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BRIEF REPORT

Frequency-tagging EEG reveals the effect of attentional focus on abstract magnitude processing

Cathy Marlair[1] · **Aliette Lochy**[1,2] · **Virginie Crollen**[1]

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Abstract
While humans can readily access the common magnitude of various codes such as digits, number words, or dot sets, it remains unclear whether this process occurs automatically, or only when explicitly attending to magnitude information. We addressed this question by examining the neural distance effect, a robust marker of magnitude processing, with a frequency-tagging approach. Electrophysiological responses were recorded while participants viewed rapid sequences of a base numerosity presented at 6 Hz (e.g., "2") in randomly mixed codes: digits, number words, canonical dot, and finger configurations. A deviant numerosity either close (e.g., "3") or distant (e.g., "8") from the base was inserted every five items. Participants were instructed to focus their attention either on the magnitude number feature (from a previous study), the parity number feature, a nonnumerical color feature or no specific feature. In the four attentional conditions, we found clear discrimination responses of the deviant numerosity despite its code variation. Critically, the distance effect (larger responses when base/deviant are distant than close) was present when participants were explicitly attending to magnitude and parity, but it faded with color and simple viewing instructions. Taken together, these results suggest automatic access to an abstract number representation but highlight the role of selective attention in processing the underlying magnitude information. This study therefore provides insights into how attention can modulate the neural activity supporting abstract magnitude processing.

Keywords Attention · Automaticity · Fast periodic visual stimulation · Magnitude integration · Numerical formats

Because magnitude is among the most salient and important semantic features of numbers, the nature of its processing has aroused considerable interest. Over the past 20 years, a substantial body of research has indeed explored the level of automaticity (e.g., Burr et al., 2010; Cipora et al., 2019, 2021; Guillaume et al., 2020; Hyde & Spelke, 2009; Vetter et al., 2008) and the format independence of magnitude processing (e.g., Holloway et al., 2010; Libertus et al., 2007; Liu et al., 2018; Marinova et al., 2021; Piazza et al., 2007). For instance, it has been demonstrated that individuals' performance in determining whether a number is smaller or larger than 5 can be influenced by the presentation of a subliminal prime (Naccache & Dehaene, 2001). Participants responded more quickly when the prime and target numbers were congruent (i.e., both smaller or both larger than 5) and when the numerical distance between the prime and target was small (e.g., prime: 3–target: 4) rather than large (e.g., prime: 1–target: 4). This phenomenon, known as the priming *distance effect* (Dehaene et al., 1998; Moyer & Landauer, 1967) supports the idea that the prime's magnitude is automatically accessed, leading to the assumption that subliminal numbers can be processed unconsciously up to a semantic level (but see Damian, 2001, for an alternative hypothesis). While Naccache and Dehaene (2001) found that priming effects generalized over numerical formats (i.e., they occurred even when primes were Arabic digits and targets were number words or vice and versa), other findings challenged the existence of a format-independent numerical priming. Kunde et al. (2003) indeed observed that priming effects did not generalize to numbers of a format not consciously seen (e.g., when primes were number words but targets were only Arabic digits). Therefore, the authors argued

✉ Cathy Marlair
cathy.marlair@uclouvain.be

[1] Psychological Sciences Research Institute (IPSY), Université Catholique de Louvain, Place Cardinal Mercier 10, 1348 Louvain-la-Neuve, Belgium

[2] Institute of Cognitive Science and Assessment, Department of Behavioral and Cognitive Sciences, Faculty of Humanities, Social and Educational Sciences, Université du Luxembourg, Esch-sur-Alzette, Luxembourg

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that the impact of subliminal stimuli is crucially determined by the participant's prestimulus intentions. The unconscious primes will activate responses to the extent that they match the prespecified (task-defined) response alternatives (Kunde et al., 2003). While these results do not rule out the possibility of an automatic access to magnitude representation across different formats, they do suggest that subliminal priming tasks may not be a suitable method for assessing it.

An EEG study using the implicit *fast periodic visual stimulation* (FPVS) oddball design (Norcia et al., 2015) recently provided evidence that the human's brain automatically generalizes magnitude information across Arabic digits, number words, canonical finger, and dot patterns (Marlair et al., 2022a, 2022b). In that study, participants were visually presented with a stream of one base numerosity at a constant frequency of 6 Hz, and a deviant numerosity was periodically inserted within the stream every fifth stimulus (i.e., at 6 Hz/5 = 1.2 Hz). Both base and deviant numerosities were presented in randomly mixed codes. Results revealed clear electrophysiological responses at 1.2 Hz, reflecting the brain's capacity to discriminate the deviant numerosity from the base and to generalize over the deviant's presentation codes (i.e., digit, word, fingers, and dots). Most importantly, larger discrimination responses were observed when the deviant numerosity was numerically distant from the base numerosity (e.g., base/deviant = 2/8) than when they were numerically closer (e.g., base/deviant = 2/3). The presence of this neural distance effect thus confirmed the processing of abstract magnitude information in posterior brain regions (Guillaume et al., 2020; Marinova et al., 2021). Since it avoids the implication of decision-making processes, the FPVS technique is often seen as a highly valuable tool for assessing the automaticity of a specific cognitive function (Guillaume et al., 2020; Rossion, 2014). Referring to the "four horsemen of automaticity" introduced by Bargh (1994), FPVS indeed induces a low level of awareness (i.e., participants are unaware of the stimuli's periodic occurrence), intentionality (i.e., they cannot intentionally elicit the periodic brain response), controllability (i.e., they cannot manipulate the process) and efficiency (i.e., it should not require attentional resources). In the study of Marlair et al., 2022a, b, however, participants' attention was preoriented to magnitude. They were indeed instructed to report, at the end of the sequence, the smallest or largest numerosity they had perceived. Thus, although participants were not required to perform any explicit comparison task during the stimulation, they actively attended to magnitude information in order to respond, which may have enhanced number-processing activity.

This raises an intriguing question about how attentional focus and instructions can modulate the neural mechanisms of abstract magnitude processing. To examine this issue, the current study used the same multi-code FPVS paradigm as in Marlair et al. (2022a, 2022b) to evaluate abstract magnitude processing (i.e., across different numerical codes) with a robust marker (i.e., the distance effect). Crucially, the instruction given to the participants prior to the experiment varied in order to investigate whether access to the common magnitude representation underlying digits, words, dots and fingers can occur under different attentional conditions. In a first condition ("None"), participants received no instruction other than to fixate the middle of the screen. In a second testing condition ("Color"), participants' attention was preoriented toward a low-level visual feature of the stimuli by asking them to report the colors appearing during the sequences. In a third and final condition ("Parity"), participants were told to pay attention to the numerosities presented during the stimulation sequences in order to be able to report which was (were) the odd or even numbers. One should note that the instruction was never directed to the detection of the deviant numerosity per se, but rather aimed at inducing processing of the whole sequence with attention focused on one specific aspect of the stimuli (or none). In addition to the newly acquired data, we decided to reanalyze those previously obtained by Marlair et al., 2022a, b in order to compare the impact of orienting number processing at the level of magnitude (previous study) to (1) orienting attention to another numerical feature (i.e., parity), (2) orienting attention to the processing of a non-numerical visual feature (i.e., color), and (3) not orienting attention to any specific feature.

Method

Participants

The current study involved two groups of 30 participants. The first group (16 males and 14 females, M_{AGE} = 24.1 years, SD_{AGE} = 3.4) took part in another experiment on reading abilities, giving us the opportunity to test them twice (for two instructions: None and Parity), 1 week apart. The Color instruction was completed by a second group of 30 participants (nine males and 21 females, M_{AGE} = 24.8 years, SD_{AGE} = 3.7). Data retrieved from Marlair et al. (2022a, 2022b) were acquired on 23 participants (eight males and 15 females, M_{AGE} = 22.17 years, SD_{AGE} = 2.8). All of them were French speakers, had corrected-to-normal vision and did not present any neurological disorder. They gave their written informed consent and were compensated for their participation. The procedures were in line with the Declaration of Helsinki and approved by the local ethics committee of Saint-Luc–UCLouvain (2019/12SEP/400 – B403201941534).

EEG procedure

The experimental design was created and executed with a software running on JavaScript (Java SE Version 8, Oracle Corporation, USA). Sequences of 63-s stimulation, including 2 s of gradual fade-in and 1 s of gradual fade out, were displayed on a screen with a 800 × 600-px resolution placed 1 m away from the participants. A sequence consisted in the presentation at a constant 6-Hz frequency (i.e., six stimuli per second) of one base and one deviant numerosity, with the deviant appearing periodically every fifth stimuli, so at 1.2 Hz (i.e., 6 Hz/5; see Fig. 1). As in Marlair et al., 2022a, b, numerals 2, 3, 8, and 9 were selected as base and deviant stimuli in order to create four *close* sequences (i.e., base/deviant = 2/3, 3/2, 8/9, 9/8) and four *distant* sequences (i.e., 2/8, 8/2, 3/9, 9/3). The experiment thus included eight sequences in total, presented in a random order for each participant. Stimuli were displayed at the center of the screen for 0.166 s (corresponding to the 6-Hz presentation rate) by means of sinusoidal modulation of contrast from 0 to 100 % and with a resolution of 236 × 236 px (Fig. 1). Both the base and the deviant numerosities were presented under different codes including Arabic digits, number words, canonical dot patterns (i.e., patterns found on play cards) and canonical finger configurations (i.e., typical Belgian finger-counting configurations), randomly selected during the sequence with no immediate repetition of the same stimulus. To add some variability in the low-level perceptual features, Arabic digits and number words were written in six different fonts, fingers were drawn in six different ways and dots varied in shapes (circles, squares or triangles), size and density (examples of stimuli are depicted in Fig. 1).

Before the experiment started, participants were given an instruction aimed at orienting their attentional focus toward a specific feature (or not). In the first "None" instruction, they were simply required to stare at the center of the screen, where they would observe various symbols appearing (i.e., no feature). In the second "Parity" instruction, participants were asked to look closely at the stimuli so that, at the end of the sequence, they could say which was (were) the odd or even number(s) they had seen (i.e., semantic feature = parity). In a final "Color" instruction, colored stimuli (both bases and deviants) appeared randomly during the sequence for approximately seventy times, so that color changes occurred the same amount of time as numerosity changes (60s of stimulation at 6 Hz with a deviant every fifth stimuli result in 360/5 = 72 deviant numerosities per sequence). Importantly, however, these colored stimuli did not appear periodically and thus, were not expected to elicit any periodic brain response. Participants were directed to focus their attention on the stimuli so that, at the end of the sequence, they could indicate which color(s) they had observed (i.e., low-level visual feature = color). As for the numerosities, four different colors were selected: blue, green, yellow and

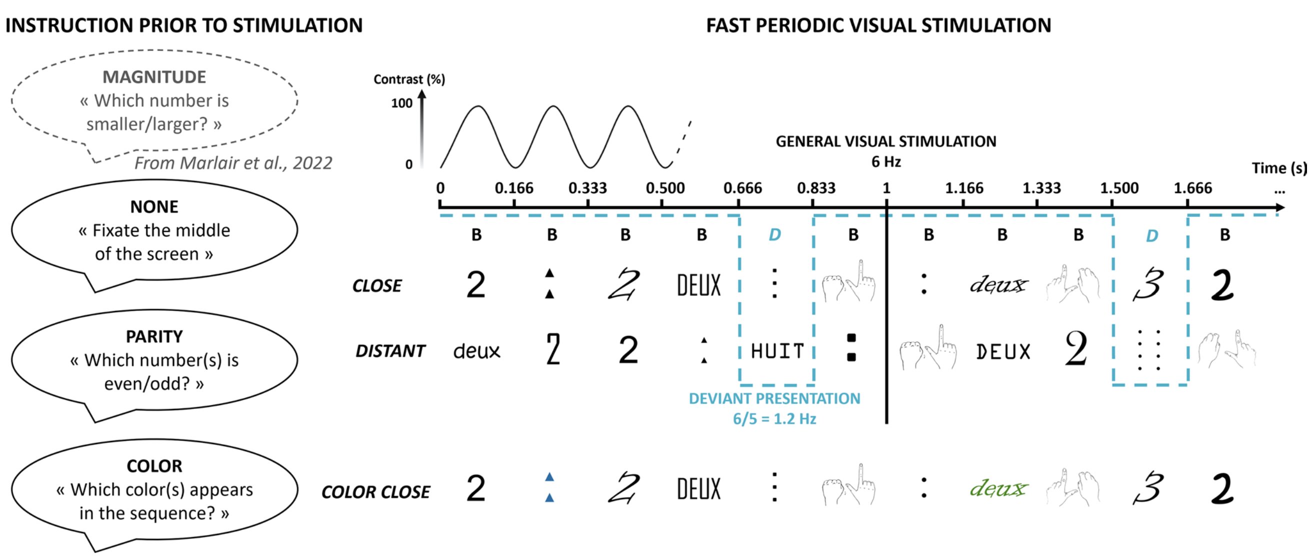

Fig. 1 Experimental design. Participants were given an instruction before the stimulation: None, Parity or Color. Data for the Magnitude instruction were retrieved from Marlair et al. (2022a, 2022b), accessible via the Dryad Digital repository (https://doi.org/10.5061/dryad.612jm6469). During the experiment, numerosities were presented in randomly mixed codes and by means of sinusoidal modulation of contrast at a constant frequency of 6 Hz (i.e., six stimuli per second), reflecting the general visual stimulation. The deviant (D) numerosity (in the example, "3" in the close sequence, "8" in the distant sequence) appeared periodically every fifth base (B) stimuli (e.g., "2"), resulting in a deviant presentation frequency of 6 Hz/5 = 1.2 Hz. In the Color instruction, 70 colored stimuli (both bases and deviants) were randomly (i.e., not periodically) introduced in the sequences. Note: "deux" means "two" in French and "huit" means "eight"

orange. Those varied according to the sequence with a maximum of two colors per sequence (e.g., blue and green in the sequence 2/3; green in the sequence 9/3) so that the maximum amount of information to retain during a sequence was two, as in the Parity instruction.

The first group of participants underwent the None and Parity instructions in two different sessions, separated by 1 full week to prevent any learning effect. The None instruction was always presented first, to ensure that participants would not direct their attention toward parity in that condition. A second group of participants did the Color instruction. In both Parity and Color, all participants were able to give the correct answers (i.e., which numbers are even/odd or which colors appear during a sequence) 100% of the time.

EEG acquisition and preprocessing

EEG was recorded at 2048 Hz with a 68-channel BioSemi Active II system (BioSemi, The Netherlands). Sixty-four electrodes were placed according to the standard 10–20 system, and four extra channels were added on posterior sites (PO9, PO10, I1, and I2). The magnitude of the offset of all electrodes, referenced to the common mode, was held below 50 mV. Analyses of the EEG data were carried out using Letswave 6 (https://www.letswave.org), an open-source toolbox running on MATLAB (The MathWorks, Natick, MA, USA). Data were downsampled to 512 Hz to decrease the processing time. Then, a band-pass filter with cut-off values of 0.1–100 Hz and a multinotch filter at three harmonics of 50 Hz were applied. Data were segmented 2 s before and 1 s after each sequence to simplify the inspection of signal quality. Data cleaning included independent component analysis (ICA) to remove artifacts due to eye blinks and linear interpolation for bad channels (<5% of the whole scalp with 1% of posterior channels). Sequences containing excessive noise were removed from the analyses (<5% in each instruction) with a maximum of one sequence per condition (close or distant) and per subject. Finally, data were segmented again from the stimulation onset until 60 s, to include the largest amount of integer presentation cycles (72 cycles of 833.33 ms at the 1.2-Hz frequency), and all channels were rereferenced to the common average.

EEG frequency domain analyses

Frequency domain analyses were conducted separately for each instruction (i.e., None, Parity, and Color). A fast Fourier transformation was applied to each sequence and normalized amplitude spectra were obtained for the 68 channels with a frequency resolution of 0.0167 Hz (1/60 s). Based on the grand-averaged amplitude spectrum within each condition (i.e., close or distant), Z scores were computed to assess significant responses at the frequencies of interest (i.e., 6 Hz and 1.2 Hz) with the formula: $Z(x) = \frac{x - mean(noise)}{standard\ deviation\ (noise)}$, where x represents a frequency bin and the *noise* is defined as the 20 surrounding bins of each target bin excluding the immediately adjacent and the extreme (min and max) bins (Liu-Shuang et al., 2014; Rossion et al., 2012; Srinivasan et al., 1999). Harmonics with a Z score larger than 1.64 ($p < .05$, one-tailed, signal > noise) indicated significant responses. Then, *noise-corrected amplitudes* (i.e., [signal − noise] for each frequency bin) were summed for the significant harmonics of the general visual stimulation frequency (6 Hz) and the discrimination frequency (1.2 Hz) to quantify the responses of the participants in each condition (Retter et al., 2021). The number of harmonics to be summed was determined as the largest consecutive chain of significant harmonics and applied to both conditions, in order to include an equivalent number of harmonics in the close and distant responses. Finally, a ranking procedure (Lochy et al., 2018; van de Walle de Ghelcke et al., 2021) was used to identify a left and right region of interest (ROI) based on the channels showing the largest response amplitudes, separately for each instruction. Noise-corrected amplitudes of the selected channels (four in each hemisphere) were averaged. The same analysis steps were performed on the data acquired by Marlair et al. (2022a, 2022b) to compute responses for the Magnitude instruction.

Statistical analyses

General visual responses (at 6 Hz) and discrimination responses (at 1.2 Hz) were analyzed with a linear mixed model (LMM) including both *fixed* and *random* effects (Brown & Prescott, 2015; Littell et al., 2006). The incorporation of random effects enabled us to account for potential systematic differences between participants due to the repetition of subjects in two instructions (None and Parity). Our LMM thus included three fixed factors: *Instruction* (none, color, parity or magnitude), *Condition* (close or distant), and *Lateralization* (left or right), as well as a random intercept by subject. As such, it controlled for group variability by letting the intercept term vary across subjects and thus improved our ability to describe how fixed effects could influence the response amplitudes.

Results

General visual responses

General visual responses (GVR) were significant over 6 consecutive harmonics in Parity, Color, and None instructions (from 6 to 36 Hz) while it extended to the seventh harmonic in Magnitude (from 6 to 42 Hz). The ranking procedure used for each instruction consistently revealed a cluster of parieto-occipital channels including O2, PO8, PO10, P8 and O1, PO7, PO8, P7, that were averaged in order to create respectively the right and left ROIs. LMM run on the GVR showed that 80% of the residual variance could be accounted for by systematic differences between subjects, *Estimate* = .95, *SE* = .16, $p <$ .001. While controlling for this effect, a significant interaction between *Instruction* and *Lateralization* was found, $F(3, 355) = 6.10$, $p < .001$. In the left ROI, amplitude of the GVR in Magnitude was not different from that of Parity, Color, and None (all *ps* > .22) whereas in the right ROI, the response found in Magnitude was similar to Parity and Color (*ps* > .10) but different from None ($p = .015$). These results might reflect a stronger involvement of the right hemisphere in processes requiring a higher level of cognitive effort or attentional resources. Most importantly, there was no main effect or interaction with *Condition* (close or distant) on the GVR (*ps* > .83). Note that the same results emerged when analyzing GVR in the same ROIs as those determined for the discrimination responses.

Discrimination responses

Six consecutive harmonics of the discrimination response (at 1.2 Hz) were significant in the None and Parity instructions (from 1.2 Hz to 8.4 Hz, but excluding the fifth harmonic which corresponds to the 6-Hz general visual stimulation frequency), 7 in Color (from 1.2 Hz to 9.6 Hz, excluding the fifth) and 8 in Magnitude (from 1.2 Hz to 10.8 Hz, excluding the fifth). For each instruction, the ranking procedure systematically revealed a cluster of parietal (P7, P8, P9, P10) and parieto-occipital electrodes (PO7, PO8, PO9, PO10) that is highly consistent with previous FPVS studies in numerical cognition (e.g., Guillaume et al., 2020; Marinova et al., 2021, Marlair et al., 2021, 2022a, 2022b). These channels were averaged to create the left (i.e., P7, P9, PO7, PO9) and right ROIs (i.e., P8, P10, PO8, PO10). For each instruction, approximately 80% of the total discrimination response amplitude (i.e., recorded over the 68 channels) was encompassed within these two ROIs. As for the GVR, the LMM computed on discrimination responses showed that a significant proportion (12%) of the residual variance could be accounted for by systematic differences between subjects (*Estimate* = .004, *SE* = .002, $p = .025$). While controlling for this effect, a significant *Instruction* × *Condition* interaction was highlighted, $F(3, 337) = 3.17$, $p = .024$ (see Fig. 2), indicating the presence of a neural distance effect (i.e., larger responses elicited for distant than close deviants) for Magnitude (0.18 μV stronger, $p = .004$) and Parity (0.13 μV stronger, $p < .001$), but only marginal for Color (0.07 μV stronger, $p = .064$) and None (0.05 μV stronger, $p = .086$). There was no main effect or interaction with Lateralization (left or right) on the discrimination responses (*ps* > .23).

Discussion

The current study explored the influence of attentional focus on abstract magnitude processing during rapid number sequences viewing. As in a previous study (Marlair

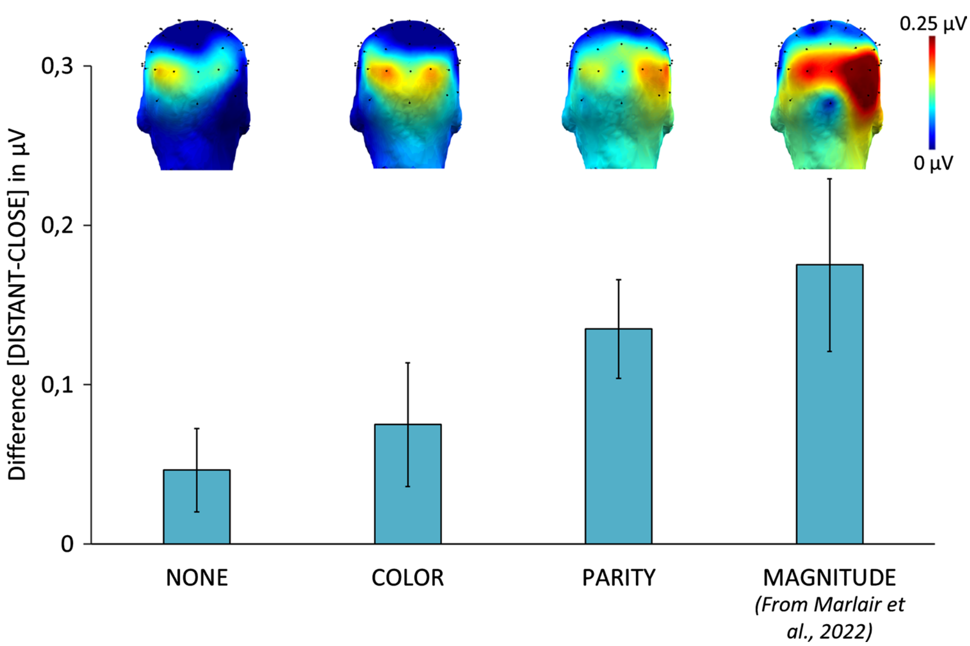

Fig. 2 Distance effect on discrimination responses (at 1.2 Hz). Difference in amplitude (μV) between close and distant discrimination responses, averaged over participants and ROIs (left and right), indicating a significant distance effect in Magnitude and Parity (*ps* < .01), a marginal effect in Color ($p = .064$) and None ($p = .086$). Bars represent standard errors of the mean. Topographies display the difference between close and distance discrimination responses over the scalp, based on the group average

et al., 2022a, 2022b), *fast periodic visual stimulation* EEG recordings were combined with a *multi-code presentation* (i.e., Arabic digits, number words, canonical dot, and finger configurations) and the *distance effect* as a marker of magnitude processing. Before the stimulation began, participants were provided with different instructions aimed at directing their attention to the *Color* feature of numbers, the *Parity* feature of numbers, the *Magnitude* feature of numbers or no specific feature (*None*). The Magnitude data were retrieved from a previous study (Marlair et al., 2022a, 2022b) while Color, Parity and None were tested on new participants. In all four instructions, we observed significant discrimination responses associated with the periodic change of numerosity (at 1.2 Hz). These findings therefore support that Arabic digits, number words, canonical dot patterns and canonical finger configurations automatically converged on a common neural representation, whether or not attentional resources were allocated to number processing. However, the sensitivity of discrimination responses to the distance effect (i.e., larger response amplitudes when the base/deviant were numerically distant than close) was strongly influenced by the instruction given to the participants. A significant effect was found in Magnitude and Parity, but there was no conclusive evidence for it (although it tended to) in the Color and None instructions.

The finding that magnitude processing (i.e., the distance effect) but not magnitude encoding (i.e., detection of the periodic numerical change) was affected by attention/instruction supports the existence of a multistage numerical processing. Numerosities would be seen and recognized through a first and early *perceptual* stage. An intermediate *integrative* stage would then convert the numerosities into abstract magnitude representations. Finally, magnitudes would be put in relation to each other in a late *processing* stage. Consequently, the distance effect would originate from this latter processing stage. Evidence that numerical processing passes through successive stages has already been reported in previous EEG studies (Dehaene, 1996; Grasso et al., 2022; Libertus et al., 2007; Park et al., 2016; Temple & Posner, 1998). For instance, Dehaene (1996) observed neural signatures associated with three consecutive steps during an explicit comparison task with Arabic digits and number words. A first occipito-temporal activation was related to numerical identification, then a right-lateralized parieto-occipital activation was modulated by the distance effect (but not by numerical format) and finally, a late activation in the motor cortex was associated with response execution. In the present study, we have shown that attention can differently affect these processing stages. To our knowledge, this is the first study examining how attention and task instruction can influence FPVS responses in the numerical cognition field. A few studies have previously investigated this question in other cognitive domains such as speech (Ding et al., 2018; Niesen et al., 2020) and face processing (Baudouin et al., 2023; Quek et al., 2018). Similar to what we have observed, Ding et al. (2018) found that attention did not influence the encoding of simple syllables, but was required to group them into words. In the same vein, Baudouin et al. (2023) showed different stages of facial expression processing (from detection to recognition), modulated by task-related top-down mechanisms.

Another interesting result from this study is that a significant distance effect was observed when participants were instructed to focus their attention on parity, suggesting that magnitude is automatically processed during parity judgment. Similar findings have already been reported in behavioral numerical comparisons tasks. When participants are asked to judge whether a number is smaller or larger than 5, using two buttons assigned to the left and right hemispaces, they tend to respond faster to small and large numbers with the left and right buttons, respectively. This observation refers to the well-known *SNARC effect* which is usually explained by the spatial distribution of magnitudes on a mental number line, with small magnitudes being represented on the left of the line and large magnitudes on the right (Dehaene et al., 1993). Crucially, the same SNARC effect was observed when participants had to decide whether a number is even or odd, indicating that magnitude was automatically activated even though it was irrelevant for the task (Cipora et al., 2019; Fias, 1996). Yet other recent findings showed no evidence of such a SNARC effect when asking participants to make simple color decisions on numbers (Cleland and Bull 2019, Experiments 1&5). Since parity and magnitude are both numerical dimensions, it is possible that the processing of the relevant dimension (parity) have *triggered* the processing of the irrelevant dimension (magnitude). The notion of triggering has been proposed by Tzelgov and Ganor-Stern (2005) and defined as "the activation of the irrelevant dimension provided by the task requirement." The idea is that the level of triggering would depend on, and vary with, the connection between the relevant and irrelevant dimensions. As such, the more related are two processes, the more triggering it would provide. Therefore, it may account for the finding of a SNARC effect during parity but not color judgments (but see Didino et al., 2019, for an alternative explanation), as well as for the observation of different distance effects in our study (see fig. 2). The level of triggering would indeed be strongest between Magnitude and Parity, then gradually decrease with Color and finally None instruction.

Tzelgov and Ganor-Stern (2005) suggested that by varying the level of triggering, one would be able to reveal the extent to which it is necessary for the occurrence of an automatic process. Therefore, it would help to distinguish between two modes of automatic processing: *unconditional* (or *autonomous*) automatic processes, that occur even if no triggering is provided by the task, and *conditional* (or *intentional*) automatic processes, which depend upon some level of triggering provided by the task (Bargh, 1992; Bargh et al., 1996; Cleland and Bull 2019; Cohen Kadosh et al., 2008; Tzelgov & Ganor-Stern, 2005; Tzelgov et al., 1996). Based on this distinction, the current results support the idea that abstract magnitude processing would rather be an intentional automatic process. Consistent with what has been observed in subliminal priming paradigms (Kunde et al., 2003; Naccache et al., 2002), it thus implies that top-down attention and task instructions can affect the automatic processing of magnitude across formats (Dehaene et al., 2006). One limitation of the current study, however, is the lack of information about what the participants actually did during the None instruction. Inconclusive evidence for a distance effect in this condition could be explained by the absence of magnitude triggering, but it may also reflect a global reduction of attention allocated to the stimulation. These two accounts are difficult to disentangle. However, the fact that the general visual response in the condition None was found to be smaller than that of the three other instructions in the right hemisphere speaks more in favor of a reduced attentional level.

Importantly, the automatic processing of magnitude in the parity instruction should not be taken as an inability to process parity, but rather as the fact that magnitude overcomes parity information. Given that a previous FPVS study found significant brain responses associated with the periodic change of parity (Guillaume et al., 2020), one could have expected a similar parity effect to emerge in the current data. Indeed, in our design, the distant sequences were systematically contrasting two odd or two even numbers as base/deviant (2/8 or 3/9) whereas close sequences contrasted odd/even numbers (2/3 or 8/9). Hence, if we consider parity instead of magnitude, one might expect that deviants with an opposite parity status to bases would be more salient than deviants with the same parity, leading to stronger discrimination responses in opposite-parity sequences (in our case, close sequences) than in same-parity (distant) sequences. Following this line of reasoning, expectations regarding the magnitude and the parity processing, in the present study, are thus opposite. Consequently, we could have expected the Parity instruction to lead to increased parity processing and magnitude neglect, thus potentially nullifying the distance effect. Although the current data did not support this hypothesis, it should be noted that the design employed in our study was specifically intended to measure the distance effect, rather than any potential effect related to parity. In order to effectively assess the presence of a parity effect, parity contrasts should be conducted on sequences with a neutral distance, such as 3/7, 4/8 for same-parity sequences versus 3/8, 4/7 for opposite-parity sequences.

To conclude, the present study provided new insights into the automaticity of abstract magnitude processing (i.e., across Arabic digits, number words, canonical dot and finger configurations). Whether participants paid attention to a numerical feature (magnitude or parity), a nonnumerical visual feature (color) or to no specific feature at all, they succeeded in detecting the periodic change of numerosity despite its code variation. We nevertheless showed that magnitude processing – adequately assessed by the presence of a distance effect on the discrimination responses – was influenced by the instruction. These results suggest that attention may play a critical role in the late processing stage of magnitude, but not in the early stages of number perception and identification.

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Declarations

Competing interest The authors declare no conflict of interest.

Ethics approval The procedures were in line with the Declaration of Helsinki and approved by the local ethics committee of Saint-Luc – UCLouvain (2019/12SEP/400 – B403201941534).

Consent to participate and to publish Informed consent was obtained from all participants included in the study, and there is no identifying information about participants.

Open practices statement The experiment reported in this article was not preregistered. The dataset generated during the current study is available from the corresponding author on request. Data for the Magnitude instruction were retrieved from a previous study of Marlair et al. (2022b) available in the Dryad Digital repository (https://doi.org/10.5061/dryad.612jm6469). The data were analyzed with an open-source toolbox (https://www.letswave.org).

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