Trick & Pylyshyn, 1993). Attention and attention orientation, either overtly through eye movements or covertly, are also known to contribute critically to building accurate representations of space (for a review, see Colby & Goldberg, 1999). Finally, the need to allocate attentional resources influences duration judgements (Brown, 1997; Thomas & Weaver, 1975), especially when making prospective judgements, that is when one knows in advance that duration is the dimension to be judged (Block & Zakay, 1997; Zakay, 1998). Attention being involved in processing each of these magnitudes, a differential contribution might underlie the asymmetrical influences that are observed. As a matter of fact, it has been suggested that processing discrete magnitudes (e.g., numerosity) would be less attention demanding than processing continuous magnitudes (e.g., time or length; Droit-Volet et al., 2008) because the latter would require more attentional resources. However, were this to be the case, processing numerosity should always overcome processing space especially when both are provided at the same time, which is not what is observed: with a simultaneous presentation, spatial cues affect more numerosity processing than the reverse (Dormal

& Pesenti, 2007). On the contrary, processing space might be less attention demanding than processing numerosity, as distances are continuously implicitly computed for example to perform reaching–grasping gestures, and should thus always overcome numerosity processing. Yet, this is, once again, not what was observed here. This suggests that, although automaticity and attentional requirements are linked, they do not constitute totally overlapping concepts and the former cannot be totally reduced to the latter.

Using the present behavioural Stroop-like paradigm does not allow us to specify at which processing step (i.e., encoding, representation or decision-making step) the interference effect between the various dimensions occurs. It could take place during a late stage, like the decision-making step, and does not necessarily imply the activation of a common representation. As it was widely investigated for the classic Stroop effect (e.g., Atkinson, Drysdale, & Fulham, 2003) or the size-congruity paradigm (e.g., Schwarz & Heinze, 1998), future studies using event-related potentials will reveal the precise temporal course of these interference effects, and will help identifying the processing step at which magnitudes interfere.

Finally, although our behavioural and the neuroanatomical findings address different levels of processing, some links can be established. First, the existence of unidirectional or reciprocal interference between magnitudes fits with the presence of partial or complete overlapping foci of activation reported in fMRI studies, especially within the intraparietal sulcus, during numerosity and length comparisons (Dormal & Pesenti, 2009), or during numerosity and duration categorizations (Dormal, Dormal, Joassin, & Pesenti, 2012), respectively. Indeed, it has been suggested that behavioural interference between relevant and irrelevant magnitudes would take place if the processing of these dimensions rely on the same neuronal structures (Fias, Lauwereyns, & Lammertyn, 2001). Secondly, some recent studies using transcranial magnetic stimulation (TMS) also appear consistent with the interference effects observed in our Stroop studies. While a disruption of performance during both numerosity and length processing was observed after stimulation of the right IPS (Dormal, Andres, & Pesenti, 2012), a mutual interference effect between these two magnitudes was present at a behavioural level, suggesting the existence of a common mechanism and/or representation for numerical and spatial dimensions. On the other hand, the asymmetric interference results observed between numerosity and duration processing are also reflected in a TMS study (Dormal, Andres, & Pesenti, 2008), in which a numerosity comparison task was affected by the stimulation of the left IPS whereas the duration judgement was not impaired. Altogether, these results demonstrate the benefit of combining behavioural and neuroimaging techniques, each providing converging and complementary information.

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