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Processing of order information for numbers and months

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Despite a great deal of research on the processing of numerical magnitude (e.g., the quantity denoted by the number 5), few studies have investigated how this magnitude information relates to the ordinal properties of numbers (e.g., the fact that 5 is the fifth integer). In the present study, we investigated order-related processing of numbers, as well as months of the year, with a novel ordering task to see whether the processing of order information differs from the processing of magnitude information. In Experiments 1 and 2, participants were shown three numbers (Experiment 1) or three months (Experiment 2) and were required to indicate whether the stimuli were in the correct order. In Experiment 3, participants were again shown three numbers; however, now they were instructed to indicate whether the three numbers were ordered in a forward, backward, or mixed direction. Whereas number comparison tasks typically reveal distance effects (comparisons become easier with increased distance between two numbers), these three experiments reveal a different pattern of results. There were *reverse* distance effects when the stimuli crossed a boundary (i.e., when numbers crossed a decade or months crossed the year boundary) and no effect of distance when the stimuli did not cross a boundary (i.e., when numbers were within a decade and months were within the January–December calendar year). These data suggest that additional mechanisms are involved in the processing of order information: a scanning mechanism and a long-term memory checking mechanism.

Processing numbers is an important cognitive skill. We can all count, estimate magnitudes, do simple arithmetic, and otherwise manipulate numbers. Contrariwise, a breakdown in number processing due to brain lesions can lead to significant deficits in activities of daily life (Geary, 1993; Osmon, Smerz, Braun, & Plambeck, 2006; Rosselli, Matute, Pinto, & Ardila, 2006; Shalev, Manor, & Gross-Tsur, 2005). Indeed, processing quantity is so fundamental a cognitive skill that a basic sense of number is present in infants, other primates, and nonprimate species (Brannon, 2002; Brannon & Terrace, 1998; Dehaene, Dehaene-Lambertz, & Cohen, 1998).

Although debate continues over subtleties of specific models, numbers are generally thought to be represented along an analogue internal number line with decreasing distance between numbers as magnitude increases (Dehaene, 2003; Dehaene & Changeux, 1993; Gallistel & Gelman, 2000; Whalen, Gallistel, & Gelman, 1999; Wynn, 1998). Two pervasive behavioral effects have been instrumental in shaping these models: the distance and size effects. The *distance effect* refers to the fact that the comparison of the magnitude of two numbers is accomplished more quickly and with greater accuracy when they span a greater distance (Moyer & Landauer, 1967). This is thought to be the result of a comparison process that is facilitated when the numbers to be compared are farther apart on the number line, making them more easily discriminated. The *size effect* is revealed in longer reaction times (RTs) to compare numbers of greater magnitude and has led to the idea that the number line is compressed, with less distance between numbers of larger magnitude (Ashcraft, 1992; Parkman, 1971).

The tasks that have led to these models of number representation almost exclusively assess the stimuli solely on the basis of their magnitude and are often collectively referred to as *magnitude comparison tasks*. These tasks typically involve asking participants to pick out the smaller or larger of two numbers or to decide whether a given number is smaller or larger than some target number. However, in addition to information about magnitude, numbers also represent information about order. For example, the number 3 can be used to describe a specific quantity or magnitude (e.g., *There are*

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three *apples on the table*), as well as the order of an item in a list (*The runner finished in* third *place*). Although the magnitude comparison tasks described above have been well studied, there have been few studies that directly assess the ordinal processing of numbers and how this may compare to the processing of magnitude information.

In one study, Turconi, Campbell, and Seron (2006) provided evidence for an order-specific process in a number comparison task. When participants were shown two numbers and asked the question "Are the numbers in the correct order?" they showed a reverse distance effect if the small-distance numbers were adjacent and ascending (e.g., 6_7 was faster than 4_7) and a distance effect for all descending pair comparisons; however, when they had to choose the larger or smaller of two numbers, they showed a distance effect, regardless of adjacency or whether the numbers were ascending or descending. The reverse distance effect suggests a scanning mechanism that accesses the number line serially, which takes longer when the numbers span a greater distance because there are more numbers to scan through. Alternatively, greater familiarity for ascending adjacent pairs raises the possibility that the reverse distance effect is simply due to easier retrieval of these trial types. This work, however, also seems problematic, because a strategy based on magnitude information can lead to the same result as one based on order. For example, deciding whether two numbers are in the correct order can be done by seeing whether the largest number is to the right or the smallest number is to the left on the number line, focusing on magnitude instead of order information. Therefore, although we acknowledge that the reverse distance effect provides evidence for a separate order process, our main criticism is that this order process may not be well characterized, because the task parameters allow for residual magnitude processing to influence this order process.

Other work on order information has been conducted mostly with young children, infants, and monkeys and has often relied heavily on magnitude information. For example, in one type of order task, participants were required to order arrays of stimuli on the basis of the number of stimuli present on the screen (Brannon, 2002; Brannon & van de Walle, 2001; Cantlon & Brannon, 2006), which resulted in distance effects. This work also seems problematic, since—for example—an array with five squares contains a greater quantity of items than does an array containing two squares, and therefore a decision can be based on a magnitude comparison strategy.

There has also been, however, recent work with a different type of order information—everyday routines—that suggests that there is distinct order-related processing for them (Franklin, Smith, & Jonides, 2007). In Franklin et al., participants were required to assess the order of two actions from an everyday routine (e.g., going to a movie). Whereas comparison tasks in this domain have typically shown distance effects (Galambos & Rips, 1982; Nottenburg & Shoben, 1980), Franklin et al. reported examples of reverse distance effects, where participants were faster for trials in which the actions spanned a lesser distance. These reverse distance effects were dependent on specific variables, such as the familiarity of the routine and the amount of exposure to the stimulus materials. For example, for routines of high familiarity, participants tended to take longer when the actions were temporally farther apart within a routine. This was taken as evidence for a scanning mechanism that processes information serially. This is in contrast to the distance effects that were described as reflecting an estimation mechanism, in which actions that are farther apart are more easily discriminated on the basis of position information. This work on order information for everyday routines (Franklin et al., 2007), together with the work discussed above using an order task with numbers (Turconi et al., 2006), provides evidence for an order-related process that need not operate exclusively in numerical domains.

The Present Study

The goal of the present study was to determine the processes involved in manipulating order information by minimizing the influence of magnitude comparison strategies. In Experiment 1, participants were shown three numbers and asked, "Are the numbers in the correct order?" As mentioned above, with two numbers, the processes of ordering and picking out the smallest/largest could be done in a similar way. Here, we sought to facilitate order-related processes with an explicit order instruction and the use of three numbers that are sometimes mixed (e.g., 12, 15, 13) which should force the participants to pay attention to all of the numbers (i.e., since 12, 15, __ could be forward—12, 15, 18—or mixed—12, 15, 13). Treating all three numbers as a triad should discourage the strategy of using binary smaller/larger judgments to correctly do the task. If, however, the participants use this type of magnitude comparison strategy, we can detect this because a behavioral distance effect should emerge.

Of interest are the types of distance effects elicited in this novel order task and the variables that influence these effects. Very few studies have used three numbers as stimuli. In one study, Brysbaert (1995; Experiments 1 and 2) analyzed the time required to read three numbers presented on the screen from left to right. In that study, reading times increased as the distance between the first and second number increased, consistent with the reverse distance effects discussed above for other order-related tasks. Another task that makes use of three numbers is the number bisection task, in which participants decide whether the middle number is the mean of the two outer numbers (e.g., 12, 15, 18) or not (e.g., 12, 14, 18; Nuerk, Geppert, van Herten, & Willmes, 2002). It has been shown that, in completing this task, participants make use of different types of number representations and processes, since there are both distance effects (e.g., participants are faster to reject a triplet if the middle number is farther away from the actual mean of the two outer numbers) and reverse distance effects (e.g., participants are faster when there is less distance between the two outer numbers). The only other studies in the literature that required participants to make judgments about more than two stimuli consist of magnitude comparison tasks (e.g., "choose the largest/smallest") with three and five numbers (Jou, 2003; Schulze, Schmidt-Nielsen, & Achille, 1991).

Although a major goal of the present study was to investigate order processing for numbers, since numbers also inherently convey magnitude information, we adapted the same task with months of the year as stimuli in Experiment 2 to help rule out numerical strategies. Here, participants were presented with three months and asked whether they were in the correct order. We reasoned that if we found similar results for numbers and for months, this would suggest a general type of order processing that applies to numbers but is not unique to them. Additionally, in order to aid in the interpretation of Experiments 1 and 2, in Experiment 3, we required participants to indicate whether numbers were presented in forward (e.g., 12, 13, 15), backward (e.g., 15, 13, 12), or mixed (e.g., 15, 12, 13) orders. This instruction allows for a more effective comparison of forward and backward trials for both numbers and months. Additionally, Experiment 3 provided evidence for the generality of these order processes with different task parameters.

EXPERIMENT 1

Method

Participants. Twenty participants were tested in Experiment 1 (11 female, mean age = 20.2 years). One participant was removed because his accuracy was close to chance (56% overall; the next lowest accuracy was 80%), leaving 19 participants for subsequent analyses.

Task and Design. In this experiment, the participants were presented with three numbers and were required to indicate whether the numbers were in the correct order (i.e., in the forward direction) or not (i.e., in the backward or mixed direction). There were three variables manipulated in this experiment: direction, distance, and decade crossing. The three numbers were ordered in the forward (e.g., 13, 14, 16), backward (e.g., 16, 14, 13), or mixed (e.g., 16, 13, 14) direction. The largest distance between the three numbers displayed was either small (three units) or large (six units). Additionally, given that there is some controversy regarding the representation of decade breaks on the number line (Nuerk & Willmes, 2005), we manipulated whether the three numbers crossed a decade (e.g., 18, 20, 21) or not (e.g., 13, 15, 16).

Stimuli. The stimuli consisted of two-digit numbers ranging from 11 to 99, presented in groups of three. There were a total of 192 unique trials. In order for there to be equal numbers of *yes* and *no* responses, half of the trials were in the forward direction, one fourth were backward, and one fourth were mixed. Half of the trials included numbers that were a small distance apart, whereas the other half included numbers that were a large distance apart. For the small-distance trials, the distance between the first two numbers for the forward direction was always one unit and the distance for the second two numbers was always two units (e.g., 22, 23, 25). For the large-distance trials, the distance between the first two numbers for forward trials was always four units and the distance for the second two numbers was always two units (e.g., 22, 26, 28). The backward trials were created by simply reversing the direction of the forward trials (e.g., small distance, 25, 23, 22; large distance, 28, 26, 22). For the mixed trials, the first two numbers were in ascending order for half of the trials and in descending order for the other half. This forced the participants to pay attention to all three numbers on all trials. Additionally, there were equal numbers of trials in which the three numbers crossed a decade or did not cross one. Table 1 shows the interitem distances for each of the distances used, together with example stimuli for the forward trials. To avoid the possible confound of number size (i.e., comparison of larger numbers takes longer), the mean number sizes for all trial types for subsequent analysis were made comparable ($M = 53$, $SD = 1.3$). Of the 192 trials, there were 24 trials for each combination of decade crossing (cross or do not cross) and distance (three or six units) for the forward trials. There were 12 trials for each combination of decade crossing and distance for the backward and mixed trials.

Table 1
Interitem Distance for Each of the Distances Used for the Forward Trials in Experiment 1

Overall Distance	Interitem Distance: Item 1 to Item 2	Item 2 to Item 3	Example	*N*
3	1	2	22, 23, 25	96
6	4	2	22, 26, 28	96

Procedure. The sequence of events on a trial was as follows: A fixation cross appeared for 500 msec, followed by the three numbers appearing side by side on the screen until a response was detected. Participants were instructed to press the "1" key on a keyboard with the left hand if the items were in the correct order (forward trials) and the "0" key with the right hand if they were in the incorrect order (backward and mixed trials). The participants were instructed to respond as quickly as possible, while maintaining a high level of accuracy. Before the experimental trials began, the participants went through 20 practice trials different from the experimental trials to ensure that they understood the task. The experiment was divided into eight blocks of 48 trials, with a rest between blocks. Since there were only 192 unique trials, the second four blocks repeated the stimuli from the first four in a different random order. The experiment lasted approximately 30 min.

Results

Table 2 shows the accuracy and RTs for each of the conditions. Since there was a significant positive correlation between RT and error rate for all conditions ($r = .82$, $p < .001$), detailed analyses were performed only on RT data. This type of correlation was reported in Turconi et al. (2006) as a way of demonstrating the similarity between RTs and error rates; a strong correlation between RTs and errors across conditions means that the error data follow a pattern similar to that for RT data and therefore do not convey any extra information. For all analyses on RTs, medians for each participant were calculated (to avoid outlier effects) using only the correct trials in the forward direction. We expected a more uniform strategy for the forward trials than for other kinds of trials, because, for the forward trials, participants

Table 2
Accuracy and Reaction Time (in Milliseconds) Data for All Conditions in Experiment 1

Condition	Accuracy *M*	Accuracy *SD*	Reaction Time *Med*	Reaction Time *SD*
Direction				
Forward	.93	.04	1,002.23	204.45
Backward	.95	.03	961.71	196.53
Mixed	.77	.10	1,050.07	211.78
Decade				
Cross	.89	.05	1,016.92	205.64
Do not cross	.90	.05	983.47	199.03
Distance				
Small	.88	.06	991.50	205.93
Large	.91	.04	1,009.02	200.61

were required to focus on all three numbers to do the task correctly; when the first two numbers were descending (e.g., 17, 13, __) the identity of the third number was not necessary to determine the correct response (i.e., both 17, 13, 14 and 17, 13, 11 require a *no* response). Consistent with the hypothesis of a fast rejection based on the first two numbers on backward trials, the participants took longer for forward than for backward trials [forward, $Med = 1{,}002$ msec; backward, $Med = 961$ msec; $F(1,18) = 12.44$, $p = .002$]. Likewise, mixed trials in which the first two numbers were ascending took longer than those in which the first two numbers were descending [ascending, $Med = 1{,}214$ msec; descending, $Med = 971$ msec; $F(1,18) = 118.972$, $p < .001$]. Therefore, backward and mixed trials were excluded from the main analysis presented below. Subsequent analyses focused on the interaction of distance and the crossing of a decade and were specific to trials in the forward direction (positive responses). For the following analyses, a two-way repeated measures ANOVA including distance and decade crossing as variables was used. Figure 1 shows the results of the RT analyses. There was an effect of distance only when the trials crossed a decade. This can be thought of as a reverse distance effect in which the participants took longer on trials with a greater distance between the numbers. There was no distance effect when the trials did not cross a decade. This interaction of distance and decade crossing was significant [$F(1,18) = 18.01$, $p = .0005$]. There were also significant main effects for distance [$F(1,18) = 32.18$, $p < .0001$] and decade crossing [$F(1,18) = 36.21$, $p < .0001$]. In addition, a significant positive correlation between number magnitude and RT ($r = .158$, $p = .001$) revealed a size effect in which participants took more time as the numbers became larger. The magnitude of a triad was computed as the mean size of the three numbers. The reported correlation is between these magnitudes and the mean latency of each triad (calculated across participants).

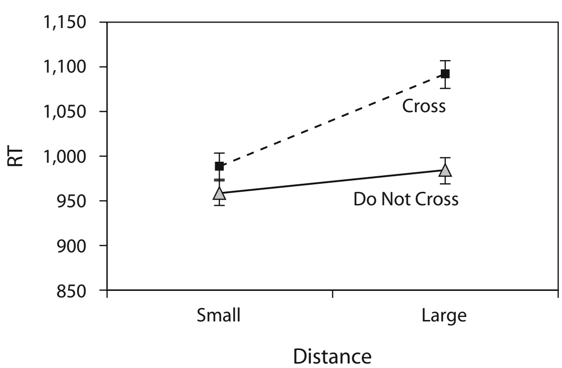

Figure 1. This figure shows the significant interaction between distance and decade crossing for reaction times (RTs) with numbers in the forward direction. There was no distance effect when the numbers were in the same decade and a significant reverse distance effect when the numbers crossed decades. Error bars representing 95% confidence intervals are plotted for this figure and for subsequent figures using methods taken from Loftus and Masson (1994).

Discussion

Whereas previous studies of number comparison have typically shown distance effects, the present study revealed a different pattern of results. There were reverse distance effects when the numbers crossed a decade and no distance effects when all of the numbers were within the same decade. These effects differ from what would be predicted on the basis of the bulk of work done with order information (e.g., Brannon, 2002; Brannon & van de Walle, 2001; Cantlon & Brannon, 2006). Although these basic order tasks have not been well studied in college-aged participants, we assume that this work (which has focused on young children, infants, and monkeys) can at least inform theories of order processing in adults. For example, these studies suggest that order tasks make use of a comparison process akin to that used for magnitude comparison tasks and should therefore yield distance effects. However, if this were the case, and participants were first comparing the first number to the second and then the second to the third, they should show distance effects on the basis of a magnitude comparison strategy. Therefore, this magnitude comparison process cannot explain the reverse distance effects in the present study, because it predicts that numbers that are farther apart should be more easily discriminated than numbers that are closer together.

These results provide evidence for two distinct order-related processes. The reverse distance effects suggest that, when the numbers cross a decade, participants make use of a scanning mechanism that takes longer when there is greater distance between the numbers. The lack of a distance effect when the numbers were within the same decade suggests another unique order-related process that will be referred to as a *long-term memory checking mechanism* (LTM-CM). This mechanism consists of decomposing the two-digit number and then focusing on the relevant ones digit. Since the order of the numbers 1–9 is well learned, participants are able to retrieve this order information without being influenced by the distance between the numbers. It is also possible that the flat distance function for numbers within a decade could be due to distance and reverse distance effects canceling each other out. If this were the case, however, one would expect greater variance when the numbers are in the same decade, which was not the case (cross trials, $SEM = 61.79$; do-not-cross trials, $SEM = 54.84$, n.s.).

Before commenting more on the details of these order-related processes, it is important to know whether these processes are unique to numbers. For example, the scanning mechanism could be due to participants' using addition or subtraction to accomplish the task. To help rule out the use of strategies specific to numbers, Experiment 2 was conducted using months of the year as stimuli. Also, given that months of the year also have a natural boundary (i.e., a calendar year starts at January and ends at December), similar to the boundary at each decade for numbers, we were interested in whether effects of crossing boundaries would be similar for both types of stimuli and, thus, perhaps generalizable to other types of well-learned sequences.

Table 3
Interitem Distance for Each of the Distances Used for the Forward Trials in Experiment 2

	Interitem Distance		
Overall Distance	Item 1 to Item 2	Item 2 to Item 3	Example
3	2	1	April, June, July
4	2	2	October, December, February
5	3	2	February, May, July
7	3	4	March, June, October
8	3	5	February, May, October
9	4	5	May, September, February

EXPERIMENT 2

Method

Participants. Twenty new participants were tested in this experiment (13 female, mean age = 20.6 years).

Task and Design. In this experiment, the participants were presented with three months of the year and were required to indicate whether the months were in the correct order (i.e., forward direction) or not (i.e., backward direction) within a 12-month calendar year. Three variables were manipulated: direction, distance, and whether the months crossed a year boundary. The three months were ordered in the forward or backward direction. The largest distance between the three months displayed was small (three, four, or five units) or large (seven, eight, or nine units). In this study, the three months either crossed a year boundary (i.e., the month January) or did not cross (i.e., they were between January and December).

Stimuli. The stimuli consisted of months, chosen from the 12 months of the calendar year, presented in groups of three. There were a total of 96 unique trials. There were equal numbers of forward and backward trials. In half of the trials, the months were a small distance apart, whereas, in the other half, they were a large distance apart. Table 3 shows the interitem distances for each of the distances used, together with example stimuli for the forward trials. The backward trials were created by reversing the direction of the forward trials. There were equal numbers of cross and do-not-cross trials. The small distances (three, four, or five units) consisted of three, four, and five trials, respectively. For the large distances (seven, eight, or nine units), there were also three, four, and five trials, respectively. This was the case for each combination of direction (forward or backward) and year crossing (cross or do not cross).

Procedure. The timing parameters and sequence of events were the same as those in Experiment 1. However, the months were presented vertically, since all three months would not easily fit on the screen with horizontal presentations. Given that similar size and distance effects have been found with horizontal, vertical, and diagonal presentations, the differences in presentation should not significantly affect the results (Nuerk, Weger, & Willmes, 2004). Similarly, participants were instructed to press the "1" key with the left hand if the items were in the correct order (top to bottom, forward trials) and the "0" key with the right hand if they were in the incorrect order (backward). Before the experimental trials began, the participants completed 20 practice trials different from those used in the experiment to ensure that they understood the task. The experiment was divided into eight blocks of 24 trials, with a rest between blocks. With only 96 unique trials, the second four blocks repeated the stimuli from the first four in a different random order. The experiment lasted approximately 30 min. Following the experiment, the participants filled out a debriefing questionnaire in which they were asked, "Did you find yourself thinking of the months in terms of their numbers (i.e., January = 1, February = 2, etc.)?"

Results

Table 4 shows the accuracy and RTs for each of the conditions. As in Experiment 1, because there was a significant positive correlation between RT and error rate for all conditions ($r = .67$, $p < .05$), detailed analyses were performed only for RT data. For all analyses on RTs, medians for each participant were calculated using only the correct trials. Given that the months are in a repeating ordinal sequence (unlike the numbers used in Experiment 1) that could cross the year boundary, the participants were required to focus on all three months on a given trial in order to perform the task correctly. Therefore, subsequent analyses focused on the interaction between distance and decade crossing, for both forward and backward trials. In order to analyze RTs, a three-way ANOVA with direction, distance, and year crossing as variables was used. Figure 2 shows the results of the RT analyses separately

Table 4
Accuracy and Reaction Time (in Milliseconds) Data for All Conditions in Experiment 2

	Accuracy		Reaction Time	
Condition	*M*	*SD*	*Med*	*SD*
Direction				
Forward	.91	.07	2,182.90	590.42
Backward	.90	.07	2,510.40	769.51
Year				
Cross	.87	.08	2,395.05	681.81
Do not cross	.94	.05	2,253.72	675.41
Distance				
Small	.93	.06	2,244.60	656.54
Large	.88	.07	2,419.80	670.40

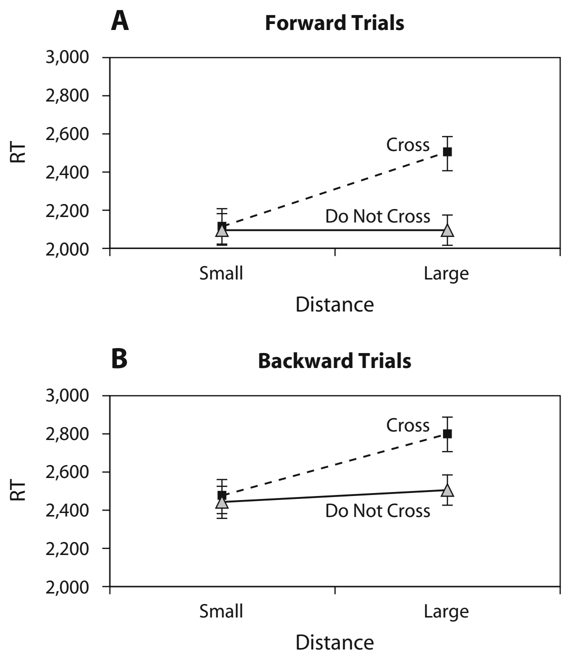

Figure 2. This figure shows the significant interaction between distance and year crossing for reaction time (RT) with months of the year for (A) forward and (B) backward trials. There was no distance effect when the months were in the same calendar year and a significant reverse distance effect when the months crossed the January border.

Table 5
Reaction Times (in Milliseconds) for the Crossing × Distance Interaction on the Basis of Strategy for Experiment 2

	Reaction Time			
	Cross		Do Not Cross	
Strategy	Small	Large	Small	Large
Number (n = 6)	2,323.17	2,576.50	2,370.92	2,348.16
Nonnumber (n = 14)	2,025.03	2,463.25	1,981.89	1,988.85

for the forward and backward trials. For both directions, the participants showed a reverse distance effect, taking longer for greater distances, but only on trials in which the months crossed the year boundary. There was no effect of distance when the months were within the calendar year. This interaction between distance and year crossing was significant [$F(1,19) = 7.76$, $p = .01$]. There were also significant main effects of distance [$F(1,19) = 31.24$, $p < .0001$], year crossing [$F(1,19) = 4.32$, $p = .05$], and direction [$F(1,19) = 9.925$ $p = .0005$]. The fact that there was not a significant three-way interaction [$F(1,19) = 0.95$, $p = .34$] reveals that forward and backward trials show a similar interaction of distance with year crossing, whereas the main effect of direction reveals that backward trials simply took longer. In addition, there was no size effect (i.e., position effect) for months. This was evidenced by the lack of a significant correlation between month position in the sequence and RT ($r = .02$, $p > .05$).

An analysis of the debriefing questions revealed that 6 out of 20 participants answered *yes* to the question regarding the use of a numerical strategy. Because this experiment was conducted to rule out the possibility that a numerical strategy would lead to these effects, we analyzed the 14 participants who did not report using a numerical strategy. There still remained a significant decade crossing × distance interaction [$F(1,13) = 14.77$, $p = .002$]. Also, although the interaction was not significant with the 6 participants who used a numerical strategy with months [$F(1,5) = 0.53$, $p = .49$], there was a similar pattern of RTs (see Table 5). This result suggests that it was the order task in general, rather than specific numerical operations, that led to the pattern of distance effects present in both experiments.

Discussion

The results from Experiment 2 suggest that similar order-related processes are involved in processing months of the year as well as numbers. Although the participants took longer and had more errors with the months as the stimuli, they showed the same interaction pattern: reverse distance effects when the months crossed a year boundary and no distance effects when all three months were within the same calendar year. These behavioral effects for Experiment 2 differ from the distance effects found with previous comparison tasks with months (Friedman, 1983; Gélinas & Desrochers, 1993; Seymour, 1980a, 1980b). This discrepancy is probably due to the fact that the tasks reported in these articles showing distance effects are more akin to the typical magnitude comparison tasks with numbers. In these tasks, participants see two months and are required to pick out the month that is earlier/later within a December–January calendar year. Our results support the findings from Experiment 1 that this task requires the use of specific order-related processes consisting of a scanning procedure when the stimuli cross a boundary and an LTM-CM when the stimuli did not cross. The fact that the results were not influenced by a numerical strategy indicates that this task taps a more general type of order processing that is not specific to numbers. An analysis of the backward trials revealed a similar pattern of results. Although, overall, participants took longer on the backward trials, there were reverse distance effects when the trials crossed the year boundary and no distance effect when they did not cross. Two different strategies are consistent with these findings. It is possible that participants engage in forward and backward scanning, with forward scanning being the default mode and backward scanning initiated only *after* forward scanning has revealed that the triad is not ascending. Participants may also always scan forward (i.e., check to see whether the items are in ascending order) but may stop when the items are out of sequence and may recheck the order of the triad starting from the third item and working backward.

Since, in Experiment 1, the participants made a single response for backward and mixed trials and did not need to look at all of the numbers to reach a decision on the backward trials, it was not possible to compare backward trials in Experiments 1 and 2. Therefore, in Experiment 3, participants were required to make a separate response for forward, backward, and mixed trials with numbers. This new instruction required participants to focus on all three numbers and allowed an examination of the backward trials. Additionally, we were able to see whether the effects for forward trials generalized to this new task.

EXPERIMENT 3

Method

Participants. Twenty new participants were tested in the experiment (13 female, mean age = 20.3 years).

Task and Design. In this experiment, participants were presented with three numbers and were required to indicate whether the numbers were in the forward, backward, or mixed direction. The design for Experiment 3 was the same as that for Experiment 1. The only differences were the instructions and the participants' responses.

Stimuli. The stimuli consisted of two-digit numbers ranging from 11 to 99, presented in groups of three. There were a total of 216 unique trials. The set of stimuli were designed in the same way as those in Experiment 1, except for the addition of trials to create equal numbers of forward, backward, and mixed trials. Of the 216 trials, there were 18 trials for each combination of decade crossing (cross or do not cross) and distance (three or six units) for all three directions.

Procedure. The sequence of events on a trial was as follows: A fixation cross appeared for 500 msec, followed by the three numbers appearing side by side on the screen until a response was detected. The participants were instructed to respond with their right hand, pressing the "1" key on a keyboard if the items were in the forward order, the "2" key if they were backward, and the "3" key if they were mixed. The participants were instructed to respond as quickly as possible while maintaining a high level of accuracy. Before the experimental trials began, the participants went through 20 practice trials different from those used in the experiment to ensure that they understood the task. The experiment was divided into eight blocks of 54 trials, with a rest between blocks. Since there were only 216 unique trials, the second

Table 6
Accuracy and Reaction Time (in Milliseconds) Data for All Conditions in Experiment 3

Condition	Accuracy *M*	Accuracy *SD*	Reaction Time *Med*	Reaction Time *SD*
Direction				
Forward	.89	.15	1,247.50	297.53
Backward	.83	.19	1,379.75	287.11
Mixed	.75	.24	1,421.08	280.13
Decade				
Cross	.81	.18	1,389.53	292.74
Do not cross	.85	.22	1,319.06	306.60
Distance				
Small	.82	.21	1,347.08	314.91
Large	.83	.19	1,365.11	288.26

four blocks repeated the stimuli from the first four in a different random order. The experiment lasted approximately 35 min.

Results

Table 6 shows the accuracy and RTs for each of the conditions. Since there was a significant positive correlation between RT and error rate for all conditions ($r = .91$, $p < .001$), detailed analyses were performed only on RTs. For all analyses, medians for each participant were calculated using only the correct trials. The main analysis of interest was the interaction between distance and decade crossing for all three directions. Forward and backward trials were analyzed separately from mixed trials in order to make comparison easier with Experiment 2. Also, mixed trials are different from forward and backward trials in that they are not an ordered sequence. In order to analyze RTs, a three-way ANOVA including direction (forward or backward), distance, and year boundary crossing as variables was used. Figure 3 shows the results of the RT analyses separately for the forward and backward trials. For both directions, the participants showed a reverse distance effect, taking longer for greater distances only on trials in which the numbers crossed a decade. There was no effect of distance when the numbers were within a decade. This interaction of distance and decade crossing was significant [$F(1,19) = 16.79$, $p = .001$]. There were also significant main effects of distance [$F(1,19) = 26.86$, $p < .0001$], decade crossing [$F(1,19) = 17.44$, $p = .05$], and direction [$F(1,19) = 21.48$, $p < .0001$]. The insignificant three-way interaction [$F(1,19) = 0.69$, $p = .41$] reveals that forward and backward trials show a similar interaction of distance with year crossing, whereas the main effect of direction reveals that backward trials simply took longer.[1]

Discussion

The results from Experiment 3 replicate and extend the findings of Experiments 1 and 2. For both forward and backward trials, participants showed reverse distance effects for cross trials and no distance effect for trials that did not cross. This is the same interaction that was present in Experiment 1 for forward trials and in Experiment 2 for forward and backward trials. These results strengthen the claim that there are distinct order-related processes—namely, a scanning mechanism and LTM-CM that operate with both ordered numerical and nonnumerical stimuli under different task parameters.

GENERAL DISCUSSION

The results of Experiments 1–3 provide evidence for specific order-related processes that differ from those found in typical magnitude comparison tasks. Specifically, we have shown that, when participants are given an instruction to judge the order of three numbers, there are no typical distance effects (i.e., faster decision times when the numbers are farther apart). Rather, under conditions in which the numbers cross a decade (e.g., 18, 21, 24), the participants showed a reverse distance effect and took longer for large-distance triads. The reverse distance effect suggests a scanning mechanism that accesses the number line serially. This is akin to the serial comparison process described by Sternberg (1966), in which participants scan through a memory set sequentially, one item at a time. Following this process, it takes longer for larger distances, because there are more numbers to cover before reaching the target number. When all three numbers were within a decade (e.g., 21, 24, 27), there was no effect of distance. The lack of a distance effect suggests a mechanism that accesses the information from long-term memory (i.e., the LTM-CM) independent of the distance between the numbers. Similar results with months of the year suggest that these effects are not specific to numbers and that the

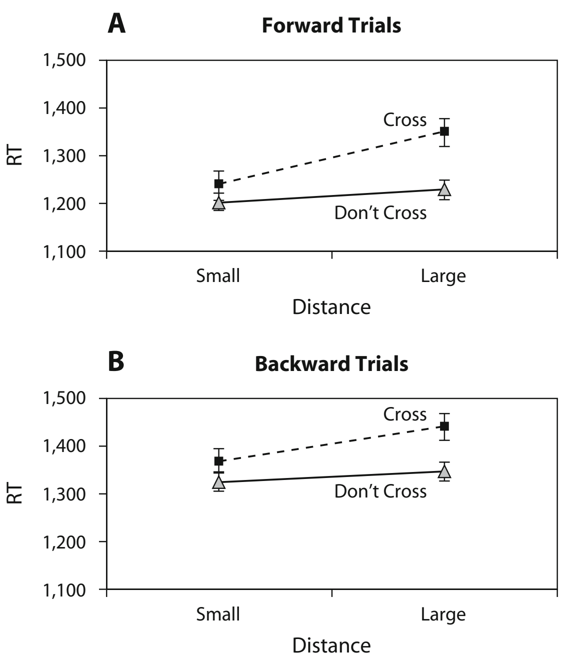

Figure 3. This figure shows the significant interaction between distance and decade crossing for reaction times (RTs) with numbers in the (A) forward and (B) backward directions. There was no distance effect when the numbers were in the same decade and a significant reverse distance effect when the numbers crossed decades.

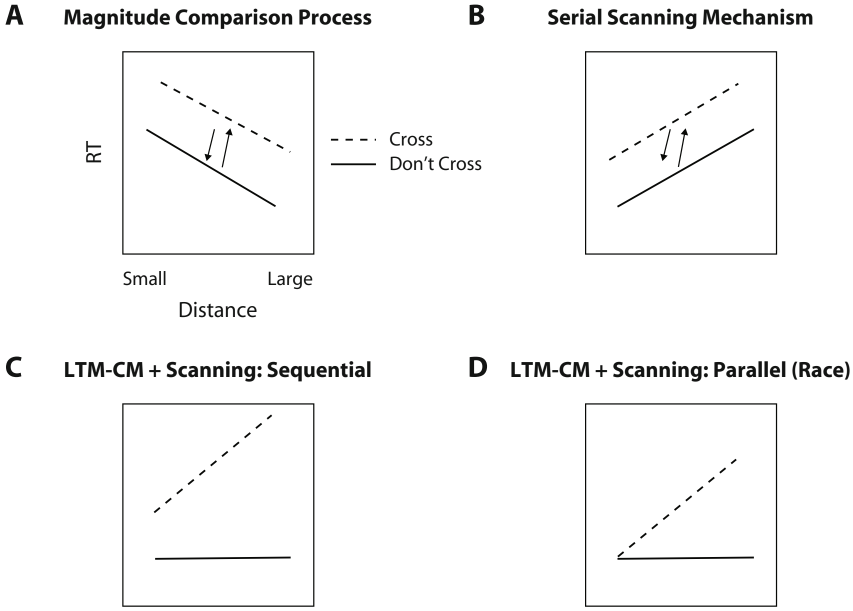

Figure 4. This figure displays the behavioral predictions of the four models relevant to Experiments 1–3: (A) A model consisting of a magnitude comparison process; reaction times (RTs) are faster for large-distance trials regardless of decade crossing (distance effect). The arrows here (and for panel B) indicate that this model makes no claim regarding differences due to decade crossing. (B) A model that consists of a serial scanning mechanism; RTs are slower for large-distance trials regardless of decade crossing (reverse distance effect). (C) A sequential model where a long-term memory checking mechanism (LTM-CM) occurs first for do-not-cross trials (no distance effect), followed by a scanning mechanism for cross trials (reverse distance effect with overall slower RTs). (D) A race model in which the LTM-CM and scanning occur in parallel (same predictions as in panel C, with no effect of decade crossing for small-distance trials).

order processes uncovered may apply more generally to other types of sequential information.

Four Alternative Models: Magnitude Comparison Versus Scanning, Sequential Versus Parallel Processing

Given these findings, it is important to consider how they relate to current models of number processing, as well as to the processing of order information in general. The lack of a typical distance effects suggests that the present results cannot be explained by a typical magnitude comparison process (see Figure 4A). So although the participants could have completed the task by engaging in a multistage magnitude comparison process (first number vs. second, second vs. third, etc.), the results suggest otherwise. If these results were due solely to the operation of a scanning mechanism, reverse distance effects would have been found regardless of decade crossing (see Figure 4B). In contrast, the lack of a distance effect for within-decade trials is most consistent with an LTM-CM as described above. However, although there was no significant reverse distance effect for the do-not-cross trials in any of the three experiments, the slight trend toward a reverse distance effect (see Figures 1–3) does leave open the possibility that scanning may be used for these trials, just at a much faster rate.

Our findings suggest that there are multiple order-related processes operating in parallel (see Figure 4D), a scanning mechanism that leads to a decision for cross-decade trials, as well as an LTM-CM operating for within-decade trials. If participants initiated the scanning mechanism after the LTM-CM, there should be a different pattern of results (see Figure 4C). Specifically, cross trials should take significantly longer for both small- and large-distance trials; however, there was no significant effect of crossing for small-distance trials. This suggests that scanning small distances takes about the same amount of time as does the LTM-CM. Although there are no significant effects of decade crossing for the small-distance trials, the trend across the two number experiments (Experiments 1 and 3) raises the possibility that these two processes occur sequentially, with the LTM-CM initiated first, followed by the scanning mechanism.

Decomposed Versus Holistic Number Representation

Given the order processes suggested by the present task, we now consider how these processes fit into a traditional (magnitude-based) model of number representation. For example, one issue that the present experiments can address is how the break between decades is represented on the number line when ordinal information is emphasized. The interaction between distance and decade crossing is consistent with work by Nuerk, Weger, and Willmes (2001), which showed that there is a break in the number line at each decade. The present results suggest that, in an order task, when numbers are within the same decade, they can be decomposed, with only the ones units being compared. This decomposition is consistent with work showing that both the ones and tens units are relevant in number comparison tasks. The evidence for these claims is based on compatibility effects in which RTs are faster when comparing the size of 2 two-digit numbers if both the ones and the tens units are larger or smaller than the comparison number, regardless of overall distance (e.g., 12 and 45 are compatible, and 25 and 31 are incompatible; Nuerk et al., 2004; Nuerk & Willmes, 2005). The flat distance function for our within-decade trials can be attributed to the fact that the order of the digits 1–9 is well learned, so that participants can retrieve this information without being influenced by the distance between the numbers when order is an important aspect of the task.

There was also no effect of distance for order judgments with months in which all three months were within a calendar year. This effect, with months, suggests the possibility not only that decade effects are due to the decomposition of the numbers, but that they may also be related to the way in which numbers are learned. After all, months are in no way decomposed, but there are still significant boundary effects, which are likely due to the way people learn and think about the months as an ordered set of items. For example, since we learn the months of the year as an ordered set of items starting with January and ending with December, participants are able to directly retrieve information about the order of three months from long-term memory for trials in which all the months are between January and December. When the months cross the canonical year boundary (i.e., January), they are forced to rely on a scanning mechanism rather than on long-term memory processes.

Other evidence for the LTM-CM comes from an order task with letters in which participants were required to indicate whether the letters were forward or backward (Fulbright, Manson, Skudlarski, Lacadie, & Gore, 2003). In Fulbright et al., no distance effects were reported, which could be attributed to the fact that letters are an ordinal sequence without clear boundaries, which allows the order information to be retrieved independent of distance.

In addition to the within-decade effects, the interaction between distance and decade crossing also suggests that, when numbers cross a decade, participants do not simply decompose the two-digit number. Instead, participants treat the number holistically and use a scanning strategy to reach a decision. This strategy leads to longer RTs when the numbers span a greater distance. This result is consistent with work by Dehaene, Dupoux, and Mehler (1990) showing that, for a task that involves assessing whether a given number is larger or smaller than some target number (e.g., 65), there were no discontinuities in the number line at decade breaks. So, when participants were faced with a two-digit number from a different decade (e.g., 71), instead of making a quick decision on the basis of the tens digit (7), which would be sufficient to reach a decision, they treated the number as whole. For example, participants were faster when comparing 78 with 65 than when comparing 71 with 65, which supports a holistic view of number representation in which two-digit numbers are treated as a single magnitude rather than as separate ones and tens digits.

Role of Size Effects in the Number Line Representation

One notable difficulty that traditional analogue magnitude models of number representation have in explaining the present results has to do with the size effect. The size effect is typically taken as evidence for either a compressed number line as numbers get larger (Dehaene, 2003) or for increased variability in ordinal position as numbers get larger (Gallistel & Gelman, 1992, 2000). If scanning makes use of the same number line representation, these models would predict that scanning should be faster for larger numbers because they are closer together, which is contrary to our findings. The size effect as interpreted in the context of the present study suggests a longer scanning time for larger numbers.

These contrary findings are consistent with work dissociating size and distance effects (e.g., Verguts, Fias, & Stevens, 2005; Verguts & van Opstal, 2005) that suggests that size effects are not inherently tied to a mental number line and may instead be task related. Results from these studies show that tasks such as number naming, parity judgment, and *same–different* judgments show distance effects but no size effects, which suggests that participants are accessing a mental number line that does not obey Weber's law. Likewise, the lack of a size effect for months also supports the idea that size effects need not be incorporated into representations of order information in general. This being the case, scanning time is dependent on the total number of items to be scanned, not on the distance between individual items along an analogue representation. Although the possibility remains that there could be a different compressed number line representation used for magnitude comparisons, recent neuroimaging studies support a single representation for both magnitude and order in the intraparietal sulcus (Fias, Lammertyn, Caessens, & Orban, 2007; Franklin & Jonides, in press; Jacob & Nieder, 2008).

Relation of the Present Results to Other Findings in the Literature

There have been other studies that have found results similar to those in the present study. Turconi et al. (2006) compared performance on a magnitude comparison task—in which participants chose the larger of two single-digit numbers—with an order task in which participants were asked whether the two numbers were in the correct order. The order instruction led to a reverse distance effect for adjacent ascending numbers. The reverse distance effect in their order task was interpreted as an order-specific process; however, there remains the possibility that these effects are due to the familiarity of adjacent numbers in memory. Therefore, the results from Turconi et al. do not conclusively show that the reverse distance effect is due to participants' scanning a mental number line. The fact that we found reverse distance effects using nonadjacent triplets suggests that the reverse distance effect found in these order tasks is related to a scanning mechanism.

In another study, Brysbaert (1995; Experiment 4) tested different theories of number representation by using a task in which participants named a target number shown at various stimulus onset asynchronies (SOAs) after a prime. A plot of the interaction of distance and decade crossing revealed a pattern similar to our results for each of the SOAs and was statistically significant for the SOA of 400 msec. There was no slope for numbers within a decade and a positive slope for numbers that crossed a decade. It may be, then, that naming numbers involves accessing ordinal information about numbers, which led to similar results as in the present study. However, given the differences both in the magnitude of the reverse distance effects and in overall RTs in our study (reverse distance effect $>$ 100 msec, overall $>$ 1,200 msec) compared with those found in the Brysbaert study (reverse distance effect $=$ 20 msec, overall $<$ 800 msec), further work will be needed to clarify the relation between these two studies.

Conclusion

Recent debate concerning the relation between magnitude and order processing has, in large part, been fueled by neuroimaging results that suggest that both types of information are processed by similar brain regions (Fias et al., 2007; Jacob & Nieder, 2008). However, due to our use of a task with three numbers to block a magnitude strategy, the present results suggest that behavioral differences emerge when comparing the processing of magnitude and order information. Therefore, the present work adds to our knowledge of number processing by showing that, although numbers, as ordinal sequences, retain the analogue properties of a mental number line, they are processed by distinct order-related mechanisms: a scanning mechanism for numbers that cross a decade boundary, and an LTM-CM for numbers that are within a decade. The experiment with months helped to demonstrate that the order processes revealed by the present task are not dependent on numerical processing. Due to our use of a novel task that emphasized the processing of order information, the present results have revealed a more complete view of number processing and, more generally, the processing of other well-learned ordered sequences.

AUTHOR NOTE

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NOTE

1. The results differed for the mixed trials, with no significant interaction of distance and decade crossing and no significant main effect for distance. There was, however, a trend toward a main effect for decade crossing [$F(1,19) = 3.49$, $p = .08$], with participants taking longer when the trials crossed a decade. In addition, there was a significant positive correlation between number magnitude and RT ($r = .18$, $p = .001$), which is evidence for a size effect in which participants took more time as the numbers became larger.

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