Appendix

As we mentioned in the *Method* section of Experiment 1 (footnote 1), an alphabetic order task (deciding if a pair of letters is presented in the alphabetic order or not) was also included in Experiment 1 with the aim to compare the mechanisms involved in processing order information on quantitative (i.e., numbers) and non-quantitative (i.e., letters) sequences.

In addition to pair-distance and pair-order effects, the serial position of letters in the alphabet was also classically shown to affect alphabetic order judgments. The serial position (or end) effect refers to the finding that it takes longer to decide the relative order of two letters drawn from the middle portion of the alphabet than from the beginning or the end of the sequence (e.g., Jou, 1997; Jou & Aldridge, 1999).

Comparing performance in relative order judgments with letters and numbers may shed some light on the effects that are specific to the alphabetic sequence processing (e.g., serial position), from those that generalize to the numerical sequence (e.g., distance and pair-order) and thus possibly reflect more general (i.e., independent of stimulus material) order coding mechanisms.

Besides, the inclusion of a size-congruity manipulation in the present alphabetic task could be informative as to whether "coding for order involves the use of a magnitude code similar to that employed in numerical tasks". This hypothesis was recently proposed by Marshuetz and colleagues (2000) to account for the finding that parietal regions engaged in processing the order of letters overlapped brain areas involved in number processing. In our view, the activation of similar brain regions in letter and number processing tasks might receive a different interpretation and be explained by the pure sequential nature of letters and numbers, without the need of an additional activation of magnitude information. Hence, the presence or absence of a size congruity effect in the alphabetic task might be helpful in disentangling these issues. If Marshuetz et al. (2000)'s hypothesis of an underlying magnitude-coding mechanism is correct, processing the order of incongruent letter pairs (i.e., pairs in which the letter coming later in the alphabet has the smaller physical size; e.g., E B) should elicit longer RTs than processing pairs in which the letter's physical size is congruent with its corresponding "magnitude"[1] or position in the sequence (e.g., E B). In this case, we should find a similar size-congruity effect in the alphabetic task as the one reported with numerical stimuli. Conversely, if letter processing is based on the serial order of items in the sequence, no such (magnitude-based) size congruity effect is expected.

Method.

The alphabetic task was identical to the numerical order task, with each number replaced by the letter occupying the corresponding position in the alphabet (i.e., 2 replaced by B, 3 replaced by C, etc.). Subjects had to decide whether the pair of letters was presented in the alphabetic order (e.g., B C) or not (C B). The eight different letter pairs (four close/consecutive pairs: B-C, C-D, F-G, G-H; and four far pairs: B-E, C-F, D-G, E-H), together with unanalyzed filler pairs (A-B, A-D, F-I, H-I), were presented in each of the three congruity conditions (congruent, neutral, incongruent)[2]. All pairs were presented in both ascending (i.e., conventional, alphabetic order; e.g., B C) and descending (e.g., C B) order. The alphabetic task was performed twice: once with "Yes" responses assigned to the left-hand, and once to the right-hand. The order of the three tasks (alphabetic, numerical quantity and numerical order) was counterbalanced across subjects. The general procedure of the alphabetic task (temporal sequence of events, size of stimuli, etc.) was identical to that described for numerical tasks.

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[1] The "magnitude" of a letter depends on its position in the alphabet and corresponds to the magnitude of the digit occupying the same position in the number sequence (e.g., magnitude 2 for letter B, 3 for letter C, etc.).

[2] For the sake of simplicity, we used the same labels in the alphabetic task as those employed in numerical tasks. In the congruent condition, the letter coming later in the alphabet was the physically larger; in the neutral condition, both letters had the same intermediate physical size; in the incongruent condition, the letter coming later in the alphabet was the physically smaller.

Results

The mean error rate in the alphabetic task was 7.2%, which is significantly higher than the error rate in the order on numbers task (4.7%; $t(23) = -4.8$; $p < 0.0001$). Similarly, processing the order of letters took more time (mean RT: 1292 ms) than processing the order of digits (709 ms; $t(23) = -12.8$; $p < 0.0001$). Higher error rate and slower RT in alphabetic relative to numerical order judgments is consistent with previous research (e.g., Parkman, 1971; Jou, 2003) and might be explained by a weaker knowledge of the alphabetic relative to the numerical series (e.g., letters can hardly be recited backwards; see Pesenti, 1995).

In the alphabetic task, mean error rates and mean RTs were positively correlated across cells [$r = 0.615$, $p = 0.033$], discarding any speed-accuracy trade-off. We thus present detailed analyses of RT only.

A first ANOVA including Distance (1, 3), Pair-order (ascending, descending) and Congruity (congruent, neutral, incongruent) as within-subjects factors, and Order of tasks[3] as a between-subjects variable was computed on mean correct RTs. This analysis showed a complex carryover effect from the order in which tasks were performed, as revealed by the four-way interaction between Order of tasks, Distance, Congruity and Pair-order [$F(2,44) = 7.52$, MSE = 17838.92, $p < 0.002$]. This indicates that previous processing of numerical quantity potentially modulated strategies and performance on the following alphabetic order task. Consequently, as we did with numerical tasks, we focused on the group of subjects who processed alphabetic order before quantity.

Mean correct RTs for each Distance x Pair-order x Congruity cell for the alphabetic task-first group appear in Table 3. The source table for the corresponding ANOVA appears in Table 4.

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[3] In order to highlight an eventual bias of quantity processing in the alphabetic order task, we included the order in which these two tasks were performed (quantity before order on letters, or the reverse) as a between-subjects variable.

Table 3 Mean correct RT (in ms) in the alphabetic order task for each pair-order (ascending, descending) x distance (close, far) x congruity (congruent, neutral, incongruent) condition.

	Alphabetic order task			
	Ascending order		Descending order	
Congruity	Close pairs	Far pairs	Close pairs	Far pairs
Congruent	1191	1213	1437	1248
Neutral	1172	1222	1467	1293
Incongruent	1197	1265	1457	1255

Table 4 Three-way analysis of variance for mean correct RT in the alphabetic order task, with distance (close, far), pair order (forward, backward) and size congruity (congruent, neutral, incongruent) as within-subjects variables.

Source	df	F
	Within subjects: Distance	
Distance (D)	1	4.15 (*p*-value: 0.066)
MSE	11	(118450.68)
	Within subjects: Pair-order	
Pair-order (P)	1	47.71***
MSE	11	(26730.83)
	Within subjects: Congruity	
Congruity (C)	2	0.15
MSE	22	(42163.40)
	Within subjects: Distance x Pair-order	
D x P	1	16.15**
MSE	11	(82654.77)
	Within subjects: Distance x Congruity	
D x C	2	0.31
MSE	22	(32186.77)
	Within subjects: Pair-order x Congruity	
P x C	2	1.02
MSE	22	(28079.84)
	Within subjects: Distance x Pair-order x Congruity	
D x P x C	2	1.90
MSE	22	(27895.59)

Note. Values enclosed in parentheses represent mean square. *$p < 0.05$; **$p < 0.01$; ***$p < .001$.

The main effect of Pair-order was significant since letter pairs in the alphabetic order (1176 ms) were processed 133 ms faster than letter pairs in descending (non-alphabetic) order (1309 ms). Comparing the pair-order effect in the two order tasks revealed that this was larger with letters than numbers [$F(1,22) = 7.90$, MSE = 9346.49, $p < 0.01$].

As reported in Table 3, size congruity did not principally affect alphabetic order processing and did not enter in any significant interaction. The main effect of Distance did not reach significance but was modulated by Pair-order. Pairs in the ascending order were processed faster when adjacent (1149 ms) than farther apart in the alphabet (1203 ms), but this effect did not reach significance [$F(1,11) = 1.06$, n.s.][4]. When letter pairs were presented in the descending order, a standard distance effect was observed (close pairs: 1419 ms, far pairs: 1200 ms; [$F(1,11) = 16.66$, MSE = 51727.29, $p < 0.002$]).

Since the serial position of letters was shown to influence performance in alphabetic tasks, we included this variable in the analyses and tested whether and how it affected strategies and RT in the present alphabetic order task. Stimuli were divided into "early" (B-C, C-D, B-E, C-F) and "middle" (F-G, G-H, D-G, E-H) letter pairs, according to their position in the alphabet (beginning or middle of the sequence). A new ANOVA including Distance, Pair order, Congruity and Serial position (early, middle) as within-subjects factors was computed on mean correct RTs, only for subjects in the alphabetic order-first group. The main effect of serial position was significant [$F(1,11) = 35.40$, MSE = 158684.51, $p < 0.0001$] and showed that letter pairs at the beginning of the alphabet (1103 ms) were processed 279 ms faster than letter pairs towards the middle of the sequence (1382 ms). Serial position interacted with distance [$F(1,11) = 15.90$, MSE = 99333.71, $p < 0.002$]. Separate analysis of early and middle letter pairs revealed that early pairs were processed 65 ms faster when letters were adjacent in the alphabet (1070 ms)

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[4] Note that the pattern of error rates reinforces this trend. In the ANOVA with Distance, size Congruity and Pair order the significant interaction between Distance and Pair order [$F(1,11) = 13.84$, MSE = 1.31, $p < 0.003$] proved that pairs in the alphabetic order were less error prone when consecutive (5.9%) than more distant (8.0% [$F(1,11) = 5.2$, MSE = 0.86, $p < 0.043$]), whereas pairs in descending order showed a standard distance effect (close pairs: 9.0% errors, far pairs: 5.2% [$F(1,11) = 5.42$, MSE = 2.79, $p < 0.04$]).

relative to farther apart [1136 ms; $F(1,11) = 8.39$, MSE = 18409.02, $p < 0.015$], thus producing a reverse distance effect. Conversely, pairs of letters closer to the middle of the sequence showed a standard distance effect, with a 231 ms advantage for far letter pairs (1267 ms) compared to close letter pairs [1498 ms; $F(1,11) = 9.61$, MSE = 199375.38, $p < 0.01$].

Serial position and Distance also entered in a three-way interaction with Pair-order [$F(1,11) = 5.12$, MSE = 32761.69, $p < 0.045$], which is depicted in Figure 1. Further modulation by pair-order revealed that the reverse distance effect for early letter pairs was limited to pairs in the ascending order (close: 967 ms, far: 1120 ms [$F(1,11) = 14.72$, MSE = 28770.19, $p < 0.003$]) and was not significant when pairs were presented in the descending order (close: 1174 ms, far: 1151 ms [$F<1$]). With respect to middle letter pairs, modulation by pair-order showed that the standard distance effect was limited to pairs in descending order (close: 1664 ms, far: 1248 ms [$F(1,11) = 17.81$, MSE = 174185.54, $p < 0.001$]) and was not significant for pairs in the alphabetic order (close: 1332 ms, far: 1286 ms [$F<1$]). Finally, the four-way interaction involving Serial position, Distance, Pair order and Congruity [$F(2,22) = 3.69$, $p < 0.045$] suggested that size congruity affected the processing of early close letter pairs presented in the alphabetic order (that is, pairs B-C and C-D). For these pairs only, congruent trials (876 ms) were processed faster than incongruent trials (1047 ms [$F(2,22) = 12.94$, MSE = 22897.20, $p < 0.001$]).

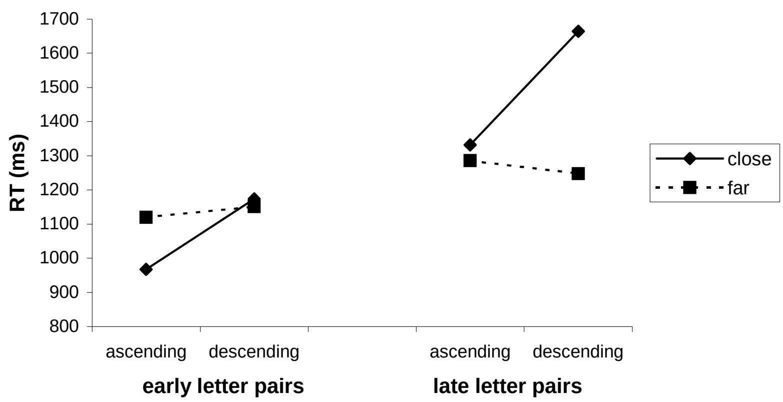

Figure 1. Mean correct RT by position of letters in the alphabet (early, middle), pair-order (ascending, descending) and distance (close, far).

In order to test whether serial position would similarly affect performance in number processing and in particular in the numerical order task, we ran new analyses of variance including this variable. Number pairs were divided (like letters) into "early" (i.e., small: 2-3, 3-4, 2-5, 3-6) and "middle" (i.e., large: 6-7, 7-8, 4-7, 5-8). The ANOVA with Serial position, Distance, Pair-order and Congruity as within-subjects variables, and Task (quantity-first, numerical order-first) as a between-subjects factor was computed on mean correct RTs. This revealed a main effect of Serial position [$F(1,22) = 34.52$, MSE = 5248.22, $p < 0.0001$] which was similar in the two tasks [Serial position x Task interaction: $F(1,22) = 1.5$, *n.s.*]. Early pairs (640 ms) were processed on average 36 ms faster than middle pairs (676 ms). More crucially, serial position did not modulate the distance effect [Serial position x Distance interaction: $F(1,22) = 1.97$, *n.s.*] in any of the numerical tasks [interaction with Task: $F < 1$] and did not enter in a three-way interaction with Distance and Pair-order [$F < 1$]. This suggests that the strategies involved in processing quantity or order on single-digit numbers were not modulated by numbers' position in the sequence.

Discussion

Overall, the results reported in the alphabetic order task (i.e., pair order, distance and serial position effects) were consistent with previous research on alphabetic order processing. What is more, comparing the results from the alphabetic and the numerical order tasks revealed that order judgments were affected by the same variables, such as pair-order and distance, whatever the type of stimuli (letters or numbers) to be processed.

Alphabetic order judgments were shown to be affected by pair-order, since these judgments were made faster when letter pairs were presented in the ascending (e.g., B C) relative to the descending order (e.g., C B). These results replicated previous research on alphabet processing (Grenzebach & McDonald 1992; Hamilton & Sanford, 1978; Lovelace & Snodgrass, 1971). When comparing the effect of pair-order in the alphabetic and the numerical order tasks, we found that letter sequence processing was more affected by pair-order than number sequence processing.

Pair-order was also shown to modulate the distance effect produced when judging the order of letters in a pair. This modulation was similar to that reported in numerical order judgments since pairs in the ascending order were processed faster when adjacent than farther apart in the sequence, while pairs in the descending order produced a standard distance effect (i.e., faster processing of far than close pairs). However, the alphabetic distance effect was additionally influenced by items' (i.e., letters') serial position in the sequence, which was not the case for the numerical distance effect. Hence, when letter pairs were presented in the descending order, a standard distance effect was observed for letters from the middle portion of the alphabet, while the distance effect was not significant for letters from the beginning of the sequence (see Figure 1). Conversely, when letter pairs were in the ascending (i.e., alphabetic) order, a reverse distance effect was produced, but this was restricted to letters from the beginning of the alphabet. This pattern of results suggests that different cognitive mechanisms were used in the alphabetic order task, depending on both pair-order and the serial position of letters in the alphabet.

The standard distance effect for descending middle letter pairs (e.g., faster processing of pair G-D than pair G-F) entails a comparison strategy (e.g., Jou, 1997). Since a similar distance effect was reported on descending number pairs in numerical tasks (as well as on ascending pairs in the numerical quantity task), the present data suggest that processing the order of either two letters from the middle portion of the alphabet or two numbers could be mediated by a similar cognitive mechanism, when pairs are presented in the descending (i.e., non-conventional) order. This mechanism was also involved in numerical quantity judgments.

The reverse distance effect (i.e., faster order judgments for consecutive relative to non-consecutive letters) reported on ascending pairs of letters from the beginning of the alphabet could receive two interpretations (see also the General Discussion section of the paper). The first and most common account for the reverse distance effect is in terms of the activation of a serial search process (Jou, 1997, 2003); in the present case, activation of the alphabetic sequence recitation. This process would produce an increasing RT with the increasing number of intervening items in a pair, thus generating a reverse distance effect. Research on alphabetic order processing has usually reported that the reverse distance effect for well-ordered (i.e., ascending) pairs was restricted to a significant increase in RT from Distance 1 (i.e., consecutive pairs) to Distance 2 (e.g., Grenzebach & McDonald, 1992; Jou, 2003). The present data show that for letters at the beginning of the alphabet, the increase in RT is significant also from Distance 1 to Distance 3. These data are compatible with the use of a serial search process, but the absence of Distance 2 letter pairs in our design prevents us from observing a parametric variation of the reverse distance effect with pair-distance. If the reverse distance effect were purely modulated by pair-distance (i.e., if RT for Distance 2 pairs were intermediate between RT for consecutive and Distance 3 pairs), it would reinforce the hypothesis that subjects resort to a serial search (i.e., recitation) process when judging the order of letters from the beginning of the alphabet, when letters are presented in the alphabetic order. In the absence of such evidence, a second hypothesis should be taken into account to explain for the reverse distance effect in the present experiment. Faster order judgments for early well-ordered consecutive pairs (e.g., B-C), relative to more distant (e.g., B-E) letter pairs, might be explained by the special status of consecutive pairs, as they are more familiar and more frequently associated in the language than non-consecutive (but still well-ordered) stimuli. The special status of ascending consecutive pairs might call for a special processing mechanism (e.g., direct recognition of their order), while processing non-consecutive pairs would require a different (possibly comparison) mechanism.

Yet, according to the present data, the hypothesis of a special mechanism for processing order on ascending consecutive pairs should be restricted to letters in the early portion of the alphabet, since letters drawn from the middle of the sequence did not show such reverse distance effect. To the contrary, middle letter pairs in the ascending order were processed equally fast whether they were consecutive in the sequence or they had a distance of 3. The same profile (i.e., absence of a distance effect) was also reported for descending pairs of letters from the beginning of the alphabet. Hence, the absence of a distance effect in these two conditions (middle ascending pairs and early descending pairs) suggests the use of a mixture of two modes of order construction (i.e., serial search and comparison), with each mode having an equal probability to be adopted on each trial (see also Jou, 1997).

The serial position of letters in the alphabet was also shown to affect the speed of alphabetic order judgments, as these judgments were faster for letters from the beginning, relative to the middle portion of the sequence (e.g., Jou, 1997). A similar serial position effect was also reported in numerical tasks, and was equivalent when processing quantity or order on numbers. Since the serial position of numbers is in direct correspondence with their magnitude, the reported numerical serial position effect is equivalent to the well-known numerical size (or magnitude) effect. Faster processing of small (i.e., early in the sequence) relative to large (i.e., late in the sequence) numbers has been classically reported in number comparison studies (e.g., Dehaene et al., 1990; Parkman, 1971) and received different interpretations according to various models of the number line (compressed number line towards large numbers, Dehaene, 1992; scalar variability in the mapping from the input units to the number line, Gallistel & Gelman, 199; magnitude-coding, Zorzi & Butterworth; 1999; non-linear mapping from the number line to the output units, Verguts, & al., 2005; see this latter paper for a detailed account of how number line models account for the size effect).

In the alphabetic task, however, the serial position of letters in the sequence further modulated the strategies involved in order judgments. Processing the order of ascending letter pairs drawn from the beginning of the alphabet was mediated either by a serial search mechanism or by a special mechanism (e.g., direct recognition of order), when letters were consecutive. Conversely, when ascending letter pairs were drawn from the middle portion of the sequence (e.g. G H), their order was not predominantly processed through serial search, as confirmed by the absence of a reverse distance effect for these letter pairs. This finding can be explained in light of the study of Lovelace, Powell, & Brooks (1973) who reported an increased difficulty in reciting the alphabet when starting with a letter from the middle, relative to the beginning, of the sequence. These authors argued that increasing recitation time with the position of the starting letter moving towards the end of the alphabet did not result from weaker interletter associative strength towards the end of the sequence, but from an increased difficulty to enter the alphabetic sequence towards the middle or the end of the series (see also Jou & Aldridge, 1999; Jou, 2003; Klahr, Chase, & Lovelace, 1983; see also Lovelace & Snodgrass, 1971, on the question of the accessibility of letters in memory with respect to their position in the sequence). Hence, because the alphabet is more difficult to recite from a letter towards the middle of the sequence (e.g., G), serial search would be used much less often on middle letter pairs, thus preventing the occurrence of a main reverse distance effect on these pairs.

No interaction between serial position (that is, numerical size in the case of numbers) and distance was reported in numerical tasks. In fact, resorting to a serial search (i.e. counting) strategy when judging the order of ascending number pairs was not restricted to small numbers, i.e., items from the beginning of the sequence (e.g., 2 3), but was used equally often for larger single-digit number pairs (e.g., 7 8). This finding is consistent with adults' ability to count forward starting from a number different than 1 (see Fuson's concept of bidirectional chain; Fuson, 1988) and suggests that the memory accessibility of numbers is quite homogeneous along the scale (see also Jou, 2003).

Comparing data from the alphabetic (serial position per distance modulation) and numerical (no such modulation) order tasks suggests that weaker knowledge of the alphabetic relative to the numerical sequence (cf. the contrasting abilities in backwards recitation for each kind of material) might explain why the serial position modulated the distance and pair-order effects in the alphabetic task, but not in numerical order judgments.

Modulation of the distance effect by pair-order in both numerical and alphabetic tasks, and additionally by letters' position in the sequence in the latter task, suggests that the distance effect might not purely reflect the activation of a magnitude representation (e.g., Dehaene, 1992; Dehaene et al., 1990). What is more, interactions with presentation order and serial position entails that order information, that was shown to be automatically activated (cf. Gevers et al., 2003), might also contribute to the distance effect (see Wiese, 2003).

With respect to size congruity, contrary to numerical tasks, it did not primarily affect performance in the alphabetic task. Since the size congruity effect is thought to reflect the automatic activation of magnitude information, its absence in alphabetic order judgments goes against Marshuetz, et al.'s (2000) hypothesis that order coding (of letters) is mediated by a ‘magnitude code’[5] similar to that employed in numerical tasks.

One exception to this finding was observed for pairs B-C and C-D since the order of these pairs was judged faster when the physical size of letters agreed with their corresponding "magnitude", or serial position in the alphabet (e.g., B-C), relative to when they disagreed (e.g., B-C). This may suggest that letters from the beginning of the alphabet (i.e., letters B, C and D in the present experiment) could be associated with their corresponding magnitude (respectively, 2, 3 and 4), while it would not be the case for letters from latter portions of the sequence (see Butterworth, 1999).

Finally, comparing the pattern of results in the numerical and alphabetic order tasks suggests that similar strategies, i.e., comparison and serial search, were used with both kinds of material (numbers and letters; see Jou, 2003 for a similar result). Hence, resorting to one or the other strategy did not depend much on the quantitative or non-quantitative nature of the sequence, but rather on task demands (e.g., order or quantity in the case of numbers) and on other information activated by the stimulus (e.g., congruity with the forward sequence recitation and accessibility of the items in memory). For instance, the recruitment of a serial search mechanism was facilitated by certain conditions, such as the proximity of items in the sequence, their ascending presentation order, and the position of items at the beginning of the sequence, in the case of letters.

[5] The ‘magnitude code’ could be viewed as a metaphor referring to the order of items in a sequence, but then we think using ‘order coding’ instead of ‘magnitude code’ is less confusing.

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