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# Judging the order of numbers relies on familiarity rather than activating the mental number line

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ABSTRACT

A series of effects characterises the processing of symbolic numbers (i.e., distance effect, size effect, SNARC effect, size congruency effect). The combination of these effects supports the view that numbers are represented on a compressed and spatially oriented mental number line (MNL) as well as the presence of an interaction between numerical and other magnitude representations. However, when individuals process the order of digits, response times are faster when the distance between digits is small (e.g., 1-2-3) compared to large (e.g., 1-3-5; i.e., reversed distance effect), suggesting that the processing of magnitude and order may be distinct. Here, we investigated whether the effects related to the MNL also emerge in the processing of symbolic number ordering. In Experiment 1, participants judged whether three digits were presented in order while spatial distance, numerical distance, numerical size, and the side of presentation were manipulated. Participants were faster in determining the ascending order of small triplets compared to large ones (i.e., size effect) and faster when the numerical distance between digits was small (i.e., reversed distance effect). In Experiment 2, we explored the size effect across all possible consecutive triplets between 1 and 9 and the effect that physical size has on order processing. Participants showed faster reactions times only for the triplet 1-2-3 compared to the other triplets, and the effect of physical magnitude was negligible. Symbolic order processing lacks the signatures of the MNL and suggests the presence of a familiarity effect related to well-known consecutive triplets in the long-term memory.

## 1. Introduction

Mathematical competence is positively associated with life success, whether expressedas economic or as health outcomes (Dougherty, 2003; Gerardi, Goette, & Meier, 2013; Parsons & Bynner, 2005; Reyna, Nelson, Han, & Dieckmann, 2009). Therefore, much interest has been devoted to early numerical predictors of mathematical competence. For instance, recent meta-analyses have convincingly demonstrated that symbolic magnitude comparison, as indexed by efficiently choosing the larger between two Arabic digits, is one of the best predictors of mathematical achievement (Schneider et al., 2016; Schwenk et al., 2017).

Symbolic number ordering is another numerical skill that has been related to mathematical achievement already 30 years ago (LeFevre & Bisanz, 1986). Renewed interest in symbolic number ordering has emerged following some recent studies, which have shown that number ordering is a stronger predictor of mathematical competence than symbolic number comparison in children from second grade onwards (Lyons, Price, Vaessen, Blomert, & Ansari, 2014; Sasanguie & Vos, 2018) and in adults (Sasanguie, Lyons, De Smedt, & Reynvoet, 2017). Accordingly, several other studies have demonstrated the relationship between symbolic ordering skills and the performance on a mathematical test (Attout & Majerus, 2017; Goffin & Ansari, 2016; Lyons et al., 2014; Lyons & Ansari, 2015; Lyons & Beilock, 2011, 2013; Morsanyi, Mahony, & Mccormack, 2016; Morsanyi, van Bers, O'Connor, & McCormack, 2018; Rubinsten & Sury, 2011; Sasanguie & Vos, 2018; Vogel et al., 2017; Vogel, Remark, & Ansari, 2014; Vos, Sasanguie, Gevers, & Reynvoet, 2017). Moreover, it has been shown that children and adults with dyscalculia perform worse on a symbolic ordering task when compared with controls (Attout & Majerus, 2014; De Visscher, Szmalec, Van Der Linden, & Noël, 2015; Kaufmann, Vogel, Starke, Kremser, & Schocke, 2009; Morsanyi et al., 2018; Rubinsten & Sury, 2011).

In a typical symbolic number ordering task, participants judge whether three horizontally presented digits are in (ascending) order or not (e.g., 1-2-3 versus 2-1-3). A signature of ordinal processing is the reversed distance effect (RDE), whereby responses are faster for close (e.g., 1-2-3) compared to far apart digits (e.g., 1-3-5; Goffin & Ansari, 2016; Lyons & Ansari, 2015; Lyons & Beilock, 2013; Morsanyi et al., 2016; Sasanguie et al., 2017). The RDE presents an opposite pattern compared to the standard numerical distance effect observed in the digit comparison task, whereby responses are faster for far (e.g., 2-9) compared to close digits (e.g., 8-9; Moyer & Landauer, 1967), as a reflection of the overlap of activation between close numbers on the

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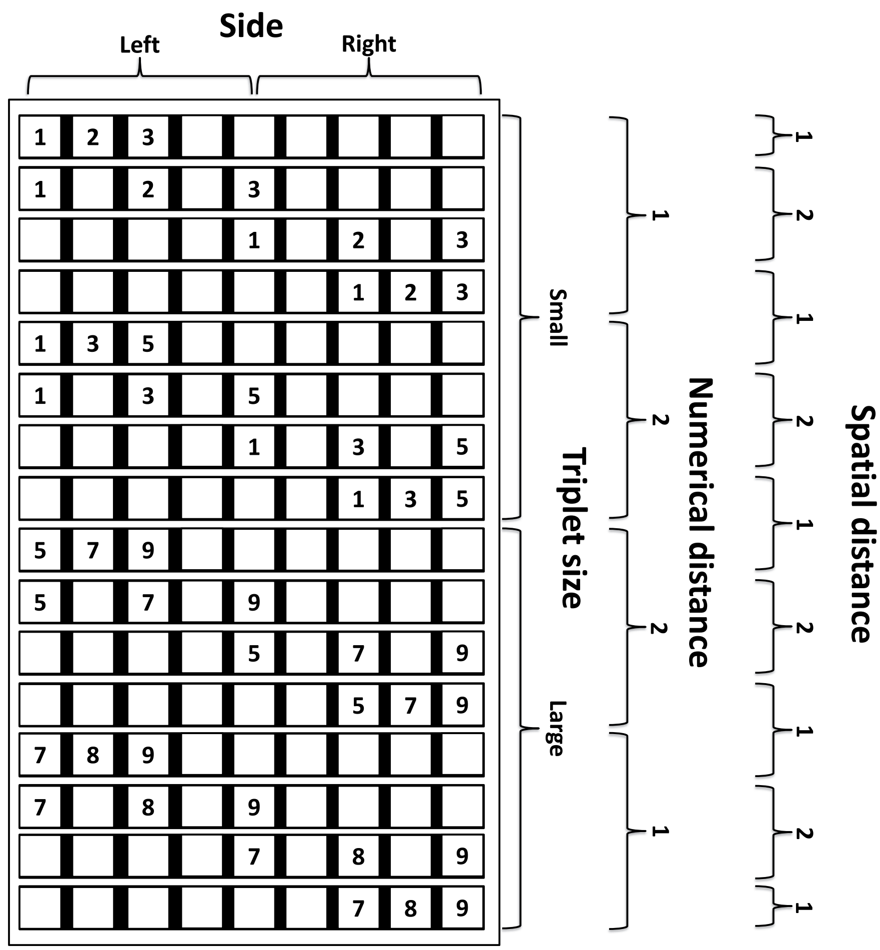


**Fig. 1.** The 16 combinations presented in the Visuospatial Order task categorised according to side of presentation [Left, Right], size of triplet [Small, Large], numerical distance between the three digits [1, 2], and spatial distance between the three digits [1, 2].

mental number line (Dehaene, 2003; Feigenson, Dehaene, & Spelke, 2004). For non-ordered sequences (e.g. 1-3-2 versus 1-5-3), however, the standard distance effect is observed. Results have shown that is easier to indicate that a sequence is not presented in order when the distance between digits is larger (Lyons & Beilock, 2009; Lyons & Beilock, 2013; Morsanyi et al., 2016; Vogel et al., 2017). Several researchers suggested that individuals perform a double comparison when processing non-ordered series (Lyons & Beilock, 2013; Vos et al., 2017). That is, the first digit is compared to the second and then the second is compared to the third digit in the sequence (e.g. processing the sequence 1–3-2 results in separate comparisons of 1-3 and 3-2). The standard distance effect then emerges from the comparison of digits, which implies accessing their corresponding numerical magnitude representation. In the case of ordered sequences, instead, the reversed distance effect indicates that a different strategy is conducted for judging ordered ascending trials.

One possible explanation states that ordered small distance sequences are retrieved from long-term memory (Caplan, 2015; LeFevre & Bisanz, 1986). In line with associative chaining models (e.g., Serra & Nairne, 2000), inter-item associations can be formed between neighbouring items (e.g., between "one" and "two", between "two" and "three"…). In these chains, each item serves as a trigger for the next (or previous) item in the sequence (e.g., 2 triggers 3; Serra & Nairne, 2000). Abrahamse, van Dijck, Majerus, and Fias (2014) suggested that chains emerge especially when items have to be retained and stored for a longer time, which is the case for sequences of digits. Similarly, items which often co-occur in language will have stronger inter-item associations and as a consequence trigger the neighbouring items even more (Serra & Nairne, 2000). Vos et al. (2017) suggested that these chaining based mechanisms may be involved when participants make decisions about the order of digits. Consecutive sequences, such as 1-2-3, have a higher co-occurrence in everyday language than other non-consecutive sequences, such as 1-3-5, and therefore stronger associations might exist between these consecutive items, resulting in faster reaction times observed for small distance trials. These chaining mechanisms can also account for the fact that the highest correlation between performance on the ordinal judgment task and arithmetic fluency, another heavily memory-based process (DeStefano & LeFevre, 2004; Hitch, 1978; McLean & Hitch, 1999; Passolunghi & Siegel, 2001), was observed for consecutive triplets of digits (Lyons et al., 2014). Both the verification of correctly ordered small distance sequences and arithmetic fluency might address the same process, namely retrieving sequence knowledge ("1 2 3" and "2 times 3 is 6").

Alternatively, the processing of ordered numerical sequences might prompt participants to process the ordinal information as part of the mental number line (MNL; Dehaene, 1992). According to the logarithmic model of the MNL (Dehaene, 2003; Feigenson et al., 2004; Piazza, 2010), each numerosity is represented as Gaussian distribution of activation on a compressed number line with increasing overlap between the number representations for larger numerosities and in which numbers are spatially arranged with increasing magnitude from left to right, at least in Western cultures (for a review of cross-cultural studies see Gobel, Shaki, & Fischer, 2011). The MNL entails specific effects that are associated with the numerical representation of symbolic numbers. As described above, indicating the larger between two close numbers takes more time as their internal representations largely

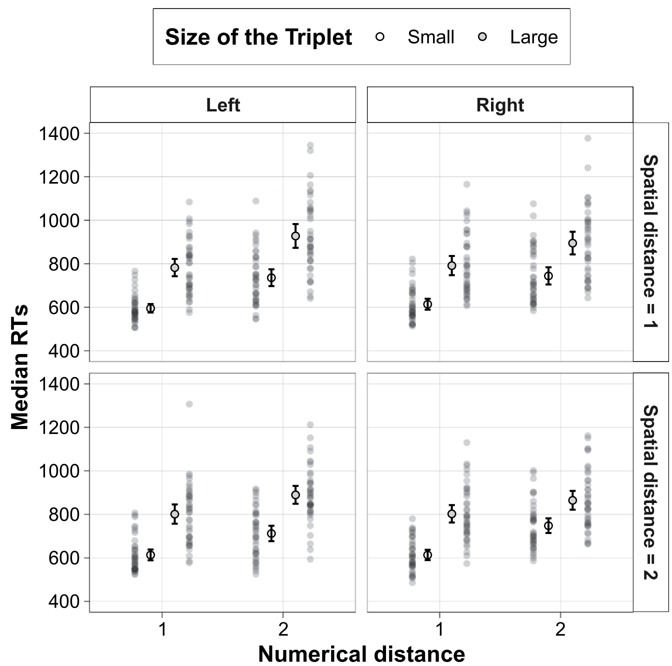


**Fig. 2.** Mean of median RTs (y-axis) as a function of size of the triplet [Small = white dots, Large = grey dots], side of presentation [Left = left panels, Right = right panels], spatial distance between digits [1 = top panels, 2 = bottom panels], and numerical distance (x-axis). Error bars represent 95%CI whereas the transparent dots on the side are individual median RTs.

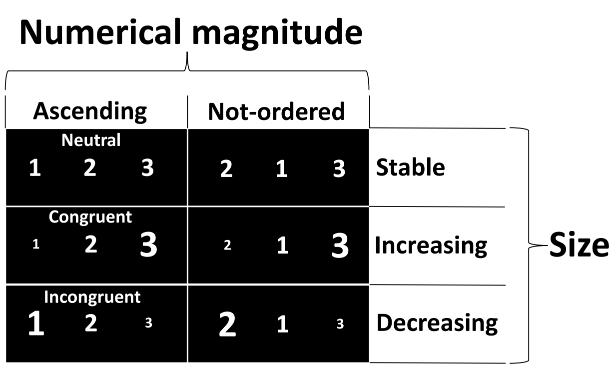


**Fig. 3.** Example of a trial in the Ordinal Size Congruity task. The three digits were presented in ascending numerical order or in a not-ordered combination. Within the number conditions, the size of the three digits was stable, increasing or decreasing. A trial was neutral in case of ascending numerical magnitude and stable size, congruent in case of ascending numerical magnitude and increasing size, incongruent in the case of ascending numerical magnitude but decreasing size.

overlap on the number line (i.e., distance effect). The overlap also increases with increasing numerical magnitude as a consequence of the logarithmic compression (i.e. size effect). In addition, small numbers are associated with the left side of the space and large numbers with the right side of the space (i.e., Spatial Numerical Association Response Codes; SNARC effect; Dehaene, Bossini, & Giraux, 1993). It has also been argued that other than numerical magnitude dimensions are represented on the MNL (Dormal & Pesenti, 2012; Walsh, 2003), leading to different types of number-magnitude congruency effects, of which the number-size congruency effect, i.e., the finding that numerical decisions are easier when the numerical largest number is also the physical largest stimulus (e.g., (e.g., 2 8)) than the other way around (e.g., 2 8 ), is the most well-known (Cohen Kadosh et al., 2007, 2005; Cohen Kadosh & Henik, 2006; Henik & Tzelgov, 1982). Ordinal information could also be represented on the MNL and, as a consequence, be characterised by the above-mentioned effects. For example, it has been proposed that when deciding whether a sequence is correctly ordered or not, the number line is scanned for the digits that are part of the presented sequence (Franklin & Jonides, 2009; Turconi, Campbell, & Seron, 2006). In this light, the RDE effect emerges as a consequence of the fact that small distance sequences (e.g. 1-2-3) only require three items to be scanned, whereas for large distance sequences (e.g. 1-3-5) more items have to be scanned, resulting in faster reaction times for smaller distance sequences. Another evidence that ordinal information may be spatially arranged comes from studies by Gevers and colleagues (Gevers, Reynvoet, & Fias, 2003, 2004), who showed that individuals responded faster with their left hand to items that come earlier in an ordinal sequence (e.g., months, days of the week, numbers and letters) and faster with their right hand to items that come later in the sequence. Such SNARC-like effects suggest that ordinal processing might resemble the spatial connotation of the MNL. Finally, the congruency between physical and numerical order (e.g., (e.g., 1-2-3)) makes participants faster in judging whether three digits have increasing physical size compared to incongruent conditions (e.g., (e.g., 1-3-2;; see Vogel et al., 2019), thereby suggesting a possible interaction between numerical and non-numerical ordinal processing.

In this paper, we present two experiments aiming to unravel symbolic number ordering processing in adult participants. Specifically, we verified whether symbolic number order processing reveals the effects that are usually associated with the MNL. In Experiment 1, participants judged whether three digits were in ascending order while different dimensions were manipulated: the numerical distance between digits (i.e., 1 or 2 units), the spatial distance between digits (i.e., 1 or 2 positions apart; [1][2][3], [1][ ][2][ ][3]), the size of the triplet (i.e., small or large; 1-2-3 and 1-3-5 vs 5-7-9 and 7-8-9), and the side of presentation (i.e., left or right). We predict faster responses when the numerical distance was 1 (i.e., consecutive digits) compared to 2 (i.e., non-consecutive) as an index of the RDE. Responses should be faster in case of spatial distance 1 compared to 2 as participants have less space to scan within the number line. However, the spatial distance might interact with the numerical distance, resulting in faster reaction times when spatial and numerical distance are congruent (e.g., [1][2][3] and [1][ ][3][ ][5]) compared to incongruent (e.g., [1][3][5] and [1][ ][2][ ][3]). Responses should also be faster when small triplets are presented on the left side of the screen compared to the right side whereas responses should be faster when large triplets are presented on the right side compared to the left side, in a SNARC-like effect. Finally, responses should be faster for small compared to large triplets according to the compression of the MNL (i.e., size effect).

In Experiment 2, we verified whether ordinal processing is influenced by another magnitude dimension, namely the physical size of the digits. Again, participants indicated whether three presented digits were in order while the physical size of the digit was manipulated in three conditions: stable (e.g., 1-2-3), congruent (e.g., (e.g., 1-2-3)), and incongruent (e.g., (e.g., 1-2-3)). In case of the influence of the physical non-numerical dimension, we expected faster responses in the congruent condition compared to the incongruent condition. Additionally, we presented all possible consecutive triplets ranging from 1 to 9 (from 1-2-3 to 7-8-9), enabling us to assess the size effect similarly as in Experiment 1. In case of a size effect, response times should gradually decrease with increasing numerical size of the triplet.

## 2. Experiment 1

### *2.1. Participants, procedure and apparatus*

Forty-seven undergraduates took part in the study after they gave their informed consent. Due to an error, we collected age of 36 participants ($M$ = 18.8, range: 18–21) and sex of 38 participants (11 males). Participants were seated individually in dimly lit cubicles to perform

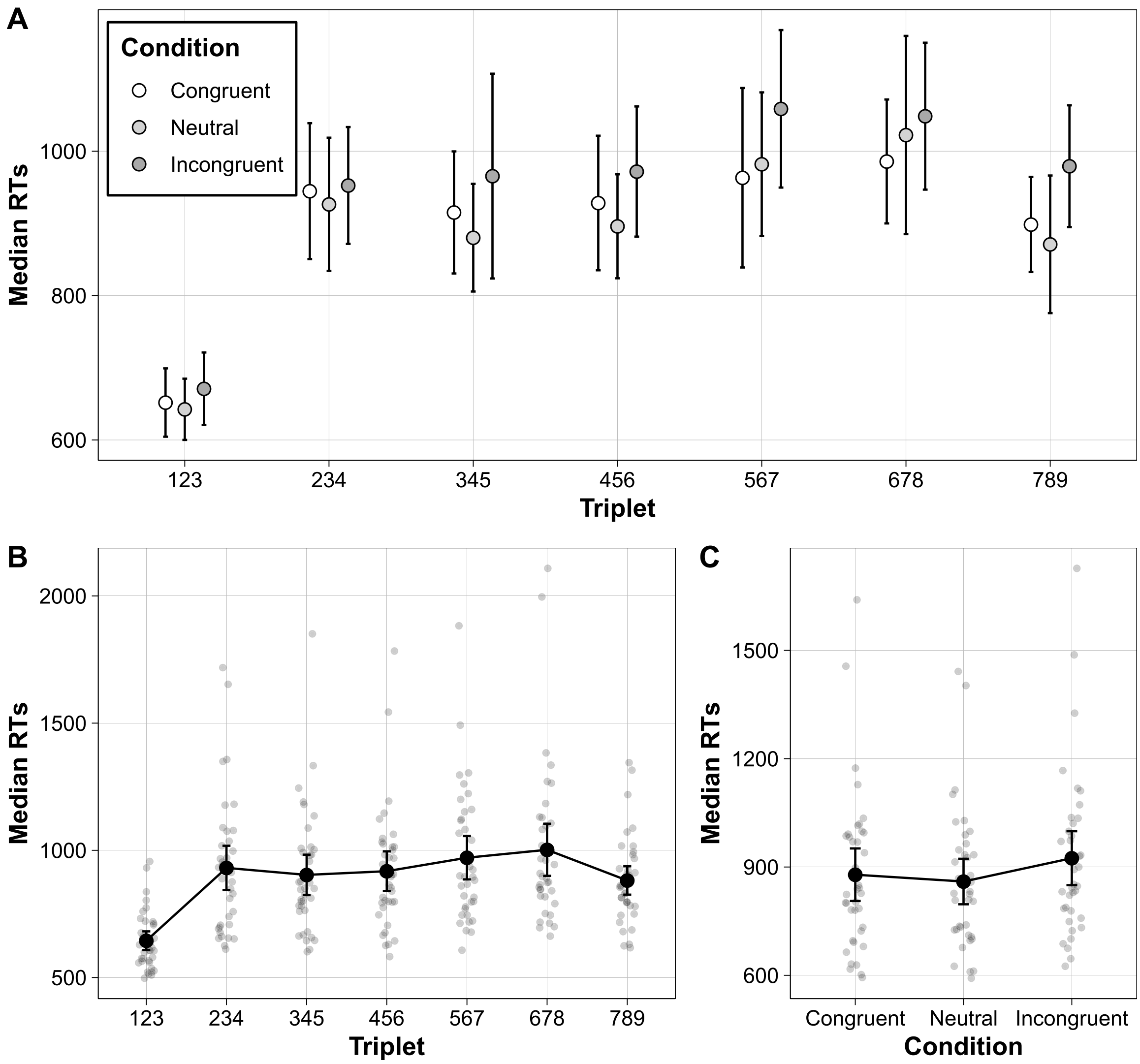


**Fig. 4.** A) Mean of median RTs (y-axis) as a function of triplets (x-axis) separately for congruent (white dots), neutral (light grey), and incongruent (dark grey) condition. B) Mean of median RTs (y-axis) separately for each triplet (x-axis). C) B) Mean of median RTs (y-axis) separately congruent, neutral, and incongruent trials (x-axis). Error bars represent 95%CIs, whereas the transparent dots are individual median RTs.

the experimental task. Stimuli were presented on a 17-inch. monitor (60 Hz, spatial resolution = 1280 × 1024) located approximately 75 cm from the subject. Stimulus presentation and response registration were controlled by *E*-Prime 2.0 (Psychology Software Tools, Pittsburgh, PA). Data of six participants were removed because they performed at chance level (see the Results section for more details). This study was approved by the Ethical Committee of the KU Leuven (G-2017 10,951).

### 2.2. Visuospatial order task

Three digits were presented inside three of nine white boxes, which were horizontally aligned in the centre of the computer screen. Four dimensions were manipulated: side of triplet [left, right]; size of triplet [small, large], numerical distance between digits [1, 2], and spatial distance between digits [1, 2]. Fig. 1 illustrates the sixteen combinations of the four manipulated dimensions for the selected triplets of digits (i.e., 1-2-3, 1-3-5, 5-7-9, and 7-8-9). For each combination, a triplet was presented 10 times in ascending order (e.g., 1-2-3), 8 times in all possible not-ordered combinations (e.g., 3-1-2) and twice in descending order (e.g., 3-2-1). Consequently, there were 160 trials with triplets in ascending order, and 160 trials with triplets not in order or in descending order. To avoid congruency between stimulus presentation on the screen and responses, participants were instructed to immediately press the spacebar with both index fingers only when triplets were in ascending order. There were eight practice trials in which different triplets were presented (i.e., 3-4-5 and 4-6-8) and feedback was provided. In each trial, the nine white boxes were shown for 500 ms, then the triplet of digits was displayed for 1500 ms or until the spacebar was pressed. Afterwards, nine hashtags appeared inside the nine white boxes for 500 msec. Participants could take a short break every 80 trials.

### 2.3. Results

We ran statistical analyses using the free software R (R Core Team, 2016) along with the BayesFactor package (Morey & Rouder, 2015) using default priors for Bayesian analyses. We report Bayes factors ($BF_{10}$) expressing the probability of the data given H1 relative to H0 (i.e., values larger than 1 are in favour of H1 whereas values smaller than 1 are in favour of H0). When comparing regression models, we report the Bayes factors (BF) as the ratio of $BFs_{10}$ between compared models. If the ratio between $BF_{10}$ of model A and $BF_{10}$ of model B is higher larger than 1, then there is evidence for model A. Conversely, if the ratio is smaller than one there is evidence for model B. We describe

**Table 1**
$BF_{10}$ for the pairwise comparisons of median RTs of all triplets.

| Comparison | $BF_{10}$ |
|---|---|
| 123 vs 234 | $3.4 \times 10^7$ |
| 123 vs 345 | $3.3 \times 10^7$ |
| 123 vs 456 | $1.1 \times 10^8$ |
| 123 vs 567 | $3.3 \times 10^9$ |
| 123 vs 678 | $2.7 \times 10^7$ |
| 123 vs 789 | $5.6 \times 10^9$ |
| 234 vs 345 | 0.35 |
| 234 vs 456 | 0.21 |
| 234 vs 567 | 0.99 |
| 234 vs 678 | 2.5 |
| 234 vs 789 | 0.87 |
| 345 vs 456 | 0.21 |
| 345 vs 567 | 5.8 |
| 345 vs 678 | 47 |
| 345 vs 789 | 0.24 |
| 456 vs 567 | 3.6 |
| 456 vs 678 | 14 |
| 456 vs 789 | 0.51 |
| 567 vs 678 | 0.3 |
| 567 vs 789 | 20 |
| 678 vs 789 | 20 |

the evidence associated with BFs as "anecdotal" ($1/3 < BF < 3$), "moderate" ($BF < 1/3$ or $BF > 3$), "strong" ($BF < 1/10$ or $BF > 10$), "very strong" ($BF < 1/30$ or $BF > 30$), and "extreme" ($BF < 1/100$ or $BF > 100$) (Jeffreys, 1961). The raw data and R code of the analyses of Experiment 1 and 2 can be found on the Open Science Framework (https://osf.io/79cve/?view_only=c0233b53f53940c388b54bf2b0c0c48b).

We restricted our analysis only to those trials in which the three digits were in ascending order (160 trials) and, therefore, participants had to respond by pressing the spacebar. We removed six participants who responded below the chance level (i.e., at least 91 trials out of 160 according to a $p$-value < .05 of the binomial distribution). We removed 4% of the trials with missed responses, and 3 trials in which the response time (RT) was below 200 ms. Then, for each participant, we calculated the median RTs in each condition (Fig. 2). We analysed the median RTs in a Bayesian repeated measures ANOVA with side [Left, Right], size of the triplet [Small, Large], numerical distance [1, 2], and spatial distance [1, 2] as within-subjects variables (Fig. 2).[1] The model including the main effects of size of triplet and numerical distance and the interaction between size of the triplet and numerical distance yielded the highest evidence ($BF_{10} = 2.2 \times 10^{132}$). However, there was anecdotal evidence ($BF = 1.03$) for its superiority compared to a more parsimonious model including the main effects of size of triplet and numerical distance ($BF_{10} = 2.1 \times 10^{132}$). Participants were faster in determining the ascending order of small triplets compared to large ones and faster when the numerical distance between digits was one (i.e., consecutive digits) compared to two.

### 2.4. Discussion

In Experiment 1, participants had to determine whether three digits were in ascending order or not. We manipulated the numerical and the spatial distance between the three digits, the size of the triplet and the side of presentation to investigate whether number order processing reveals the effects such as spatial-numerical congruency effects and size effects that are typically associated with the MNL. Participants were faster in responding when the numerical distance between the digits was 1 compared to 2, thereby replicating the reversed distance effect (Lyons & Beilock, 2013; Morsanyi et al., 2016; Vogel et al., 2017; Vos et al., 2017). We found no evidence for a spatial-numerical congruency effect. No effect of the side of presentation (SNARC-like), nor from spatial distance between the digits was observed. Participants were faster though in responding to small compared to large triplets of digits, as in agreement with the size effect, an indicator of access to the compressed MNL. In Experiment 2 we aim to explore this size effect in more detail: in Experiment 1, the difference between trials 1-2-3 and 1-3-5 compared to 5-7-9 and 7-8-9 was used as a crude indicator of the size effect. Moreover, the observed difference between small and large triplets could also stem from a faster recognition of highly familiar sequences (i.e., 1-2-3): the sequence 1-2-3 is indeed presented much more frequently in daily life than the sequence 7-8-9. In this vein, the size effect and familiarity effect are confounded as they both predict faster reaction times for small familiar sequences. Therefore, in Experiment 2, all ascending consecutive triplets between 1 and 9 (i.e., 1-2-3, 2-3-4…7-8-9) were presented. If the difference observed in Experiment 1 is caused by the logarithmic compression of the MNL, a linear increase in reaction times should be observed with increasing magnitude. By contrast, if the difference between 1-2-3 and 7-8-9 is caused by familiarity, the effect of magnitude should be most pronounced for sequence 1-2-3 compared to all other sequences. In addition to a more fine-grained analysis of the size effect, we also verified whether order processing interacts with other magnitudes dimensions (i.e., physical size). More specifically, participants decided whether three digits are in ascending order or not while also the physical size (increasing, decreasing or stable) of the sequence was manipulated.

## 3. Experiment 2

### 3.1. Participants, procedure and apparatus

Thirty-eight undergraduates (11 males, $M_{age} = 18.7$ years, range, 18–21) took part in the study after they gave their informed consent. Participants were seated individually in dimly lit cubicles to perform the experimental task. Stimuli were presented on a 17-in. monitor (60 Hz, spatial resolution = 1280 × 1024) located approximately 75 cm from the subject. Stimulus presentation and response registration were controlled by *E*-Prime 2.0 (Psychology Software Tools, Pittsburgh, PA). This study was approved by the Ethical Committee of the KU Leuven (G-2017 10,951).

### 3.2. Ordinal size congruity task

We presented three digits horizontally in the middle of the computer screen (Fig. 3). Participants indicated whether the three digits were in ascending order (e.g., 1-2-3) or not by pressing the "a" and "p" key on an AZERTY keyboard. There were seven triplets (i.e., 1-2-3, 2-3-4, 3-4-5, 4-5-6, 5-6-7, 6-7-8, and 7-8-9), which were arranged in ascending order (e.g., 1-2-3) or in four possible not-ordered not-descending combinations (e.g., 3-1-2, 2-3-1, 2-1-3, 1-3-2). We also manipulated the size of the digits, which was increasing from left-to-right (e.g., (e.g., 1-2-3)), stable (e.g., 1-2-3), or decreasing from left-to-right (e.g., (e.g., 1-2-3)). Each triplet was presented 24 times, half of the time in ascending order and the other half as not-ordered. Within the ascending and not-ordered condition, the three digits were increasing, stable, and decreasing in size in one-third of the trials, respectively.

### 3.3. Results

We restricted our analysis only to those trials in which the three digits were in ascending order (84 trials). All participants performed above the chance level (i.e., at least 51 trials out of 84 according to a $p$-value < .05 of the binomial distribution). We removed 5% of the trials with wrong responses. Then, for each participant, we calculated the median RTs for each triplet in case of neutral (i.e. ascending numerical magnitude and stable size), congruent (i.e. ascending numerical

[1] We reported a table with $BFs_{10}$ for all the possible models on the OSF.

magnitude and increasing size), and incongruent trials (i.e. ascending numerical magnitude but decreasing size). We analysed the median RTs in a Bayesian repeated measures ANOVA with triplet [1-2-3, 2-3-4, 3-4-5, 4-5-6, 5-6-7, 6-7-8, 7-8-9], and condition [Neutral, Congruent, Incongruent] as within-subject factors (Fig. 4a). The model with the two main effects provided the highest evidence ($BF_{10} = 4.1 \times 10^{48}$). We ran a series of Bayesian *t*-tests to perform pairwise comparisons of the median RTs between all triplets. Participants responded consistently faster to the triplet 1–2-3 compared to all the remaining triplets (Fig. 4b and Table 1). Participants were faster in responding to neutral than to incongruent trials ($BF_{10} = 1160$; Fig. 4c), and to congruent compared to incongruent trials ($BF_{10} = 8.77$, moderate evidence), whereas similar response times were observed for neutral and congruent trials ($BF_{10} = 0.39$).

### 3.4. Discussion

In Experiment 2, participants indicated whether three digits were in order or not, while the size of the digits was manipulated so that it could be stable, increasing from left-to-right or decreasing from left-to-right. Response times did not increase with numerical magnitude, as one would expect in case of a size effect, but were faster only for the triplet 1-2-3 compared to all other triplets. This indicates that faster reaction times for 1-2-3 (in both Experiments) are probably driven by faster recognition of a highly familiar sequence and are not caused by characteristics (i.e., compression) of the MNL. There was also only moderate evidence for an effect of ordinal size congruity, with participants responding slower in case of incongruent trials compared to congruent trials. At first sight, this finding is in contrast with a recent study of Vogel et al. (2019), who did demonstrate an interaction between numerical and physical order in an ordinal judgment task. However, in that study, participants had to decide whether the physical size was in order (numerical size was irrelevant for the task), whereas here the opposite instructions were given, i.e., is the numerical size in order. It is possible that this asymmetry has caused these different results: when ordinal decisions about physical size have to be made, as in Vogel et al. (2019), participants are obliged to rely on a magnitude based dimension on which also numerical size can be represented, causing the interaction. When, in contrast, decisions on numerical order have to be made, we believe that alternative verbal memory retrieval processes may be at play (Vos et al., 2017), certainly for the sequences presented here. We will elaborate on this more in our general discussion.

## 4. General discussion

The aim of this contribution was to get more insight into the underlying processes of symbolic number ordering processing in adult participants. More specifically, we examined in two experiments whether symbolic number order processing relies on magnitude processing by verifying whether the effects that are usually associated with the MNL, i.e., a size effect, spatial-numerical congruency effect and a size congruity effect, also show up in order processing. Our results showed no evidence for a size effect, nor for spatial-numerical associations neither from the manipulation of spatial distance between the digits, nor from side of presentation. In addition, only moderate evidence was obtained for an ordinal size congruity effect. In sum, evidence for the involvement of the MNL in order processing is not convincing. As a consequence, we can conclude that ordinal judgements are not based on the mental number line.

Although only limited evidence for the involvement of the MNL was found, we observed two robust effects that are in line with a long-term memory account for order processing (Caplan, 2015; LeFevre & Bisanz, 1986): First, we replicated the RDE in Experiment 1, whereby responses are faster in the case of close (e.g., 1-2-3) compared to far apart digits (e.g., 1-3-5). Second, in Experiment 2 we observed that 1-2-3 is processed significantly faster than all other consecutive sequences (2-3-4, 3-4-5…). Consecutive sequences have higher co-occurrence in everyday language than other non-consecutive sequences resulting in better storage and faster recognition of these items. The sequence 1-2-3 is by far the most frequently encountered one in everyday language, explaining the faster recognition in Experiment 2 compared to other consecutive sequences. Such a long-term memory explanation is in line with findings from LeFevre and Bisanz (1986) who observed that ordinal judgements were better for consecutive sequences such as 4-5-6, but also for non-consecutive ones that were highly familiar such as counting by fives: 5-10-15. A memory explanation was also proposed by Vos et al. (2017) who contrasted the performance on ascending sequences (e.g., 1-2-3; 1-3-5) and descending sequences (e.g., 3-2-1; 5-3-1) and observed a larger reversed distance effect in ascending than in descending trials, which they ascribed to a more rapid retrieval for ascending sequences due to their larger familiarity as a consequence of their higher occurrence. We also observed faster reaction times for the triplet 7-8-9 compared to the two nearby triplets, which additionally excludes the presence of a size effect. There might be, instead, evidence for an "end effect", whereby the number 7-8-9 has a special status as it is quickly recognised as the final part of the ordered sequence from 1 to 9. However, the pattern of reaction times casts some doubts on the presence of a genuine "end effect" as the reaction times for 7-8-9 were different from 5 to 6-7 and 6-7-8 but similar to the remaining smaller triplets, except 1-2-3.

We should note that both experiments focused on small ascending ordered sequences (e.g. is 1-2-3 in order?). The focus on these type of trials was motivated by the observation that performance on these trials is the best predictor for arithmetic (Lyons et al., 2014; Lyons & Ansari, 2015). We do not exclude that characteristics of the MNL could be observed when decisions on non-ordered sequences (e.g., 1-5-3) would be analysed. In fact, Vos et al. (2018) already argued that for those non-ordered trials, decisions are based on magnitude because such non-ordered sequences are not stored in memory. As a consequence, performance on such trials might exhibit effects that are typically associated with the MNL. The take-home message of this contribution is that ordering decisions of small ascending sequences are based on efficient retrieval from (verbal) long term memory. Because performance on these trials explains the most variance in arithmetic performance, the relation between order judgements and arithmetic is probably due to the fact that both heavily rely on retrieval processes (see Sasanguie & Vos, 2018, for a similar reasoning why order processing becomes increasingly predictive for arithmetic fluency only from second grade onwards). In this vein, the retrieval of sequences from long-term memory is a process that is shared by both the number ordering and arithmetic fluency. This process appears to be mostly domain-general, rather than domain-specific, as several studies have already demonstrated that also the ordering of non-numerical sequences is related to arithmetic (O'Connor, Morsanyi, & McCormack, 2018;Sasanguie et al., 2017; Vos et al., 2017). However, there is evidence for a domain-specific component as well, because the number ordering explains additional variance in arithmetic over and above the ordering of non-numerical sequences (Sasanguie et al., 2017; Vos et al., 2017).

## Declaration of competing interest

The authors declare no conflict of interest.

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