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**The role of general and number-specific order processing in adults' arithmetic
performance**

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Abstract

Digit order processing is highly related to individual differences in arithmetic performance. To examine whether serial scanning or associative mechanisms underlie order processing, order tasks (i.e., deciding whether three digits were presented in an order or not) were administered in two experiments. In the first experiment, digits were presented in different directions namely ascending, descending and non-ordered. For each direction, close and far distance sequences were presented. Results revealed reversed distance effects for ordered sequences, but ascending sequences elicited faster performance and stronger reversed distance effects than descending sequences, suggesting that associative mechanisms underlie order processing. In the second experiment, it was examined to which extent the relation between order processing and arithmetic is number-specific by presenting order tasks with digits, letters and months. In all order tasks similar distance effects were observed and similar relations with arithmetic were found, suggesting that both general associative mechanisms and number-specific mechanisms contribute to arithmetic.

Keywords: Order processing, Arithmetic, Associations, Serial scanning

Introduction

Numerical symbols make it possible to engage in numerical operations in various contexts, from daily operations like computing the amount of food that needs to be prepared to operations involved in major decisions such as buying a house. Not surprisingly then, efficient processing of numerical symbols has consistently shown to be an important determinant of arithmetic (see De Smedt, Noël, Gilmore, & Ansari, 2013, for a review). The central role of numerical symbols for arithmetic may be a result of two inherent aspects of numbers: cardinality and ordinality (Sury & Rubinsten, 2012). Cardinality refers to the number of elements in a set and is used to indicate numerical quantities (e.g., a football team consists of eleven football players). Ordinality refers to the position of an item in a sequence (e.g., the football team is ranked second) and is used to indicate the relation between numbers.

Cardinality processing is typically studied in digit comparison tasks, where participants need to select the largest (or smallest) of two digits (Castronovo & Göbel, 2012; Holloway & Ansari, 2009; Moyer & Landauer, 1967). The comparison of digits typically results in a distance effect, i.e., the observation that it is easier to compare digits when the numerical distance between them is larger. Generally, the distance effect is explained assuming that digits are represented along a mental number line from small to large with overlapping representations for neighbouring digits making it more difficult to compare digits when the distance between them is small. The distance effect is considered to be an indicator of how precisely the numerical value of the digit is represented (Dehaene, 2003). Arithmetic has been shown to be related to the performance on a digit comparison task. More specifically, faster performance on the digit comparison task is related to higher scores on mathematics tests (Holloway & Ansari, 2009; Sasanguie, De Smedt, Defever, & Reynvoet, 2011; Sasanguie, Van den Bussche, & Reynvoet, 2012; for a meta-analysis, see Schneider et al., 2016).

Until recently the literature about the relation between ordinality and arithmetic has been sparse, but in the past few years there has been a growing interest in the role of order processing in arithmetic. Initially, studies on order processing mostly presented pairs of digits that had to be classified as ascending or descending (Turconi, Campbell, & Seron, 2006), or a digit had to be classified as coming before or after 15 (Turconi, Jemel, Rossion, & Seron, 2004). Even though these studies have suggested distinct processing mechanisms for cardinality and ordinality, it cannot be excluded that when judging the order of pairs a decision is made on the basis of cardinal processing (e.g., 5 is larger than 4). To reduce the possibility that participants are relying on cardinality, recent studies on order processing used an order task consisting of three or more items. The instruction in the order task is typically to classify a sequence as ordered or non-ordered (Kaufmann, Vogel, Starke, Kremser, & Schocke, 2009; Lyons & Beilock, 2011; Franklin & Jonides, 2008; Franklin, Jonides, & Smith, 2009; Fullbright, Manson, Skudlarski, Lacadie, & Gore, 2003; Rubinsten & Sury, 2011). Presenting three or more items puts emphasis on the ordinal relationship among items in a sequence (Sury & Rubinsten, 2012). Using such tasks, the ability to efficiently process order information has been shown to be strongly related to arithmetic in adults (Goffin & Ansari, 2016; Lyons & Beilock, 2011). Congruent evidence was obtained using the same approach in developmental contexts. For instance, it has been found that order processing is an important predictor of arithmetic in children (Lyons, Price, Vaessen, Blomert, & Ansari, 2014; Lyons & Ansari, 2015). In line with these findings, it has also been shown that adults and children with developmental dyscalculia show a numerical order processing deficit (Attout & Majerus, 2014; De Visscher, Szmalec, Van Der Linden, & Noël, 2015; Kaufmann et al., 2009; Rubinsten & Sury, 2011). In sum, the processing of ordinal information seems a robust predictor of arithmetic (see Lyons, Vogel, & Ansari, 2016, for a review). Consequently, because the processing of order is such a robust predictor of arithmetic, it is crucial to reveal which mechanisms play a role when processing

different sequences of digits. Studies that used sequences of three or more digits provided interesting insights into the processing mechanisms underlying order processing which can be divided in three lines of research that will be described in more detail below. First, we will review studies that have examined the effect of numerical distance and direction (i.e., ascending, descending or non-ordered) in order tasks and we will outline what these studies suggest about the underlying mechanisms playing a role in this task (Franklin & Jonides, 2008; Lyons & Beilock, 2013; Turconi et al., 2006). Second, we will highlight the contribution of different sequences differing with regard to distance and direction to arithmetic (Lyons & Ansari, 2015). Third, various studies have examined ordered sequences of numerical stimuli and non-numerical stimuli. These studies provided insight into the question whether the mechanisms involved in digit order processing are similar or distinct from order processing of non-numerical sequences (e.g., Franklin et al., 2009; Fullbright et al., 2003; Gevers, Reynvoet, & Fias, 2003).

Numerical distance and direction in order processing

Typically, numerical distance and direction are features that are manipulated in ordering studies. The numerical distance between digits in a sequence can differ, i.e., the distance between digits can be small (e.g., 1-2-3) or large (e.g., 1-5-9). In contrast to the standard distance effect in a digit comparison task (i.e., higher reaction times and lower accuracies when the distance is small), a reversed distance effect is found for the processing of ordered sequences in order tasks: reaction times are faster and accuracies are higher when the distance between the digits of the sequence is small (e.g., 2-3-4) than when the distance is larger (e.g., 1-4-7).

A sequence can also be presented in three directions, i.e., ascending (e.g., 1-2-3), descending (e.g., 3-2-1) or non-ordered (e.g., 1-3-2 or 3-1-2). Most of the studies using

sequences only considered ascending sequences as ordered sequences (Franklin et al., 2009; Kaufmann et al., 2009; Lyons & Ansari, 2015; Lyons & Beilock, 2011), while descending sequences have been often investigated together on one pile with non-ordered sequences. Therefore, it is unclear whether there is a reversed distance effect in descending sequences. However, as both ascending and descending sequences reflect the counting sequence, it can be argued that descending sequences are also a type of ordered sequences.

Based on the findings of studies that examined the performance in these different types of sequences, different mechanisms underlying the processing of ordered sequences have been proposed. One explanation is that ordered sequences are processed by a serial scanning mechanism, suggesting that participants scan the counting sequence item by item to find the digits that are presented in the given sequence (Franklin & Jonides, 2008; Franklin et al., 2009; Turconi et al., 2006; Turconi et al., 2004). Therefore, it takes longer to process sequences with larger distances, because there are more digits to scan before a judgement is made about all the digits. For example, it will take considerably less time to scan the sequence 1-2-3 which requires to scan three items than the sequence 1-5-9 which requires to scan nine items. An alternative explanation states that ordered sequences are processed through associations between the items (e.g., Ebbinghaus, 1964; Caplan, 2015; Lewandowsky & Murdock, 1989). Sequences with a small distance between the items co-occur more often, resulting in stronger associations between these items and faster reaction times. For instance, the sequence 1-2-3 contains digits that co-occur often in language and therefore are strongly associated with one another. In contrast, the digits from the sequence 1-5-9 have weaker associations because they do not co-occur (or only sporadically) in language. Because the associations between the digits are weaker, processing the order of this sequence will require more time.

Note that the reversed distance effect in ascending sequences can be explained by both serial scanning and associations. Participants can respond faster to sequences with a small

distance because they have to scan a smaller distance or because there are stronger associations between the items. However, these explanations can be disentangled when taking descending sequences into account. Viewed from a serial scanning mechanism, the reversed distance effect in descending sequences would be equally large or larger than the reversed distance effect in ascending sequences. If the time needed to scan the counting sequence in forward and backward direction is the same, no differences in reversed distance effects for ascending and descending sequences are expected. Alternatively, if more time is needed to scan the counting sequence in a backward direction, because the backward counting sequence is less practiced, larger reversed distance effects for descending sequences are predicted: the difference between one and two or more serial scanning steps on the counting sequence would be larger in the backward direction. Different results are predicted according to the association explanation. Here, the processing of ascending and descending sequences will differ, because items of ascending sequences co-occur more often and would thus have stronger associations between the items than descending sequences. This would result in shorter processing times for ascending sequences than for descending sequences. Furthermore, because ascending small distance sequences (e.g., 1-2-3) have stronger associations than their parallel descending small distance sequences (e.g., 3-2-1) also more pronounced (reversed) distance effects can be predicted for ascending than for descending sequences.

Order processing and arithmetic

Although several studies have shown that order processing is related to arithmetic (e.g., Goffin & Ansari, 2016; Lyons et al., 2014; Lyons & Beilock, 2011), the underlying processing mechanism remains unclear. One way to unravel the relation between order processing and arithmetic is to examine which aspect of the order task, and its corresponding underlying mechanism, explains additional variance in arithmetic on top of the other types of sequences.

To the best of our knowledge only one study has addressed this issue so far. Lyons and Ansari (2015) administered an order task in children. The instruction was to indicate whether digits were presented in an ascending order or not. Results showed that the evaluation of ascending small distance sequences (e.g., 2-3-4) explained more unique variance in arithmetic than the ascending large distance sequences (e.g. 2-4-6, 1-4-7), non-ordered small distance sequences (e.g. 5-3-4) and non-ordered large distance sequences (e.g. 7-1-4, 6-2-4). However, this study only took into account ascending and non-ordered sequences and considered descending sequences as non-ordered sequences. In the current study, we used both ascending and descending sequences and investigated whether we could confirm in adults that ascending small distance sequences are indeed most related to arithmetic. Based on the findings of Lyons and Ansari (2015), we hypothesized that ascending small distance sequences explain more unique variance in arithmetic compared to ascending large distance sequences, descending sequences and non-ordered sequences.

Domain-specificity of order processing

Previous research has compared digit order processing with other ordered (i.e., non-numerical) sequences, such as letters or months. These studies have reported contradictory results concerning the domain-specificity of order processing. For instance, Franklin et al. (2009) found similar results when a sequence of three numbers or months was presented and participants were instructed to indicate whether the items were presented in a correct order (i.e., ascending order) or incorrect order (i.e., descending or non-ordered). They reported reversed distance effects for both digits and months when sequences crossed the boundary of a decade or a calendar year. In contrast, in a study by Fullbright et al. (2003), participants had to judge whether two digits or two letters were presented in the correct order: different results were observed for both types of stimuli. More specifically, a standard distance effect for digits was

found (i.e., faster performance on pairs where the digits are further apart compared to pairs where the digits are closer together) but no distance effect was observed for letters. Together, this shows that it is unclear whether the digit order processing on the one hand and non-numerical sequences (letters and months) on the other hand are processed similarly (i.e., by the same underlying mechanisms). The current study systematically examined distance and direction in processing sequences of letters and months to understand whether the mechanisms involved in order processing of digits are similar or distinct from order processing of non-numerical sequences. In addition, the relation between arithmetic and processing of sequences of digits, letters and months was investigated to see whether the mechanisms underlying the relation between arithmetic and digit order processing are domain-general or domain-specific. As the literature supports both the domain-general and domain-specific claim about order processing (Franklin et al., 2009; Fullbright et al., 2003; Gevers et al., 2003), we hypothesized that ordered sequences of digits, letters and months are processed similarly and that arithmetic is partially explained by the performance on domain-general order tasks (i.e., with letters and months), but on top of that also by the performance on a domain-specific order task with digits.

The current study

To test the aforementioned hypotheses, two experiments were conducted. In Experiment 1, the influence of distance and direction in digit order processing was investigated. Furthermore, the relation between digit order processing and arithmetic was examined. In Experiment 2, we conducted order processing tasks with digits, letters and months to examine whether the order processing is similar for numerical and non-numerical stimuli. In addition, we examined whether the mechanisms involved in digit order processing which evoke the relation with arithmetic are domain-general or domain-specific.

Experiment 1

Method

Participants

Participants were 72 first-year Psychology students who took part for course requirements. One participant was removed from the analyses because of too many errors ($>3SD$ above the group mean). Consequently, the final sample consisted of 71 adults ($M_{\text{age}} = 18.94$ years; $SD = 3.27$; 64 women). Of these participants, forty-eight participants also took part in a collective testing organized at the beginning of the academic year where arithmetic and processing speed scores were collected. The relation between order processing and arithmetic was only analysed for these 48 participants.

Procedure

The study was approved by the local ethics committee. Participants were tested individually or in small groups of maximum 10 participants depending on the number of sign-ups for a certain session. Participants were informed about the general nature of the procedure followed by the instruction to read and sign the informed consent before starting the experiment. Afterwards, they performed the order task. Arithmetic and processing speed scores were requested from a database of all first-year students who participated in a collective testing organized at the beginning of the academic year.

Measures

Order task. The order task was conducted using 15-inch color screen laptops running the Windows 7 operating system. The experiment was presented by E-prime Professional software, version 2.0 (Psychological Software Tools, Pittsburgh, PA, USA). Each trial started with a fixation cross that was presented for 600 ms. Subsequently, three single digits (range: 1–9)

were simultaneously presented from left to right on the screen for 1000 ms after which a blank screen was presented. Participants had to indicate whether sequences were ordered (either ascending or descending) or not. If all three digits were in an order (ascending or descending), participants were instructed to press the 'a' key on an AZERTY keyboard with their left hand. If the sequence was not presented in an order (e.g., 1-3-2), participants were instructed to press the 'p' key with their right hand. Participants could respond during stimulus presentation or during the blank screen. After their response, an intertrial interval of 1500 ms followed. First, five practice trials were presented and feedback was given to familiarize the participants with the task demands. Next, 168 experimental trials were administered. In half of the trials, the distance between digits of the sequence was small (i.e., 1) and in the other half of the trials the distance between the digits of the sequence was larger than one (i.e., 2, 3 or 4). In addition, a distinction was made between ascending, descending and non-ordered sequences. This resulted in 6 conditions consisting of 28 trials each: ascending small distance trials (e.g., 1-2-3), ascending large distance trials (e.g., 1-3-5), descending small distance trials (e.g., 3-2-1), descending large distance trials (e.g., 5-3-1), non-ordered small distance trials (e.g., 3-1-2) and non-ordered large distance trials (e.g., 5-1-3). The sequences appeared in a random order.

TTR. The Tempo Test Arithmetic (TTR; De Vos, 1992) was used to measure arithmetic. The TTR is a time-limited test consisting of five subtests: addition, subtraction, multiplication, division and one with mixed operations. Each subtest consists of forty items presented in increasing difficulty. Participants got one minute to solve as many problems as possible in a subtest. For each correct item, one point is given.

General processing speed. A processing speed task was used to control for general processing speed. The general processing speed task was presented by Affect version 4.0 (Spruyt,

Clarysse, Vansteenwegen, Baeyens, & Hermans, 2010). The task was similar to the one described by Reigosa-Crespo et al. (2011). A black square was presented at the center of the screen until a response was given and participants were instructed to press the space bar as soon as the square appeared. After the response, the square was removed and followed by an inter-stimulus presentation time varying between 500 and 1500 ms. The test consisted of 20 trials, there were no practice trials.

Results

The effects of Distance and Direction in order processing

Accuracies. Table 1 presents the mean accuracies for each condition. To examine the influence of distance and direction for accuracy data, we conducted a repeated-measures ANOVA with direction (3: ascending, descending, non-ordered) and distance (2: small distance, large distance) as within-subject variables. In the case of violation of the assumption of sphericity, degrees of freedom were corrected using Greenhouse-Geisser estimates. There was no main effect of distance, $F(1, 70) = 0.99, p = .322, \eta_p^2 = .01$. A main effect of direction was found, $F(1.63, 113.91) = 26.58, p < .001, \eta_p^2 = .28$, showing more accurate performance on ascending ($M = .93$) than descending trials ($M = .90$) and non-ordered trials ($M = .84$). An interaction between distance and direction was observed, $F(1.45, 101.81) = 57.16, p < .001, \eta_p^2 = .45$. To further examine this interaction post-hoc tests were conducted for each direction separately. Paired sample t-tests indicated the presence of a reversed distance effect for both ascending and descending trials ($t(70) = 4.29, p < .001, d = 0.51$ and $t(70) = 3.07, p = .003, d = .36$ respectively), but a standard distance effect for non-ordered trials, $t(70) = -9.19, p < .001, d = -1.09$. Furthermore, we calculated the size of the reversed distance effect for ascending and descending trials by subtracting the performance on the small trials from the performance on

the large trials. A paired sample t-test showed no significant difference between the size of the reversed distance effect of ascending and descending trials, $t(70) = -0.55, p = .587, d = -.06$.

Reaction Times. Table 1 presents the median reaction times for correct answers in each condition. Median reaction times were used because they are less sensitive for a skewed distribution (Whelan, 2008). For the reaction time data, the same analyses were conducted as for the accuracy data. There was no main effect of distance, $F(1, 70) = 0.89, p = .348, \eta_p^2 = .01$. A main effect of direction was observed, $F(1.75, 122.34) = 109.27, p < .001, \eta_p^2 = .61$. Paired sample t-tests showed faster performance on ascending ($M = 839.67$) than descending trials ($M = 922.65$) and non-ordered trials ($M = 1050.06$). As for accuracy, an interaction effect between distance and direction was found, $F(1.73, 121.12) = 101.46, p < .001, \eta_p^2 = .59$. Paired sample t-tests demonstrated a reversed distance effect for both ascending and descending trials (respectively $t(70) = -7.71, p < .001, d = -.91$ and $t(70) = -2.06, p = .044, d = -.24$) and a standard distance effect for non-ordered trials, $t(70) = 10.01, p < .001, d = 1.19$. Reversed distance effects were calculated by subtracting the performance on small trials from the performance on large trials. The reversed distance effect was significantly larger for ascending trials (112 ms) than for descending trials (35 ms), $t(70) = 4.53, p < .001, d = .54$.

(INSERT TABLE 1 ABOUT HERE)

(INSERT FIGURE 1 ABOUT HERE)

Order processing and arithmetic

In the sub-sample of participants who also performed the arithmetic test, we investigated the relation between the different types of ordered trials and arithmetic

performance. No significant relation between the TTR and processing speed was found, $r = .02$, $p = .905$ ¹. Therefore, processing speed was not included in the following analysis. We conducted bivariate correlations between the different types of ordered trials and arithmetic (Table 2). All types of trials correlated significantly with the arithmetic scores. The strongest correlation was found with non-ordered large distance trials, $r = -.51$, $p < .001$ and the weakest correlation was found with ascending small distance trials, $r = -.38$, $p < .001$. To test whether there was a difference between the strongest and the weakest correlation, a Hotelling-Williams test was conducted showing no significant difference between the strongest and the weakest correlation, $t(45) = -1.74$, $p = .088$, $d = -.25$.

Similarly to Goffin and Ansari (2016), we also calculated the size of the reversed distance effect to examine whether there was a relation between reversed distance effects and arithmetic. Reversed distance effects were calculated for both accuracies and reaction times by subtracting the performance on the small trials from the performance on the large trials. However, in contrast to the findings of Goffin and Ansari (2016), we did not observe a relation between reversed distance effects and arithmetic. For accuracies, no correlations were found between reversed distance effects of ascending and descending trials and arithmetic (respectively $r = -.18$, $p = .221$ and $r = -.08$, $p = .609$). Similarly, for reaction times no correlations were found between reversed distance effects of ascending and descending trials and arithmetic (respectively $r = -.26$, $p = .073$ and $r = .13$, $p = .385$), although there was a trend towards a significant correlation between ascending trials and arithmetic.

(INSERT TABLE 2 ABOUT HERE)

¹ See also Appendix A for partial correlations between arithmetic scores and median RT on the different type of trials of the order task controlling for processing speed. When controlling for processing speed all the conditions still correlate significantly with arithmetic scores.

Discussion

The aim of Experiment 1 was twofold. First, we systematically investigated the specific influence of distance and direction in processing ordered numerical sequences. As previously discussed, most previous studies investigating order processing have only taken ascending sequences into account as ordered sequences. The reversed distance effect in ascending sequences can be explained by both serial scanning and strong associations between the items in the sequence. By taking into account descending sequences, these two explanations can be disentangled. The influence of direction was examined by presenting sequences in ascending and descending order and the influence of distance was investigated by presenting sequences with a small and large distance between the items. In Experiment 1, ascending sequences were processed more accurately and faster than descending sequences. In addition, the reaction times analysis showed a more pronounced reversed distance effect for ascending sequences. These findings are in concordance with the association explanation: As ascending sequences have stronger associations between the digits, ascending sequences are retrieved more easily from memory, resulting in faster reaction times. Furthermore, this leads to stronger reversed distance effects for ascending sequences compared to descending sequences, because in ascending sequences the difference in associations between close and far digits is larger than in descending sequences (e.g., 1-2-3 and 1-5-9 differ more in associative strength than 3-2-1 and 9-5-1).

Our results further showed that the processing of non-ordered sequences generated a standard distance effect, similar to the distance effect frequently observed in the digit comparison task (e.g., Castronovo & Göbel, 2012). This suggests that participants decide on some of the sequences making use of a comparison strategy. From these results it can be concluded that both association based solution strategies and comparison based solution

strategies are involved in the order judgement task. A solution strategy that can be applied for both ordered and non-ordered sequences might be the comparison strategy. For example, ordered sequences with large distances and non-ordered sequences have both weak associations between the digits (e.g., 1-5-9 or 1-9-5), resulting in a decision based on a comparison of two pairs of digits (i.e. 1-5 and 5-9 respectively). Based on these two comparisons, it is decided whether a sequence is ordered or non-ordered. However, digits, and especially close digits that often co-occur, are also associated with one another. When the associations between digits are strong a decision based on associations will be easier and faster than making a decision based on comparison.

Second, we studied whether certain sequences explain more unique variance in arithmetic. Results showed that all sequences correlated with arithmetic. The strongest correlation was found with non-ordered large distance sequences, but this correlation did not significantly differ from the weakest correlation. These results are in contrast with Lyons and Ansari (2015), who observed that performance on ascending small distance sequences was related the most with arithmetic performance and as a consequence, explained unique variance (above the other conditions) in arithmetic. In that study, however, participants were children. Therefore, developmental differences might explain the different results. Because there are no significant differences between the subconditions and their relation to arithmetic, we will focus on overall reaction times when investigating the relation between order processing and arithmetic in Experiment 2.

To examine the domain-specificity of order processing and its relation with arithmetic, order tasks with digits, letters and months were presented in Experiment 2 in addition to the arithmetic test. Experiment 2 aimed to address two questions: First, Experiment 2 addressed the question, whether the processing of ordered sequences of digits is similar for other ordered sequences. Secondly, Experiment 2 aimed to provide an answer to the question whether the

mechanisms underlying the relation between order processing and arithmetic are domain-general or domain-specific.

Experiment 2

Method

Participants

Participants were 54 volunteers or first-year Psychology students who took part for course requirements. Five participants were removed from the analyses because they performed too slow or made too many errors in one of the tasks ($>3SD$ above the group mean) resulting in a final sample of 49 adults ($M_{\text{age}} = 19.80$ years; $SD = 2.92$; 43 women). For 4 of these participants processing speed scores were logged incorrectly. Therefore, the influence of processing speed on order processing and arithmetic was only analysed for 45 participants.

Procedure

The study was approved by the local ethics committee. Participants were tested individually or in small groups of maximum 10 participants depending on the number of sign-ups for a certain session. Participants were informed about the general nature of the procedure followed by the instruction to read and sign the informed consent. The experimental tasks were conducted using 15-inch color screen laptops running the Windows 7 operating system. The order task and the processing speed task were presented using E-prime Professional software, version 2.0 (Psychological Software Tools, Pittsburgh, PA, USA). Three order tasks were administered: a digit, letter and months order task. The order in which the three tasks were presented was counterbalanced according to a Latin square design (Gravetter & Forzano, 2006). Processing speed scores were collected after the order tasks. Arithmetic scores were requested from a database of all first-year students who participated in a collective testing

organized at the beginning of the academic year. For participants who did not take part in the collective testing session of all first-year students, arithmetic scores were collected afterwards.

Measures

Order tasks. The procedure of the order tasks was similar to Experiment 1. However, in contrast to Experiment 1, the stimuli appeared on the screen until the participants had responded because participants needed more time to process the stimuli in the month order task. In analogy with the digit order task (range: 1-9), letter and month sequences were created by replacing the digits with the corresponding letters of the alphabet (range: A-I) or months of the year (range: January-September).

Results

Because of the large reaction time differences between the order tasks (i.e., the reaction time in the month order task was considerably slower than in the other tasks, see Table 3), the effects of distance and direction were analysed for each task separately. Similar to Experiment 1, we conducted a repeated-measures ANOVA with direction (3 levels: ascending, descending, non-ordered) and distance (2 levels: small distance, large distance) as within-subject variables. Paired-sample t-tests were conducted to further examine standard and reversed distance effects in ascending, descending and non-ordered trials. In the case of violation of the assumption of sphericity, degrees of freedom were corrected using Greenhouse-Geisser estimates.

(INSERT TABLE 3 ABOUT HERE)

(INSERT FIGURE 2 ABOUT HERE)

The effects of Distance and Direction in order processing

Digits.

Accuracies

Results showed a main effect of distance, $F(1, 48) = 9.47, p = .003, \eta_p^2 = .17$. Furthermore, a main effect of direction was found, $F(1.63, 78.10) = 28.28, p < .001, \eta_p^2 = .37$ showing more accurate performance on ascending ($M = .96$) than on descending trials ($M = .94$) and non-ordered trials ($M = .89$). An interaction between distance and direction was observed, $F(1.67, 80.27) = 26.90, p < .001, \eta_p^2 = .36$. Paired sample t-tests for each direction separately demonstrated a marginally significant distance effect for ascending trials, $t(48) = 1.97, p = .055, d = .28$. No distance effect was found for descending trials, $t(48) = .23, p = .819, d = .03$. A standard distance effect for non-ordered trials was observed, $t(48) = -6.43, p < .001, d = -.92$. Reversed distance effects were compared, demonstrating no significant difference between the reversed distance effect of ascending and descending trials, $t(48) = -1.17, p = .246, d = -.16$.

Reaction times

There was no main effect of distance, $F(1, 48) = 0.47, p = .459, \eta_p^2 = .01$. A main effect of direction was found, $F(1.73, 83.13) = 96.45, p < .001, \eta_p^2 = .67$ demonstrating faster performance on ascending ($M = 854.31$) than descending trials ($M = 960.73$) and non-ordered trials ($M = 1103.30$). In addition, distance and direction interacted significantly, $F(1.62, 77.59) = 38.98, p < .001, \eta_p^2 = .45$. Paired-sample t-tests for each direction separately indicated a reversed distance effect for both ascending and descending trials ($t(48) = -4.50, p < .001, d = -.64$ and $t(48) = -2.05, p = .046, d = -.29$), but a standard distance effect for non-ordered trials $t(48) = 5.84, p < .001, d = .83$. Reversed distance effects were calculated by subtracting the performance on small trials from the performance on large trials. The reversed distance effect

was significantly larger in ascending trials (110 ms) than in descending trials (51 ms), $t(48) = 2.88$, $p = .006$, $d = .41$.

Letters

Accuracies

For the accuracy data of the letter task no distance effect was observed, $F(1, 48) = .14$, $p = .709$, $\eta_p^2 = .003$. A main effect of direction was found, $F(1.48, 71.12) = 21.50$, $p < .001$, $\eta_p^2 = .31$ indicating more accurate performance on ascending ($M = .94$) than on descending trials ($M = .84$) and non-ordered trials ($M = .88$). There was a significant interaction between distance and direction, $F(1.62, 77.76) = 11.79$, $p < .001$, $\eta_p^2 = .20$. Paired sample t-tests for each direction separately indicated a reversed distance effect for ascending trials, $t(48) = 2.49$, $p = .016$, $d = .36$. No effect was found for descending trials, $t(48) = .97$, $p = .336$, $d = .14$. A standard distance effect for non-ordered trials was found, $t(48) = -4.38$, $p < .001$, $d = -.63$. Reversed distance effects were compared. No significant difference between the reversed distance effect of ascending and descending trials was found, $t(48) = -.95$, $p = .346$, $d = -.14$.

Reaction times

Analyses for reaction times showed a main effect of distance, $F(1, 48) = 23.71$, $p < .001$, $\eta_p^2 = .33$. A main effect of direction was observed, $F(1.78, 85.44) = 47.17$, $p < .001$, $\eta_p^2 = .50$ demonstrating faster performance on ascending ($M = 1858.82$) than descending trials ($M = 2290.60$) and non-ordered trials ($M = 2363.22$). There was a significant interaction between distance and direction, $F(2, 96) = 29.10$, $p < .001$, $\eta_p^2 = .38$. Paired sample t-tests for each direction separately showed a reversed distance effect for both ascending and descending trials ($t(48) = -7.23$, $p < .001$, $d = -1.03$ and $t(48) = -2.48$, $p = .017$, $d = -.35$) but a standard distance effect was observed for non-ordered trials, $t(48) = 1.56$, $p = .125$, $d = .22$. Reversed distance

effects were calculated by subtracting the performance on small trials from the performance on large trials. For ascending trials the reversed distance effect was 647 ms. For descending trials the reversed distance effect was 197 ms. The reversed distance effects for ascending and descending trials were compared showing a significant difference between the reversed distance effect of ascending and descending trials, $t(48) = 5.12, p < .001, d = .73$.

Months

Accuracies

For the accuracy data of the months task a main effect of distance was observed, $F(1, 48) = 5.06, p = .029, \eta_p^2 = .10$. A main effect of direction was found, $F(1.66, 79.46) = 15.28, p < .001, \eta_p^2 = .24$ resulting in more accurate performance on ascending ($M = .92$) than descending trials ($M = .82$) and non-ordered trials ($M = .89$). An interaction effect between distance and direction was found, $F(1.66, 79.54) = 11.20, p < .001, \eta_p^2 = .19$. Paired-sample t-tests for each direction separately showed a reversed distance effect for both ascending and descending trials ($t(48) = 4.11, p < .001, d = .59$ and $t(48) = 2.84, p = .007, d = .41$) but no effect for non-ordered trials, $t(48) = -1.89, p = .064, d = -.27$. The reversed distance effect for ascending and descending trials was calculated by subtracting the performance on the small trials from the performance on the large trials. Reversed distance effects were compared showing no difference between the reversed distance effect of ascending and descending trials, $t(48) = -0.18, p = .862, d = -.03$.

Reaction times

Regarding the reaction time data, a main effect of distance was found, $F(1, 47) = 25.53, p < .001, \eta_p^2 = .35$. A main effect of direction was observed, $F(1.76, 82.67) = 26.07, p < .001, \eta_p^2 = .36$. Paired sample t-tests revealed faster performance on ascending ($M = 2080.96$) than

descending trials ($M = 2602.64$) and non-ordered trials ($M = 2497.11$). An interaction between distance and direction was observed, $F(1.46, 68.66) = 31.27, p < .001, \eta_p^2 = .40$. Paired sample t-tests for each direction separately indicated a reversed distance effect for both ascending and descending trials ($t(48) = -6.72, p < .001, d = -.96$ and $t(47) = -4.00, p < .001, d = -.58$) but no effect for non-ordered trials, $t(48) = .44, p = .659, d = .06$. Reversed distance effects were calculated by subtracting the performance on small trials from the performance on large trials. For ascending trials the reversed distance effect was 865 ms. For descending trials the reversed distance effect was 472 ms. The reversed distance effect for ascending and descending trials were compared, showing a significant difference between the reversed distance effect of ascending and descending trials, $t(47) = 5.43, p < .001, d = .78$.

Order processing and arithmetic

We examined whether the mechanisms underlying the relationship between order processing and arithmetic are domain-general or domain-specific. No significant correlation between arithmetic scores and processing speed scores was found, $r = -.05, p = .74^2$. Therefore, processing speed was not included in the following analysis. Bivariate correlations between arithmetic scores and the median reaction times on the three order tasks over all the conditions are displayed in Table 4. All the order tasks were negatively correlated with arithmetic indicating that the higher the arithmetic scores, the faster participants could indicate whether digits, letters or months were presented in an order or not. To test whether there was a difference between the different order tasks and the relation with arithmetic, Hotelling-Williams tests were conducted between the different tasks. Between none of the tasks a significant difference was found ($p \geq .221$ in each test).

² See also Appendix B for Partial correlations between arithmetic scores and median RT on the order tasks for digits, letters and months controlling for processing speed. When controlling for processing speed the performance in all the order tasks still correlates significantly with arithmetic scores.

To address whether the relation between order processing and arithmetic is mainly explained by domain-general or domain-specific tasks, we conducted a multiple regression analysis, with digit order, letter order and month order as predictors (Table 5). Collinearity between the tasks imposed no problem, since all the variance inflation factor [VIFs] were ≤ 2.05 and therefore within an acceptable range (Field, 2009). The digit order task, letter order and month order task contributed significantly to arithmetic, $R^2 = .28$.

To investigate the relative contribution of non-numerical and numerical order tasks in the total explained variance in arithmetic, a stepwise hierarchical regression analysis was conducted (Table 6). In a first step, we included the median reaction time on the letter order task and month order task followed by a second step including the median reaction time on the digit order task. The performance on the letter order task and month order task (entered in the first step of the model), explained about 23% of the variance in arithmetic. Including the performance on the digit order task in the second step did not explain unique variance although there was a trend towards significance ($\Delta R^2 = 0.05$, $p = .073$).

(INSERT TABLE 4 ABOUT HERE)

(INSERT TABLE 5 ABOUT HERE)

(INSERT TABLE 6 ABOUT HERE)

Discussion

In Experiment 2, we first examined whether the mechanisms involved in processing sequences of digits can be generalized to non-numerical sequences. The results in the different tasks showed highly similar patterns: First, reversed distance effects were found for ascending and descending sequences with digit, letter and month sequences. Second, descending sequences of letters and months were not only processed slower than ascending sequences, the reversed distance effects were also smaller in the descending sequences. This pattern of results favours the view that not only in digit order tasks, but also in month and letter order tasks at least part of the decisions is based on the strength of the associations between the items which are stronger for ascending and close sequences (e.g., Ebbinghaus, 1964; Caplan, 2015; Lewandowsky & Murdock, 1989). If such associations are absent, like for instance in non-ordered sequences, participants conduct the task based on a comparison strategy resulting in a classic distance effect. At this point, we should mention that a slightly different result was found in the non-ordered sequences of the month order task. In contrast to the digit order and letter order task, no standard distance effect was found when judging non-ordered sequences of months. Although speculative, the lack of a distance effect in the non-ordered sequences of months could be due to the fact that non-ordered sequences of months are represented differently by different participants. Possibly, some participants code months of the year as a circular sequence (Smilek, Callejas, Dixon, & Merikle, 2007). Consequently, a comparison between November and January would be close in distance while with a linear continuum this would be a large distance.

The second aim of Experiment 2 was to investigate whether the mechanisms underlying the relation between arithmetic and order processing are domain-general or domain-specific. Results showed that all order tasks correlated with arithmetic performance and these correlations did not significantly differ. The variance captured by digit order was over and above the variance explained by non-numerical order. However, a hierarchical regression

showed that the contribution in the captured variance is predominantly due to domain-general order processing (23%) and merely a small amount of the total captured variance by order processing is purely numerical (5%).

General Discussion

The main objective of the current study was to gain more insight into order processing and to contribute to a better understanding of the relation between numerical order processing and arithmetic. In Experiment 1, it was demonstrated that different mechanisms play a role in order processing depending on the characteristics of the sequence that is presented. First, ascending and descending ordered sequences showed a reversed distance effect, but the reversed distance effect was larger for ascending sequences. This finding suggest that decisions are based on associative relations between the items of the sequence. These associative relations are caused by co-occurrence in daily-life (e.g., daily language use). Associations are stronger for numerically close digits than numerically far digits (i.e., numerically close digits co-occur more often than far digits) and are stronger for ascending sequences than descending sequences (i.e., forward counting is more frequent than backward counting). Second, a standard distance effect was observed for non-ordered sequences parallel to the distance effect often observed in comparison tasks (Holloway & Ansari, 2009; Moyer & Landauer, 1967). These findings suggest that both associations and comparison are involved in the order judgement task. A comparison strategy can be used for all type of sequences, but can be bypassed by an association based solution when the associations between the items in a sequence are strong.

Because different mechanisms can play a role depending on the characteristics of the sequence (i.e., distance and direction) that is presented, it was examined whether the different types of sequences also contributed differently to arithmetic. In contrast to previous findings (Lyons & Ansari, 2015), our results indicated that all different types of sequences (i.e.,

ascending, descending, non-ordered) correlated to a similar extent with arithmetic suggesting that all sequences explained a comparable amount of variance in arithmetic. The different results might be due to developmental differences as participants in our study were adults while Lyons and Ansari (2015) examined order processing in children.

In Experiment 2 it was examined whether the mechanisms underlying digit order processing were the same as in order processing for non-numerical stimuli. Furthermore, it was examined whether the mechanisms responsible for the relation with arithmetic are domain-general or domain-specific. In line with our hypothesis, findings suggest similar processing for ordered sequences of digits, letters and months. However, the results showed that the explained variance in arithmetic is primarily explained by domain-general order processing. Only a small amount of the total captured variance by order processing is solely numerical. Intuitively, the finding that non-numerical associations are important for arithmetic seems surprising: it can be questioned why associations between non-numerical stimuli are relevant for arithmetic. A possible explanation is that a general learning mechanism underlying the formation of associations is responsible for this association with arithmetic. Recently, De Visscher et al. (2015) tested serial order learning in adults with developmental dyscalculia using a Hebb repetition learning task which is thought to measure implicit learning or automatization (Hebb, 1961). In this task, sequences of nine syllables were presented on a screen for immediate serial recall. After the presentation, the same syllables were randomly presented and participants were instructed to indicate the correct order of the presentation of the syllables. In the presentation of the sequences, most sequences were presented randomly but one particular trial was repeated every third trial. In control subjects, the performance on the repeated trial improved gradually, the so-called Hebb repetition effect (Hebb, 1961). Results showed that dyscalculics showed lower performance than control subjects in the Hebb learning task. Previously, it has also been found that dyslexics show a deficit in Hebb learning (Szmalec,

Loncke, Page, & Duyck, 2011). These studies suggest that domain-general associative learning is related to learning difficulties and is in line with our observation that there is a relation between arithmetic and both numerical and non-numerical order processing.

Further research is needed to investigate which aspect of the domain-general associations drives the relation with arithmetic. On the one hand, the relation between domain-general associations and arithmetic might be due to working memory capacities, as a higher working memory capacity facilitates the retrieval and manipulation of sequences stored in long-term memory (Barrouillet & Lépine, 2005; Rosen & Engle, 1997). On the other hand, a specific ability to process serial order might drive the relation between domain-general associations and arithmetic. In the study of De Visscher et al. (2015), it was found that the dyscalculics did not differ from the controls in a words list memory task with no order constraint and only showed different performance when the short-term memory task contained a serial order aspect. In a study of Attout and Majerus (2014) working memory capacity was investigated in children with developmental dyscalculia by comparing performance on item information and performance on order information. The children diagnosed with developmental dyscalculia performed significantly less accurate and slower than controls in retrieving order information but not in retrieving item information. These findings suggest that a specific serial order mechanism underlies the relation between domain-general associations and arithmetic, but this assumption requires more evidence.

Summarized, this study shows that both numerical and non-numerical order processing is for a large part based on associations between the items. We observed that the relation between arithmetic and order processing is for the largest part due to a general associative learning mechanism underlying the formation of numerical and non-numerical sequences.

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Table and figure captions

Table 1. *Mean accuracies, median reaction times and the corresponding standard deviations per condition for the order task with digits (Experiment 1).*

Table 2. *Bivariate correlations between arithmetic scores and median reaction times on the different types of trials of the order task (Experiment 1).*

Table 3. *Mean accuracies, median reaction times and the corresponding standard deviations per condition for the order task with digits (Experiment 2).*

Table 4. *Bivariate correlations between arithmetic scores and median reaction times on the order tasks for digits, letters and months (Experiment 2).*

Table 5. *Multiple regression with arithmetic as dependent variable and median reaction times per task as independent variables (Experiment 2).*

Table 6. *Hierarchical regression with arithmetic as dependent variable and median reaction times per task as independent variables (Experiment 2).*

Figure 1. *Median reaction times across the conditions of the order task with digits (Experiment 1).*

Figure 2. *Median reaction times across the conditions of the order tasks with digits, letters and months (Experiment 2).*

Table 1. *Mean accuracies, median reaction times and the corresponding standard deviations per condition for the order task with digits (Experiment 1).*

	Ascending	Ascending	Descending	Descending	Non-order	Non-order
	Small	Large	Small	Large	Small	Large
ACC	.96 (.04)	.90 (.12)	.92 (.07)	.87 (.14)	.78 (.14)	.91 (.11)
(%)						
RT	795 (205)	907 (245)	911 (250)	946 (249)	1160 (314)	981 (259)
(ms)						

Table 2. *Bivariate correlations between arithmetic scores and median reaction times on the different type of trials of the order task (Experiment 1).*

	1	2	3	4	5	6
1 Ascending Small						
2 Ascending Large	.87**					
3 Descending Small	.85**	.79**				
4 Descending Large	.81**	.88**	.83**			
5 Non-order Small	.86**	.85**	.82**	.80**		
6 Non-order Large	.83**	.82**	.74**	.80**	.88**	
7 TTR	-.38**	-.45**	-.46**	-.41**	-.42**	-.51**

* $p < .05$, ** $p < .01$

Table 3. *Mean accuracies, median reaction times and the corresponding standard deviations per condition for the order task with digits (Experiment 2).*

	Ascending	Ascending	Descending	Descending	Non-order	Non-order
	Small	Large	Small	Large	Small	Large
ACC Digits	.97 (.04)	.96 (.06)	.94 (.06)	.94 (.06)	.85 (.10)	.93 (.06)
RT Digits	806 (177)	916 (236)	949 (222)	1000 (292)	1178 (300)	1053 (231)
ACC Letters	.95 (.05)	.92 (.09)	.84 (.09)	.83 (.17)	.85 (.11)	.91 (.09)
RT Letters	1555 (451)	2202 (846)	2193 (642)	2390 (791)	2420 (570)	2333 (618)
ACC Months	.95 (.05)	.89 (.12)	.85 (.15)	.79 (.21)	.87 (.09)	.91 (.12)
RT Months	1722 (392)	2577 (1058)	2428 (587)	2897 (1149)	2513 (564)	2483 (591)

Table 4. *Bivariate correlations between arithmetic scores and median reaction times on the order task for digits, letters and months (Experiment 2).*

	1	2	3
1 RT Digits			
2 RT Letters	.66**		
3 RT Months	.61**	.60**	
4 TTR	-.50**	-.47**	-.36*

* $p < .05$, ** $p < .01$

Table 5. *Multiple regression with arithmetic as dependent variable and median reaction times per task as independent variables (Experiment 2).*

Independent variables	Standardized β	t	p	R ²
RT Digits	-.33	-1.84	.073	.28**
RT Letters	-.24	-1.33	.190	
RT Months	-.02	-.09	.926	

* $p < .05$, ** $p < .01$

Table 6. *Hierarchical regression with arithmetic as dependent variable and median reaction times per task as independent variables (Experiment 2).*

Step	Independent variables	Standardized β	t	p	R ²	ΔR^2
1	RT Letters	-.39	-2.44	.019	.23**	.23**
	RT Months	-.13	-.78	.442		
2	RT Letters	-.24	-1.33	.190	.28**	.05
	RT Months	-.02	-.09	.926		
	RT Digits	-.33	-1.84	.073		

* $p < .05$, ** $p < .01$

Figure 1. Median reaction times across the conditions of the order task with digits
(Experiment 1).

Figure 2. Median reaction times across the conditions of the order tasks with digits, letters and months (Experiment 2).

Appendix A. *Partial correlations between arithmetic scores and median reaction times of the different types of trials of the order task, controlling for processing speed (Experiment 1).*

	1	2	3	4	5	6
1 Ascending Small						
2 Ascending Large	.85**					
3 Descending Small	.84**	.76**				
4 Descending Large	.78**	.88**	.84**			
5 Non-order Small	.87**	.85**	.81**	.80**		
6 Non-order Large	.87**	.81**	.79**	.82**	.86**	
7 TTR	-.38**	-.46**	-.46**	-.43**	-.42**	-.51**

* $p < .05$, ** $p < .01$

Appendix B. *Partial correlations between arithmetic scores and median reaction times of the order task for digits, letters and months controlling for processing speed (Experiment 2).*

	1	2	3
1 RT Digits			
2 RT Letters	.68**		
3 RT Months	.64**	.57**	
4 TTR	-.49**	-.47**	-.40**

* $p < .05$, ** $p < .01$