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Attention to Number requires magnitude-specific inhibition

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Attention to Number requires magnitude-specific inhibition

Abstract

Recent studies have shown that the ability to process number in the face of conflicting dimensions of magnitude is a crucial aspect of numerosity judgments, relying in part on the inhibition of the non-numerical dimensions. Here we report, for the first time, that these inhibitory control processes are specific to the conflicting dimension of magnitude. Using a non-symbolic numerical comparison task adapted to a conflict adaptation paradigm on a group of 82 adults, we show that congruency effects between numerical and non-numerical information were reduced only when the conflicting dimension was the same in the preceding incongruent trial. Attention to number thus involves inhibitory control processes acting at a specific level of information. These results contribute to better characterize the domain general abilities involved in numerical cognition, and provide evidence for a specific interaction between numerosity perception and inhibitory control.

Keywords

Numerical cognition; numerical estimation; Inhibitory control; conflict adaptation

1. Introduction

One of the main objects of investigation in the field of numerical cognition in the past decades has been our number sense, that is our ability to estimate and compare the quantities of objects in a set (“numerosities”, Izard et al., 2009; Feigenson et al., 2004). Classically, the non-symbolic numerical comparison task is used to assess the precision of our number sense. In this task, the participants are asked to decide which of two rapidly presented sets of items (usually dots) is the more numerous. Because of the perceptual features of the sets of dots presented in the non-symbolic numerical comparison task, many studies have called into question its underlying mechanisms. Recently indeed,

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beyond the precision of our number sense, studies have suggested that the non-symbolic numerical comparison task also relies on the ability to process numerosities independently of competing dimensions of magnitude, such as size, density, or occupied space (hereafter referred to as “attention to number”, Wilkey & Price, 2019; see also Piazza et al., 2019). This stems in part from the systematic observation that the non-numerical dimensions of magnitude present in the stimuli, impact our performance in the task (Gebuis & Reynvoet, 2012; 2013).

One of the proposed mechanisms of attention to number is inhibitory control, which allows blocking the irrelevant, non-numerical dimensions of magnitude when processing numerosities (Fuhs & McNeil, 2013; Fuhs et al., 2016; Rousselle & Noël, 2008; Szűcs et al., 2013). Recently, using a non-symbolic numerical comparison task adapted to a negative priming paradigm, Viarouge and colleagues (2019) provided evidence for the role of inhibitory control during the numerical comparison of two arrays of dots whereby number was incongruent with dots’ size.

While inhibition seems to play a role when performing numerosity judgment tasks, studies are needed to better characterize the inhibitory control processes at play in this context. In particular, one opened question is the degree of specificity of the inhibitory control processes involved in attention to number. On one hand, one could postulate the existence of a common mechanism aimed at blocking any conflicting information of magnitude when processing numerosities. On the other hand, the inhibitory control processes at play when attending to number could be specific to the irrelevant dimension of magnitude conflicting with number.

One way to disentangle these hypotheses is by studying the congruency sequence effect, or Gratton effect (Gratton, Coles, & Donchin, 1992), consisting of a reduced congruency effect following incongruent trials. This effect has previously been observed in several classic inhibitory control tasks, such as the Stroop or the Flanker task (Hommel, Proctor, & Vu, 2004; Larson, Kaufman, & Perlstein, 2009). It is most commonly explained by the conflict adaptation account (Botvinick et al., 2001),

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which states that the cognitive control processes - including the inhibition of irrelevant information - involved in solving an incongruent trial facilitate the resolution of the next conflict.

Using such conflict adaptation paradigm, several studies have investigated the specificity of cognitive control processes in the context of numerical tasks, with mixed results. Some studies have concluded to a general inhibitory control process (Borst, Poirel, Pineau, Cassotti and Houdé, 2012; Linzarini et al., 2015). For instance, using an inter-task conflict adaptation paradigm, Linzarini and colleagues (2015) observed that 9-year-olds performed better in the incongruent trials of a Piaget-like number conservation task (two rows of tokens with either identical numbers and different lengths, or different numbers and equal lengths) when they were preceded by incongruent Stroop trials. The authors concluded that their results supported a general inhibitory control process across both tasks in 9-year-old children. In their study however, Notebaert and Verguts (2008) observed a congruency sequence effect in a group of adults across two tasks (a Simon task using on laterally presented X's and a SNARC task on centrally presented symbolic digits) only when the relevant information was the same in both tasks, leading the authors to conclude for more specific cognitive control abilities. Since the irrelevant information remained identical throughout their study, the authors argued that their results showed the specificity of the processing of the relevant information, rather than of the inhibition of the irrelevant information. To date, no study has investigated this question in the context of a non-symbolic numerical task, with a constant relevant information (i.e. numerosity) and a varying irrelevant information (i.e. conflicting dimensions of magnitude).

Thus, in the current study, we adapted a non-symbolic comparison task to a conflict adaptation paradigm, using different non-numerical dimensions of magnitude, in order to investigate whether the inhibitory control processes at play were specific to the irrelevant information, or general across the non-numerical dimensions of magnitude. We reasoned that, if attention to number requires dimension-general inhibition, then we should observe cross-dimension Gratton effects, i.e. reduced congruency effects in trials preceded by incongruent trials, regardless of the irrelevant dimension of

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magnitude conflicting with number. On the other hand, if the inhibitory control processes involved in attention to number are dimension-specific, we should only observe within-dimension Gratton effects, i.e. reduced congruency effects following incongruent trials involving the same irrelevant non-numerical dimension of magnitude.

2. Method

2.1. Participants

Participants were 82 undergraduate students at Université de Paris (4 males, mean age = 21 years, SD = 4.8), participating in the study for course credit.

The ethical board of the Faculty of Psychology ruled that in light of the potential risks for the participants of the present study, no formal ethical approval by one of the national ethical committee was needed in agreement with the Ethical law governing human research in France. Participation was voluntary after obtaining signed informed consent. All participants were tested in accordance with national and international norms governing the use of human research participants.

2.2. Procedure

The task consisted in a non-symbolic numerical comparison task adapted to a conflict monitoring paradigm. Participants were asked to indicate as quickly and as accurately as possible which of two arrays of dots, presented on the left and right side of a computer screen, contained more dots, by pressing either the D (left array) or the K (right array) key on the keyboard. The task was programmed using the jsPsych JavaScript library (de Leeuw, 2015), and the data collected online on the Cognition.run platform. Each presentation of a pair of dot arrays will thereafter be referred to as an item. A trial was defined as a sequence of two items, a prime item followed by a probe item (Figure 1).

In order to adapt the non-symbolic numerical comparison task to a negative priming paradigm, two non-numerical dimensions needed to be manipulated orthogonally, on a trial-by-trial basis. That is,

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the congruency of one dimension relative to number needed to be manipulated, at the trial level, independently of a third dimension.

Such manipulation at the trial level would prove difficult using dimensions such as average item size and total surface area, which are, by definition, correlated. This is why the arrays of dots were generated with MATLAB using the *Number, Size, and Spacing* dimensions, as defined by DeWind and colleagues (2015), which form an orthogonal space whereby the three dimensions can be manipulated independently. That is, we manipulated a combination of aspects of average item size and total surface area on one hand (the *Size* dimension), and a combination of convex hull and density (the *Spacing* dimension) on the other. By doing so, for each item (prime or probe), one non-numerical dimension of magnitude was either congruent or incongruent with Number (thereafter referred to as the “congruency-related dimension”), while the other was constant across the two arrays. Hence, the congruency-related dimension (e.g. *Size*) and its composing magnitudes (e.g. average item size and total surface area) are the only changing parameters between our conditions, at a trial-by-trial level (see Appendix A, Table A1, for a table showing the congruency and ratios of the four composing magnitudes in each condition, and Figures A1 and A2 for examples of stimuli in relation to our results). This led to four types of items depending on the congruency-related dimension (*Size* or *Spacing*), and its congruency with Number (congruent or incongruent). All possible combinations of the four types of items were presented, leading to 16 different trial conditions (i.e. prime-probe pairs). Consequently, for half of those 16 trial conditions, the congruency-related dimension was identical in the prime and in the probe items (“within-dimension trials”), while for the other half the congruency-related dimension was different between the prime and the probe (“between-dimension trials”). Each of the 16 trial conditions was presented 10 times in a random order, for a total of 160 trials.

Each trial started with a central fixation cross and two white circles (1000ms). The arrays of dots from the prime item were then presented in the white circles until the participants gave a response, for a

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maximum duration of 750ms, at which time they were replaced by a gray screen. As soon as the participants gave their response to the prime, a gray screen was presented for 1000ms, and then the fixation cross and the probe were presented. In order to separate the trials and minimize the potential effect of probes on the following primes (Linzarini et al., 2015), a visual mask was presented for 1500ms between each prime-probe pair.

Using the jsPsych calibration plugin, the stimuli were set to be presented at a fixed size of 14.7x11cm on the participants' screen. Using these settings, each array of black dots was presented on a white circle with 6.71cm diameter (visual angle 7.64° for a distance of 50cm from the screen). The center of the arrays of dots was at 4.14cm from the central fixation cross (visual angle 4.73°). In order to ensure a high enough level of performance for the analyses of the priming effects on the probe items' reaction times, all the items presented a numerical ratio of approximately 3:5. Different number pairs were presented (9-15, 10-17, 12-20, 14-23), so as to avoid recognition of the numerosities throughout the task. The ratio of the congruency-related dimension was always set at a third (with a 10% margin of error for the Spacing dimension) of the numerical ratio (i.e. approximately 1:5), and hence the underlying dimensions (item size and total surface area for Size, convex hull and density for Spacing) were also at a constant ratio with number. In a Number-Size congruent item, both item size and total surface area were congruent with number, while they were both incongruent with number in a Number-Size incongruent item. The same was true for convex hull and density when Spacing was the congruency-related dimension. As mentioned above, the third dimension (not congruency-related) was constant between the two sets of dots, and across the items. For instance, Size was constant across the two sets of dots and took the same value in the Spacing-congruent and the Spacing-incongruent trials. The underlying dimensions (e.g. item size and total surface area for Size) were also at a constant ratio between the two sets of dots and across the items. The 16 combinations of number pairs were each presented ten times across the whole task. The 4 possible combinations of the side of the correct response were also counterbalanced across the total number of trials in the task.

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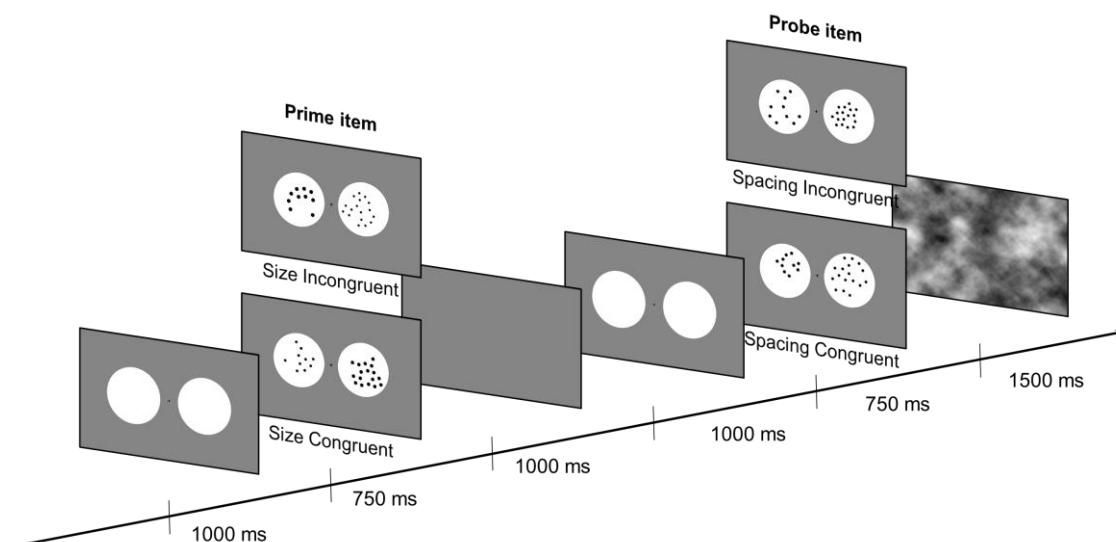


Figure 1: Examples of between-dimension trials. Both in the prime and the probe items of the trial, the congruency-related dimension can be congruent or incongruent with Number. In a between-dimension trial, the congruency-related dimensions in the prime and the probe items are different.

The task started with the presentation of 4 training trials (one for each of the 4 possible congruency pairs, 2 within- and 2 between-dimension pairs, 2 with Size as the congruency-related dimension), during which feedback on accuracy was provided. The task was divided in 5 blocks of 32 trials, for a total duration of approximately 15 to 20 minutes.

3. Results

For each participant, we removed trials with reaction times faster than 150ms and slower than 3 standard deviations above the individual mean. This led to removing 2.54% of the full dataset. One participant was removed due to their average reaction time being slower than 3 standard deviations above the average reaction time of the sample. In order to ensure that participants were sufficiently attentive and engaged with the experiment to yield reliable/valid behavioral data, we restricted our analyses to participants who performed above 75% of accuracy rate in each of the four conditions (congruent or incongruent with Size or Spacing) to be able to analyze potential congruency sequence

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effect. Sixteen participants were removed based on this criterion. The analyses described below were thus run on a sample of 64 participants, meeting the requirements of our power analysis¹.

3.1. Analyses of the prime items

A 2 (Dimension: Size, Spacing) x 2 (Congruency: congruent, incongruent) repeated measures ANOVA on the reactions times for the correctly responded prime items showed a main effect of Congruency, $F(1, 63) = 117.12, p < .0001, \eta^2_p = .65$, and a significant Congruency x Dimension interaction, $F(1, 63) = 16.86, p < .0001, \eta^2_p = .21$. Post-hoc one-way ANOVAs revealed that the congruency effects for each non-numerical dimension were both significant, with a stronger number/Spacing congruency effect (incongruent : $M = 623, 95\% CI [595.5, 650.5]$, congruent: $M = 533, 95\% CI [514.6, 551.4]$), $F(1, 63) = 113, p < .0001, \eta^2_p = .64$), than number/Size congruency effect (incongruent: $M = 598, 95\% CI [574.4, 621.6]$, congruent: $M = 559, 95\% CI [533.3, 584.7]$), $F(1, 63) = 19, p < .0001, \eta^2_p = .23$.

3.2. Analyses of the congruency sequence effects

The analyses of the congruency sequence effects were run on the reaction times for the correct responses on the probe items following correct responses on the prime items. We first ran a 2 (Prime dimension: Size or Spacing) x 2 (Probe dimension: Size or Spacing) x 2 (Prime congruency: congruent or incongruent) x 2 (Probe congruency: congruent or incongruent) repeated measures ANOVA on the reaction times. As for the analyses of the prime items, we found a significant main effect of the probe's Congruency, $F(1, 63) = 142.53, p < .0001, \eta^2_p = .69$, as well as a significant interaction between the probe's Congruency and Dimension, $F(1, 63) = 17.89, p < .001, \eta^2_p = .22$, indicating again a stronger congruency effect for Spacing (incongruent: $M = 653, 95\% CI [636.7, 669.3]$, congruent: $M = 562, 95\% CI [549.5, 574.5]$), than for the Size dimension (incongruent: $M = 627, 95\% CI [612.9,$

¹ We ran an a priori power analysis using G*Power, Version 3.1; Faul et al., 2009) in order to estimate the sample size. Based on the effect size of the negative priming effect in the non-symbolic comparison task found in adults ($\eta_p^2 = .29$, Viarouge et al., 2019), we chose a conservative effect size of $\eta_p^2 = .2$. The analysis indicated that a sample size of 55 was necessary to detect such effect size in a 2 (irrelevant dimension in the prime) x 2 (irrelevant dimension in the probe) x 2 (prime congruency) x 2 (prime congruency) repeated measures ANOVA with a power of .95 ($\alpha = .05$).

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641.1], congruent: $M = 585$, 95% CI [571.1, 598.9]). Importantly, we observed a significant 4-way interaction, $F(1, 63) = 48.73$, $p < .001$, $\eta^2_p = .44$. Separate post-hoc 2(Probe dimension) x 2 (Probe congruency) x 2 (Prime congruency) ANOVAs with Bonferroni corrected p-values for each of the prime dimensions showed significant three-way interactions (Size: $F(1, 63) = 27.3$, $p < .001$, $\eta^2_p = .3$ and Spacing: $F(1, 63) = 19.1$, $p < .001$, $\eta^2_p = .23$), which we explored further by running separate 2 (Prime congruency) x 2 (Probe congruency) ANOVAs with Bonferroni corrected p-values for each of the four combinations of the prime and probe non-numerical dimensions. Each of the four analyses revealed significant interactions between the congruency of the prime and the probe items (Size x Size : $F(1, 63) = 30$, $p < .0001$, $\eta^2_p = .32$, Size x Spacing : $F(1, 63) = 10.1$, $p = .002$, $\eta^2_p = .14$, Spacing x Size : $F(1, 63) = 5.74$, $p = .02$, $\eta^2_p = .08$, Spacing x Spacing : $F(1, 63) = 15.1$, $p < .001$, $\eta^2_p = .19$; see Figure 2).

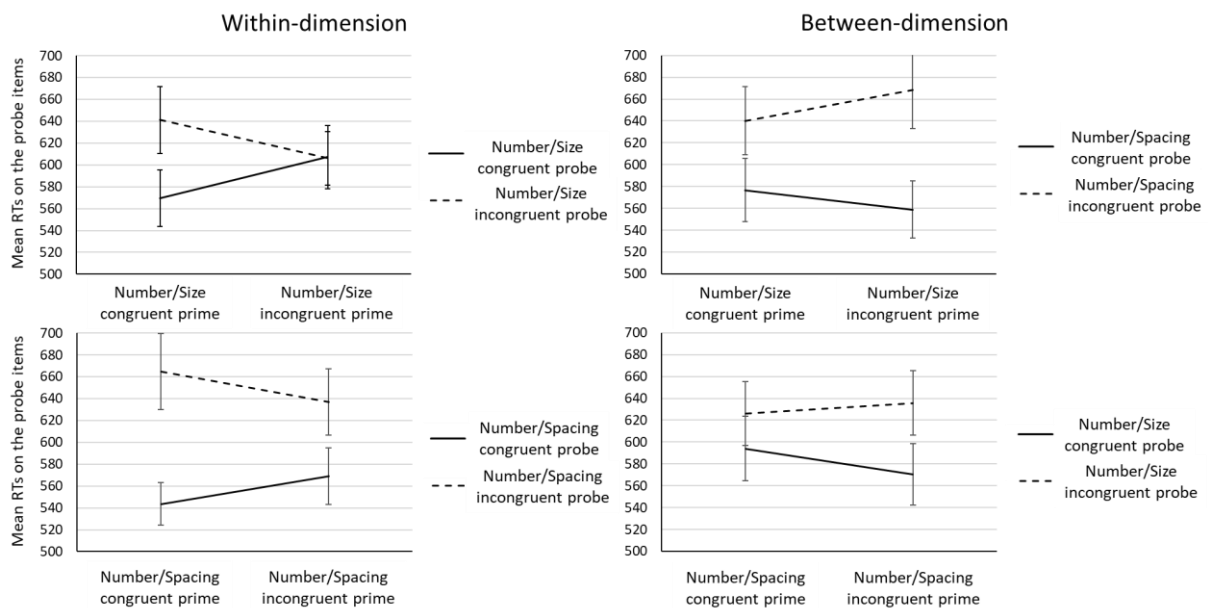


Figure 2: Congruency Sequence Effects. reaction times (ms) in the congruent and incongruent probe items depending on the congruency of the prime items, for the within-dimension (on the left) and between-dimension (on the right) trials. Error bars represent 95% confidence intervals.

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These significant interactions reflected different patterns of results (see Table 1). When the irrelevant non-numerical dimension of the prime and the probe items were the same (within-dimension trials), the congruency effects on the probe items were smaller for incongruent than for congruent prime items, reflecting a typical Gratton effect. However, this was not the case when the irrelevant non-numerical dimension of the prime and the probe items were different (between-dimension trials). In this condition, we observed a reversed Gratton effect, with a larger congruency effect on the probe items after an incongruent than after a congruent prime item.

	Within-dimension			
	Size-Size		Spacing-Spacing	
	Congruent Prime	Incongruent Prime	Congruent Prime	Incongruent Prime
Congruent Probe	$M = 570$, 95% CI [544.3, 595.7]	$M = 607$, 95% CI [578, 636]	$M = 544$, 95% CI [524.6, 563.4]	$M = 569$, 95% CI [543.2, 594.8]
Incongruent Probe	$M = 641$, 95% CI [610.3, 671.7]	$M = 606$, 95% CI [581.6, 630.4]	$M = 665$, 95% CI [630, 700]	$M = 637$, 95% CI [606.5, 667.5]

	Across-dimension			
	Size-Spacing		Spacing-Size	
	Congruent Prime	Incongruent Prime	Congruent Prime	Incongruent Prime
Congruent Probe	$M = 577$, 95% CI [548.1, 605.9]	$M = 559$, 95% CI [532.9, 585.1]	$M = 594$, 95% CI [564.7, 623.3]	$M = 570$, 95% CI [541.9, 598.1]
Incongruent Probe	$M = 640$, 95% CI [608.7, 671.3]	$M = 669$, 95% CI [633.5, 705.5]	$M = 626$, 95% CI [596.7, 655.3]	$M = 636$, 95% CI [606.5, 665.5]

Table 1. Mean reaction times (ms) and 95% confidence intervals for each of the 16 trial conditions.

4. Discussion

This study aimed at testing the specificity of the inhibitory control processes at play in the non-symbolic numerical comparison task, using a conflict adaptation paradigm. First, we observed classic congruency effects between number and non-numerical dimensions of magnitude in the prime items. Interestingly, we found stronger congruency effects between number and Spacing than between number and Size, in line with studies indicating a stronger influence of extrinsic dimensions

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(such as convex hull or occupied space) than intrinsic dimensions (such as individual item size) in adults (Gilmore et al., 2016). Since the ratios between number and the non-numerical dimensions were identical for Size and Spacing, this result could indicate a higher salience of the Spacing dimension than the Size dimension.

Second, our analyses of the congruency sequence effects showed significantly different patterns between the within- and between-dimension pairs. When the irrelevant non-numerical dimension was identical between the prime and the probe items, the congruency effect was reduced after incongruent primes, showing a classic congruency sequence effect (i.e., Gratton effect). On the contrary when the irrelevant non-numerical dimensions in the primes and in the probes were different, we observed a reversed Gratton effect with larger congruency effects following the incongruent primes. Taken together, these results indicate that the inhibitory control processes involved in the non-symbolic comparison task are specific to the non-numerical dimension conflicting with number.

Previous studies have argued that conflict adaptation was mainly due to an improved processing of the relevant information (Notebaert & Verguts, 2008). In our task, the relevant information remains constant throughout the task, thus an improved processing of the relevant information cannot in and by itself explain the different patterns observed between the within- and between-dimension trials, supporting the role of inhibitory control processes in the observed congruency sequence effect. It is important to note that other accounts based on binding effects have been proposed for the Gratton effect, which do not involve conflict adaptation (Schmidt & De Houwer, 2011). While conflict adaptation is unlikely to be the sole underlying mechanism of the Gratton effect, several studies have shown that the latter remained even after controlling for possible binding confounds (Akçay & Hazeltine, 2007; Blais et al., 2014).

Although observed in previous studies (Notebaert & Verguts, 2008; Brown, Reynolds & Braver, 2007), the increased congruency effects following incongruent prime items observed in the between-

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dimension conditions is can be surprising. One possible interpretation, further supporting the dimension-specific nature of the inhibitory control involved in our task, is in terms of switch cost between the prime and the probe items when the irrelevant non-numerical dimensions changes. This account predicts in particular that, in between-dimension trials, the performances are impaired in an incongruent probe immediately following an incongruent prime, due to the cost of switching from the specific inhibition of the previously conflicting information of magnitude to the currently conflicting new information of magnitude. While Notebaert and Verguts (2008) proposed a similar account in terms of switch cost at the level of responses (see also Brown, Reynolds & Braver, 2007, for a similar account at the task level), here our results suggest that this switch cost can not only impact the activation of the relevant information in the task, but also the processing of the irrelevant information. Following this account, the presence of a reverse Gratton effect further supports a dimension-specific inhibitory control in our task.

We would like to stress the fact that our study evidenced a specificity of inhibitory control solely in regards to the manipulated Size and Spacing dimensions, which are each defined as a combination of two covarying dimensions of magnitudes (average item size and total surface for Size, convex hull and density for Spacing), commonly used in the literature (Gebuis & Reynvoet, 2011). Our design does not allow to disentangle the role of these four dimensions in our study, and whether one or a combination of the two dimensions composing our manipulated dimensions drove the observed effects. Further studies would be very interesting to explore the specificity of inhibitory control relative to each of these dimensions.

Our study is the first to demonstrate that the mechanisms involved in the attention to number are specific to the irrelevant information conflicting with number, and contributes to better characterizing the executive mechanisms at play in numerical cognition. Using brain imaging methods, further research could allow to further identify the precise neural networks underlying this specificity. More generally, by using a task whereby the relevant information is maintained constant,

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292 our study demonstrates that the inhibition of the irrelevant information plays an important role in
293 the Gratton effect, which appears to not be solely driven by the increased activation of the relevant
294 information.

295

296 **Acknowledgments**

297 **Declarations of interest:** none.

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Appendix A.

Below is a table showing the congruency and the ratios for each of the four magnitudes composing the Size and Spacing dimensions manipulated in our study (Table A1), as well as examples of the stimuli for a within-dimension and a between-dimension conditions (Figure A1 and A2).

The ratios in the table are always calculated from our stimuli, as the smaller value over the larger value of a given dimension (e.g. for item size, ratio = (item size in the set with smaller dots) / (item size in the set with larger dots)). Thus, when the item is congruent ("C" in the table), this ratio corresponds to the value of the dimension in the less numerous set over the value in the more numerous set, and vice versa for incongruent items ("I" in the table). In some cases, there is a small jitter between the items within a condition. It was easier to generate sets of dots with precise values for Size and its sub-dimensions than for Spacing. For instance, ratio of item size in number-Size congruent items and ratio of total surface area in number-Size incongruent items are exactly the same in all the items. Since our numerical ratio was approximately the same across all the trials (~3:5), but using different number pairs, the ratios differ slightly between the four pairs. The same applies for Spacing and its sub-dimensions (convex hull and sparsity), with a bit less precision due to our program generating sets of dots until the convex hull surface falls within a small range of values.

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	<i>Size</i>		<i>Spacing</i>	
	item size	total surface area	convex hull	sparsity
Number- <i>Size</i> congruent	C ratio = .58	C mean ratio = .35, sd = .01	C mean ratio = .76, sd = .03	I mean ratio = .78, sd = .03
Number- <i>Size</i> incongruent	I mean ratio = .35, sd = .01	I ratio = .58	C mean ratio = .77, sd = .02	I mean ratio = .78, sd = .02
Number- <i>Spacing</i> congruent	I mean ratio = .77, sd = .01	C mean ratio = .77, sd = .01	C mean ratio = .34, sd = .01	C mean ratio = .57, sd = .01
Number- <i>Spacing</i> incongruent	I mean ratio = .77, sd = .01	C mean ratio = .77, sd = .01	I mean ratio = .58, sd = .01	I mean ratio = .35, sd = .01

Table A1. Congruency (C: congruent, I: incongruent) and ratios for each magnitude composing the Size and Spacing dimensions, in each of the four experimental conditions. Ratios are calculated as the smaller value over the larger value for a given dimension. Values for the magnitudes composing the congruency-related dimension are in bold.

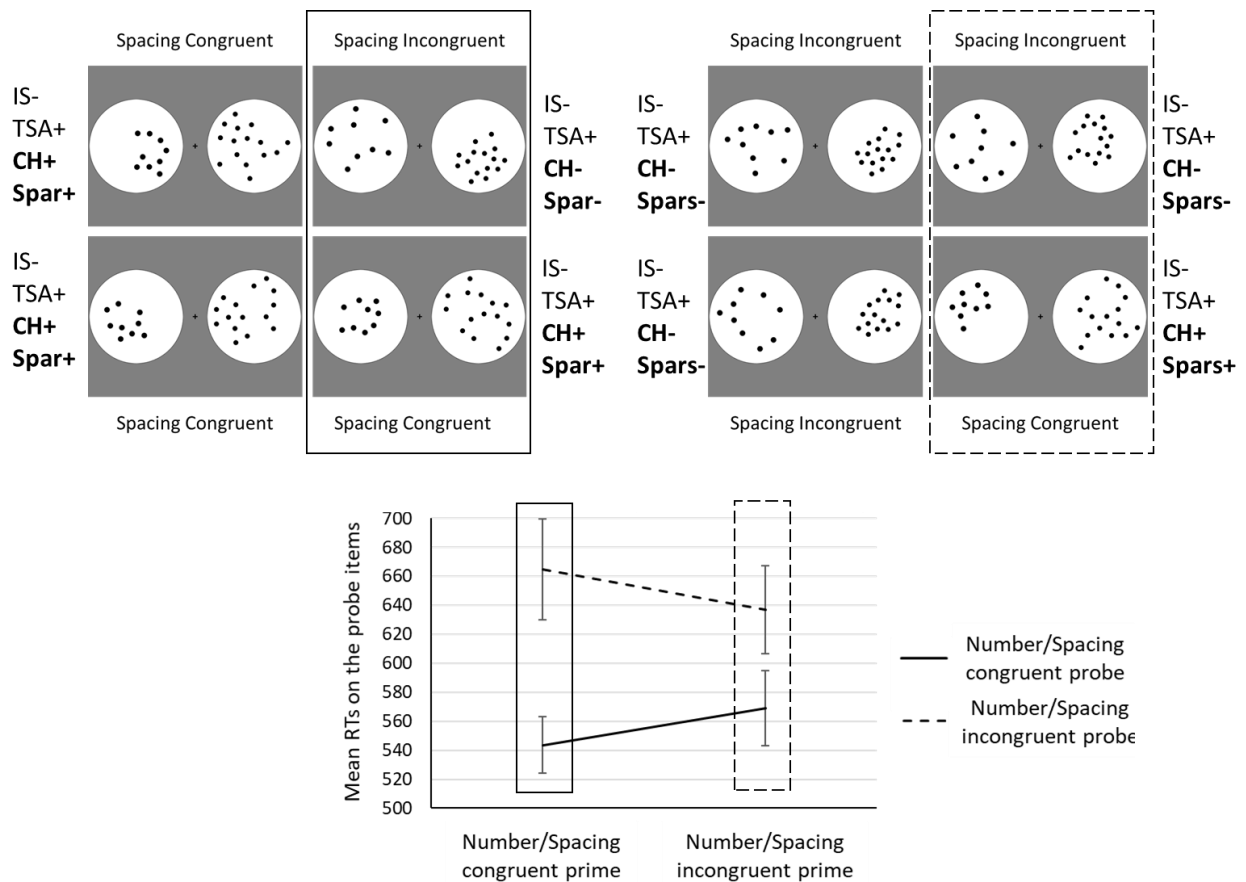


Figure A1. Example of stimuli in the within-dimension conditions, with Spacing as the congruency-related dimension. Next to each stimulus is the congruency of item size (IS), total surface area (TSA), convex hull (CH) and sparsity (Spars). + : congruent with number ; - : incongruent with number. Dimensions composing the manipulated dimension are in bold.

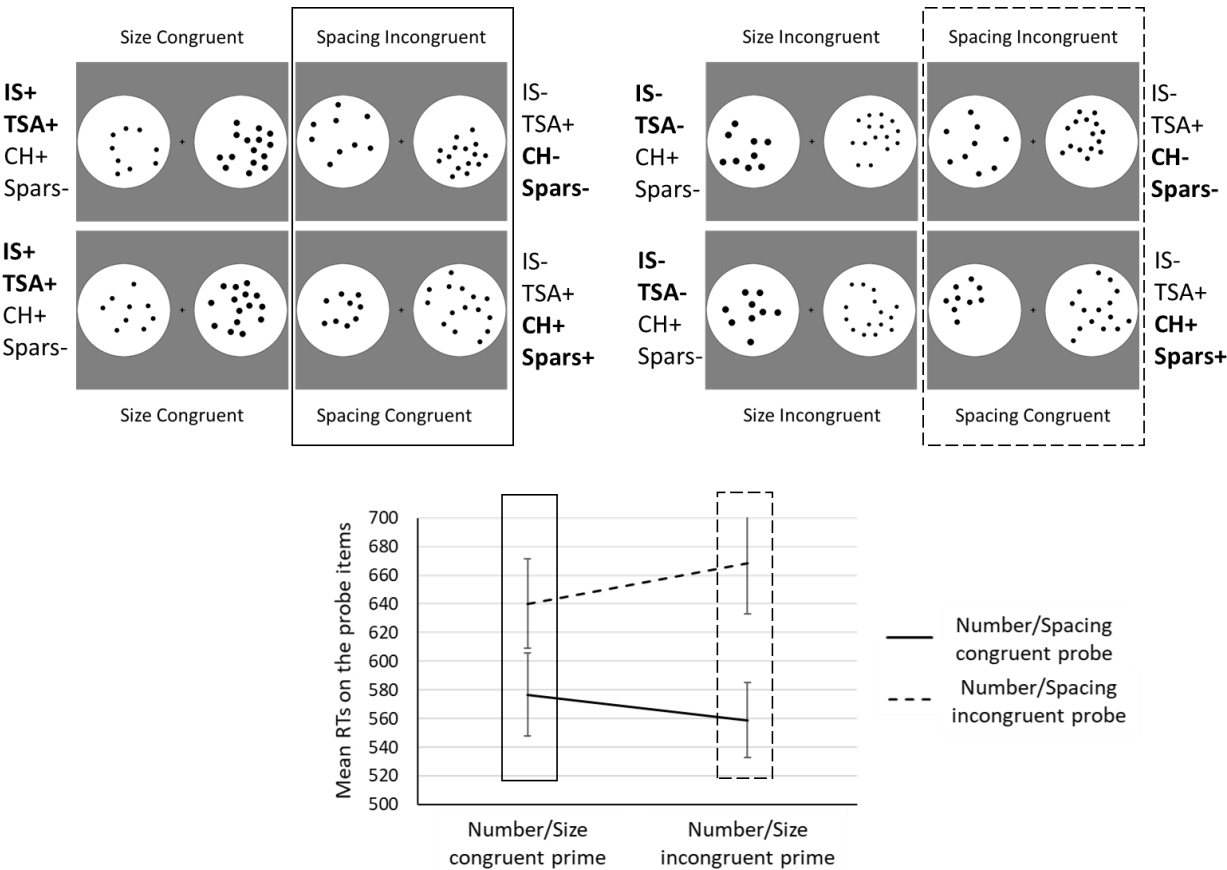


Figure A2. Example of stimuli in the between-dimension conditions, with Size as the congruency-related dimension in the prime items. Next to each stimulus is the congruency of item size (IS), total surface area (TSA), convex hull (CH) and sparsity (Spars). + : congruent with number ; - : incongruent with number. Dimensions composing the manipulated dimension are in bold.

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