

CHAPTER 3

Electrophysiological evidence for differential processing of numerical quantity and order in humans

Eva Turconi, Boutheina Jemel, Bruno Rossion, Xavier Seron

Paper published in Cognitive Brain Research 21 (2004) 22-38

Abstract

It is yet unclear whether the processing of number magnitude and order rely on common or different functional processes and neural substrates. On the one hand, recent neuroimaging studies show that quantity and order coding activate the same areas in the parietal and prefrontal cortices. On the other hand, evidence from developmental and neuropsychological studies suggest dissociated mechanisms for processing quantity and order information. To clarify this issue, the present study investigated the spatio-temporal course of quantity and order coding operations using event-related potentials (ERPs). Twenty-four subjects performed a quantity task (classifying numbers as smaller or larger than 15) and an order task on the same material (classifying numbers as coming before or after 15), as well as a control order task on letters (classifying letters as coming before or after M). Behavioral results showed a classical distance effect (decreasing reaction times [RTs] with increasing distance from the standard) for all tasks. In agreement with previous electrophysiological evidence, this effect was significant on a P2 parietal component for numerical material. However, the difference between processing numbers close or far from the target appeared earlier and was larger on the left hemisphere for quantity processing, while it was delayed and bilateral for order processing. There was also a significant distance effect in all tasks on parietal sites for the following P3 component elicited by numbers, but this effect was larger on prefrontal areas for the order judgment. In conclusion, both quantity and order show similar behavioral effects, but they are associated with different spatio-temporal courses in parietal and prefrontal cortices.

1. Introduction

Numbers may convey different meanings according to the context in which they are used [8, 36, 96]. A number may tell us how many entities are

in a set and convey a quantity meaning (e.g., five apples in a basket), or it may refer to the relative position of an element within an ordered sequence and convey order information (e.g., page 5 comes after page 4). Order information is not restricted to numbers and is shared by non-quantitative series, such as the letters of the alphabet, the days of the week and the months of the year. Hence, while properties like quantity and order are disjoined in non-numerical contexts, they are linked up with each other in the cognitive number domain: the larger the quantity a number refers to, the later it is located in the conventional number sequence [96].

Research on number processing has mainly focused on the way quantity is represented, processed and neurally implemented (see Ref. [24] for a recent review), with relatively little consideration for order information (see however Ref. [92]). Moreover, the relationship between mechanisms underlying quantity and order processing remains largely unclear, since experimental studies showed evidence of both similarities and dissociations between quantity and order neuro-functional processes.

The first evidence in favour of shared mechanisms comes from the distance and SNARC effects, since they were reported in the processing of both numbers and non-numerical ordered series. The distance effect refers to the improved ability (shorter reaction times [RTs] and better accuracy) to discriminate between two numbers as the numerical distance between them increases (e.g., Ref. [61]). This effect, which is semantic since it depends on an abstract representation of the digits' corresponding quantity, has been reported with numbers whatever their format — Arabic digits, written words or dot patterns [7, 35] — as well as with non-numerical quantifiable dimensions such as the size of objects [42, 60, 64]. These data were interpreted as evidence that quantitative information converge onto a shared analogue representation of magnitude [22, 34]. However, the distance effect is not restricted to quantifiable dimensions and has also been reported with non-numerical ordered series such as the letters of the alphabet [28, 37, 41, 47, 66, 88] and the months of the year [37]. These data suggest that quantity and order information may share a common underlying representation, coding for relative positions along a continuous (quantifiable or non-quantifiable) dimension. The Spatial Numerical Association of Response

Codes (SNARC [21]) is a second psychophysical effect common to the processing of quantity and order. The original SNARC effect was thought to reflect the association between number magnitude and spatial response preference with faster left- than right-hand responses to small numbers and faster right- than left-hand responses to large numbers [21]. This effect was also elicited in tasks that did not require any quantity processing of the digits (e.g., Ref. [32]), thus suggesting the automatic activation of an internal magnitude representation in the form of a left-to-right oriented number line, whenever numbers are processed. However, a SNARC effect has recently been reported with the series of letters and months [37], in both order relevant and order irrelevant tasks. These results suggest that the internal representation of ordered sequences is spatially coded, just as numbers, and that this spatial code is automatically activated.

Further evidence for common underlying mechanisms for quantity and order coding comes from neuroimaging. Processing numbers activates the intraparietal cortex (e.g., Refs. [10, 23, 28, 34, 67, 70]), suggesting that this area underlies the abstract representation of number magnitude. Besides, Marshuetz et al. [54] reported that regions of parietal cortex involved in processing order information on letters (i.e., non-numerical stimuli) were also engaged in number processing tasks [10]. This led the authors to suggest that ‘the underlying representation of order and numbers may share a common process’. Order also activated regions in the dorsolateral prefrontal cortex [9, 54].

A third line of evidence for commonalities between quantity and order processing comes from the association of impairments or spared processes in brain damaged patients. Patient CG [11] had a severe deficit in processing numbers (she was totally unable to deal with numbers above 4) and was also impaired in processing stimuli belonging to ordered series (she could not correctly recite the series of letters, days and months nor give the next item in the sequence), whereas patient NM [90] was severely impaired in several semantic tasks (he showed severe anomia for all categories of words), while his performance with numbers and non-numerical ordered sequences was largely preserved.

Although behavioral, neuroimaging and neuropsychological data support some common underlying mechanism in processing quantity and order, developmental and neuropsychological studies argue for potentially dissociable processes. Studies on the acquisition of number knowledge have reported dissociated learning for sequence and cardinal number meanings: children first learn the number words sequentially, without knowing which quantity they refer to, and they acquire their cardinal meaning only after learning that each position of a word in the sequence is directly related to its quantity [36, 97]. To corroborate this developmental distinction, a neuropsychological double dissociation has been reported between quantity and order processing abilities, after brain damage. On the one hand, two patients were described to be unable to access the quantity meaning of numbers ([26] and patient MAR [19]), while their ability to process order was better preserved. On the other hand, two other patients, BOO [19] and CO [91], showed the reversed pattern of dissociation, that is, a preserved performance in quantitative numerical tasks, but impaired abilities in tasks involving ordered series. More critically for patient CO, although he was good and had a normal distance effect in magnitude comparison of numbers, he was slower and less accurate when judging the same numbers according to their order—before/after—meaning. Similarly, for a same target number, he was flawless in giving a number smaller or larger, but was unable to give a number that came before or after.

To sum up, the evidence so far is not conclusive as to whether quantity and order processing rely on some common or separate underlying mechanism(s).

One possibility that has not been clearly investigated thus far is that quantity and order processing may show similar behavioral effects and neural substrates, and yet be temporally dissociated, that is, taking place in overlapping brain regions at different time scales. The present study was designed to shed light on this issue. It differed from previous investigations in two ways. First, in order to disentangle the opposing views of either common or separate mechanisms for quantity and order coding, we directly compared these processes. Second and most importantly, the possibility that they take place in the same regions at different time courses has never been

seriously considered. In the present study, we used event-related potentials (ERPs) to address this question. Two tasks were devised to investigate the relationship between numerical quantity and numerical order. In the quantity task, subjects had to judge whether a number was smaller or larger than a fixed standard, and in the numerical order task, they had to decide whether the same number came before or after that standard. In addition, subjects performed an alphabetic task, aimed at clarifying the relationship between quantifiable and non-quantifiable order. In this last condition, subjects had to decide if a letter came before or after a standard letter in the alphabet. All these tasks were supposed to elicit a distance effect, as shown in previous studies (e.g., Refs. [20, 28, 47, 66]).

Based on the findings of the few previous ERP studies of either quantity or order processing, we tracked a sequence of ERP components, from the onset of the stimulus to the subject's response. More precisely, Dehaene [16] identified three successive stages during a quantity judgement task: (1) a visual identification stage (corresponding to N1 component), which was affected by stimulus notation and involved bilateral (for Arabic numerals) or left-lateralized (for verbal numerals) occipito-temporal regions; (2) a magnitude comparison stage, affected by the distance between standard and stimuli and taking place in the left and right parieto-occipito-temporal regions on the P2p and rising part of P3 components; and (3) a response preparation and execution stage that showed activation of the motor cortices contralateral to the response key. Because these stages did not overlap, results validated a serial stage processing of numbers, suggesting convergence toward a common abstract magnitude representation of numbers regardless of their input format. More recent ERP studies have confirmed these results, albeit reporting even earlier distance effects, at the level of the N1 [70, 89]. As for order processing on ERPs, a classic distance effect was found for letters on both RTs and on a late parietally positive potential (P3, around 475 ms post-stimulus) that was reduced in amplitude for close letter judgements [58].

In sum, evidence from these ERP studies suggest that the distance effect arises at the comparison stage and reflects the activation of an abstract representation independent of input notation and coding for proximity

relations between items. Directly comparing the temporal course and topographical profile of the distance effect elicited by quantity and order processing tasks should enable us to answer the question of whether quantity and order share some common semantic representation and/or processing mechanism(s) or whether they dissociate at this stage of processing.

2. Methods

2.1. Subjects

Twenty-eight right-handed volunteers with French as their mother tongue took part in the experiment and received monetary compensation. All participants had normal or corrected to normal vision. Technical failure caused data loss for one participant and data from three other subjects were excluded from further analyses due to insufficient artifact-free trials after editing. The remaining 24 subjects (6 males)¹ were aged between 20 and 30 (average 24.6 years).

2.2. Stimuli

Numbers 11, 12, 13, 14, 16, 17, 18 and 19 in the Arabic code and capital letters I, J, K, L, N, O, P and Q were presented on a standard PC monitor on a dark gray background. All stimuli were presented from a constant viewing distance of 80 cm in an Arial 48-point font in black in the center of a white window with a visual angle of 1.07° (height) and 1.43° (width). All numbers subtended a visual angle of 0.85° (height) and 1.1° (width), except for number 11 having a smaller width (0.96°). Letters subtended a visual angle of 0.85° in height and between 0.14°, for letter I, and 0.78°, for letter Q, in width. Number and letter stimuli did not differ in luminance. Stimuli were presented one at a time for 105 ms and were preceded and followed by a dark gray screen.

¹ Note that no gender differences were reported in the normal adult population in number comparison tasks (e.g., Ref. [27]).

2.3. Experimental tasks

Subjects were asked to perform three comparative-judgment tasks: one required quantity processing and the other two order processing. In the quantity task, subjects were presented with a pseudorandom list² comprising the numbers 11 to 19 (except 15) in the Arabic code and they had to decide whether each number was smaller or larger than 15.³ In the order judgment on numbers task, subjects were presented with the same stimuli and had to decide whether each number came before or after 15 in the conventional sequence of numbers.⁴ In the order judgment on letters task, subjects were presented with a pseudorandom list comprising the letters from I to Q (except M) and they had to decide whether each letter came before or after M in the alphabet. The order of tasks was counterbalanced across subjects.⁵

Each trial started with the presentation of a stimulus for 105 ms, followed by an ISI (dark gray screen) of 2050 ms on average (varying between 1800 and 2300 ms) during which subjects responded to the target and then waited for the next trial. Each task was presented separately and included 16 training trials and 40 presentations of each target number/letter, for a total of 336 trials per task. Each task was divided into four blocks and short breaks were allowed between blocks and tasks.

In all tasks, subjects were asked to respond as quickly and as accurately as possible by pressing one of two corresponding response keys with their left or right hand. The assignment of response keys was counterbalanced across participants. Half of the subjects had to respond to “smaller/before” items by pressing the left-hand key and to “larger/after” items by pressing the right-hand key, and this assignment was reversed for the other half of the subjects.

² The same item was never presented in two consecutive trials. All items were preceded in half of the trials by a smaller/before item and in the other half by a larger/after item.

³ We used the standard 15, instead of 5, in order to place the subject in a less automatized portion of the number sequence, than the very beginning of the series. Similarly, letters from the beginning of the alphabet were avoided to the benefit of stimuli from the middle portion of the series. Moreover, we used the letter “M” as the standard letter in order to compare our results with those from previous behavioral [67] and ERP [59] studies.

⁴ Instructions emphasized on the use of a sequence (before/after) rather than a quantity (smaller/larger) strategy in this task, in order to try differentiate order processing on numbers from a quantity processing.

⁵ There were six different orders in which subjects could perform the three tasks: 1 2 3, 1 3 2, 2 1 3, 2 3 1, 3 1 2, 3 2 1, with 1 standing for the quantity task, 2 for the order on numbers task and 3 for the order on letters task.

2.4. Experimental procedure

EEG recording was conducted in a dimly lit, electrically shielded room. Following electrode application, participants were seated in a comfortable chair, their head being restrained by a chin rest. Participants were instructed to remain as still as possible and to focus on the center of the screen during stimulus delivery.

2.5. ERP recording procedures

Continuous electroencephalographic (EEG) activity was recorded from 62 tin scalp electrodes, according to the extended 10–20 system using an elastic cap (QuickCap, Neuroscan). The horizontal and vertical EOG was monitored with appropriate electrode pairs placed above and below the left eye and at the outer canthi of the eyes. All scalp electrodes were referenced to linked earlobes for recording and re-referenced off line to a common average reference. Impedances of all electrodes were kept below 8 kV during recording. Band pass was set from 0.1 to 100 Hz and the sampling rate was 500 Hz. STIM software controlled the stimulus presentation and recorded subjects' behavioral responses given within a latency range of 200 and 1600 ms after stimulus onset.

EEG data was processed using EEProbe 3.1 (ANT). Trials with eye-blinks and other artifacts were excluded from averaging if (i) the standard deviation of the EOG within a sliding 200-ms time window exceeded 40 μ V and/ or (ii) the standard deviation of any scalp electrode during this time window exceeded 20 μ V. Epochs with eye blinks were detected and corrected by subtracting from the EEG the PCA-transformed EOG components for each electrode, weighted according VEOG propagation factors (computed via linear regression) [63]. From the edited set of raw data, ERPs were extracted by averaging single trials separately for subjects, electrodes, tasks (quantity, order on numbers and order on letters) and whether the item was close (i.e., at a distance of 1: numbers 14 and 16 for

numerical tasks and letters L and N for the alphabetic task) or far (i.e., at a distance of 4: numbers 11 and 19 and letters I and Q) from the standard.⁶

All EEG segments were band-pass filtered (1–30 Hz) before averaging and baseline corrected relative to a 200-ms time window preceding target onset. Artifact-free trials were then averaged separately synchronous to stimulus onset, from 200 ms before to 800 ms after stimulus onset. Only trials with correct responses were used for the ERP average. Mean number of sweeps in each condition for each subject was 69.

2.6. Data analyses

2.6.1. Behavioral data

Median correct RTs from the ERP test were computed for each individual item for each subject and submitted to a repeated measures ANOVA with task (quantity, order on numbers, order on letters), distance (1, 4), size/position (smaller/before, larger/after the standard) as within-subject factors and assignment of response keys (smaller/before-left, smaller/before-right) and order of tasks (six levels) as between-subjects factors. Error rate was also computed for each condition.

2.6.2. ERP data

Identification of ERP components (time window and electrodes) and their counterpart was based on visual inspection of both grand average ERP waveforms and topographical maps of 10-ms duration. P1 amplitude was computed as the mean amplitude value in a window of 80–120 ms, on parietal-occipital-temporal electrodes (P7/P8, P5/P6, PO7/ PO8, PO5/PO6, O1/O2, POz, Oz), with a negative counterpart on Fz. N1 mean amplitude was similarly measured in a 130–170-ms time window, on bilateral parietal-occipital sites (P7/P8, P5/P6, P3/P4, PO7/PO8, PO5/PO6, O1/O2); its concomitant fronto-central positive counterpart was maximal on electrodes

⁶ When variable size/position of the item (smaller/before or larger/after the standard) was taken into account in statistical analyses, ERPs were averaged separately for each level of this variable.

FCz and Cz. The largest amplitude value in this window was taken as the N1 peak latency. The second posterior positivity (P2p) was measured on similar parietal-occipital-temporal regions as P1 and N1 (P7/P8, P5/P6, P3/ P4, PO7/PO8, PO5/PO6, PO3/PO4, O1/O2, POz, Oz) on a 170–210-ms time window for numerical tasks, with a maximal negative counterpart on electrode CPz. The P2p component was delayed for alphabetic material and measured in a 210–240-ms window on the same parietal-occipital-temporal regions as the numerical P2p, together with a frontocentral negativity that was maximal on FCz and Cz. The following N2 was measured on a 240–280-ms window on electrode FCz, together with the concomitant positivity over similar regions as the former P2p (P7/P8, P5/P6, P3/P4, PO7/ PO8, PO5/PO6, PO3/PO4, O1/O2, POz, Oz). Finally, the late positivity (P3) was measured on electrodes CPz and Pz in a 310–510-ms window, together with its negative counterpart on prefrontal sites (AF7/AF8, AF3/AF4, FP1/FP2, FPz).

A series of repeated measures ANOVAs was computed on the six time windows, separately for each component and its counterpart, and for midline and bilateral electrodes. Mean amplitudes, averaged over the entire time window, were used as dependent variables. To restrict the number of tests, only effects of theoretical significance were tested: task and distance and their interaction. Thus, within-subject factors were task⁷ (quantity, order on numbers, order on letters), distance (1, 4), laterality (left/right, for lateral electrodes) and electrode location. As we had no hypothesis on the influence of size/position of the item (smaller/before, larger/after the standard) on ERPs, interactions of this with other variables will be reported only when relevant for the understanding and interpretation of results. All effects and interactions with two or more degrees of freedom in the numerator were adjusted for violations of sphericity according to the formula of Greenhouse and Geisser. Degrees of freedom are reported before, exact P-values after adjustment. Significant interactions between experimental variables were clarified by either breaking them into simple effects or by means of Bonferroni post-hoc comparisons.

⁷ Note that a task effect may be either due to the type of material to be processed (numbers or letters), to the type of mechanism involved (quantity or order), or both. When the effect is only due to the type of stimuli, it will be termed task/material effect.

3. Results

3.1. Behavioral results

Mean error rate was low and did not differ statistically among the three tasks (2.6%, 2.6% and 3.3%, respectively, for the quantity, order judgement on numbers and order judgement on letters tasks). There was neither a main effect of order ($F < 1$) in which each subject performed the three tasks nor any interaction with this factor, which was thus removed from further analyses.

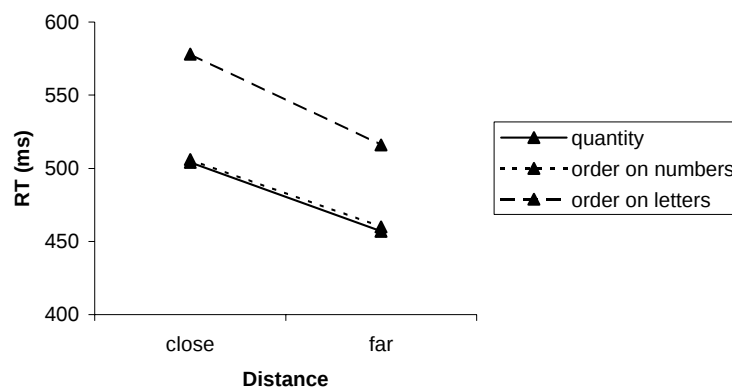


Figure 1. Behavioural distance effect in the three tasks, with close items eliciting longer response times (RTs) than far items. Note that the distance effect was identical in the two numerical tasks and had a similar shape in the alphabetic task.

There was a significant main effect of task/material [$F(2,44) = 30.90$, $P < 0.0001$] showing that mean correct RTs were significantly longer for processing letters (548 ms) compared to numbers, according to either quantity (480 ms) or order (483 ms; both P s < 0.0001) information, while RTs for both numerical tasks did not differ ($P = 1$). The main effect of distance was also significant [$F(1,22) = 144.70$, $P < 0.0001$] as subjects made faster judgements for items far from the standard compared to close items. Separate analyses showed that the distance effect was significant in each task: quantity [$F(1,23) = 195.65$, $P < 0.0001$; close pairs: 504 ms (S.D.: 14 ms), far pairs: 456 ms (12 ms)], order on numbers [$F(1,23) = 77.42$, $P < 0.0001$; close pairs: 505 ms (13 ms), far pairs: 460 ms (10 ms)] and order on

letters [$F(1,23) = 64.90$, $P < 0.0001$; close pairs: 578 ms (16 ms), far pairs: 516 ms (14 ms)]. Moreover, the distance effect was equivalent in both numerical tasks, as attested by the absence of a numerical tasks $\times$ distance interaction ($F < 1$). As shown in Figure 1, the distance effect had a similar shape for letters and numbers, and the minor task $\times$ distance interaction [$F(2,44) = 3.78$, $P < 0.049$] was due to a marginally larger effect in the alphabetic relative to the order on numbers task. In the main ANOVA, the significant interaction between size/position and assignment of response keys [$F(1,22) = 6.32$, $P < 0.02$] showed that left-hand responses were slower when processing larger/after items compared to smaller/ before items (see Table 1). This SNARC effect was equivalent in all tasks, as attested by the absence of interaction between task, size/position and assignment of response keys [$F(2,44) = 2.04$, n.s.]. Because the assignment of response keys was counterbalanced among subjects and did not interact with task or distance, this variable will not be reported in ERPs analyses. Yet, to make sure that the order in which tasks were performed did not modulate the pattern of the distance and task effects, we included tasks' order as a between-subjects' variable in all main ANOVAs, on both bilateral and central electrode locations. For the sake of simplicity, however, tasks' order effects will only be presented when they modulated the pattern of electrophysiological results.

Table 1. RT differences between left- and right-hand responses for each task and each *size/position* of the item. Left hand responses are significantly longer for larger/after items compared to smaller/before items.

Left hand RT - Right hand RT		
Task	Small/Before	Large/After
Quantity	2 ms (479 - 477 ms)	13 ms (489 - 476 ms)
Order on numbers	7 ms (487 - 480 ms)	22 ms (494 - 472 ms)
Order on letters	4 ms (539 - 535 ms)	49 ms (584 - 535 ms)

3.2. ERPs results

Grand-average ERPs over the 24 subjects elicited by the three tasks showed a similar sequence of events. Five major components were identified after stimulus onset: a first positive deflection at posterior sites, the P1, peaking around 95 ms for all three tasks and maximal over left and right parieto-occipito-temporal electrodes; a negative bilateral temporo-parietal component, N1, peaking around 147 ms for numerical stimuli and about 10 ms later for the alphabetic task; a second posterior positivity over parieto-occipital sites, P2p, peaking around 190 ms for numerical material, and around 225 ms for the alphabetic task; a second negativity over fronto-central sites, N2, peaking around 270 ms for all tasks, and, finally, a late positivity over central sites, P3, peaking around 430 ms for numerical tasks and 470 ms for the letter task.

3.2.1. First posterior positivity: P1 (80–120 ms)

Repeated measures ANOVAs on mean amplitudes of P1 showed a significant task/material effect on midline electrode sites, Oz and POz [$F(2,46) = 7.94$, $P < 0.002$], with letters eliciting a larger positivity than numbers. There was no task/material effect on bilateral posterior regions ($F < 1$). Moreover, ANOVAs on electrodes POz and Oz showed a significant task x distance interaction [$F(2,46) = 4.84$, $P < 0.014$] that was explained by the distance effect being restricted to numerical tasks [both $F_s(1,23) > 10.04$, $P_s < 0.004$; $F < 1$ for the alphabetic task]. ANOVAs on bilateral posterior regions (P7/P8, P5/P6, PO7/PO8, PO5/PO6, O1/O2) showed a similar result with a significant triple interaction between task, distance and electrode location [$F(8,184) = 3.53$, $P < 0.009$], which was clarified by separate analyses on each electrode site for each task. While there was no distance effect in the alphabetic task ($F < 1$ for all electrode locations), a significant distance effect was found on certain electrodes in the two numerical tasks [distance x electrode location, both $F_s(4,92) > 10.97$, $P_s < 0.0001$]. The distance effect was significant on electrodes O1/O2 [$F(1,23) = 5.81$, $P < 0.024$] in the quantity task, and on PO5/PO6, PO7/PO8 and O1/O2

[$F(1,23) > 5.56$, $P < 0.027$] in the order on numbers task. None of the main effects or interactions was significant on the mean amplitude measures performed on the negative counterpart of P1 over anterior regions (Fz).⁸

3.2.2. First posterior negativity: N1 (130–170 ms)

The task had no effect on the mean amplitude of N1 on bilateral posterior regions ($F < 1$), but significantly affected its latency [$F(2,46) = 43.26$, $P < 0.0001$], as this component was delayed when processing alphabetic (155 ms) compared to numerical material (147 ms for both numerical tasks). Repeated-measures ANOVAs on mean amplitudes of N1 on bilateral posterior sites (P7/P8, P5/P6, P3/P4, PO7/PO8, PO5/PO6, O1/O2) showed a laterality effect: the N1 was significantly larger on the left than on the right hemisphere [$F(1,23) = 13.77$, $P < 0.001$, see Figure 2] and the asymmetry was more pronounced for alphabetic than numerical material [task $\times$ laterality interaction: $F(2,46) = 9.99$, $P < 0.003$]. ANOVAs showed a significant task $\times$ distance interaction [$F(2,46) = 22.94$, $P < 0.0001$] revealing that the distance effect was only significant when processing alphabetic material [$F(1,23) = 35.36$, $P < 0.0001$], but not numbers ($F < 1$ for both numerical tasks). This effect, with letters close to M eliciting a larger negativity than letters far from M, did not interact with either laterality or electrode location and was significant on all electrode sites [all $F(1,23) > 16.15$, $P < 0.001$].

Repeated measures ANOVAs on the positive counterpart of N1 on electrodes FCz and Cz showed no task effect ($F < 1$), but a significant task $\times$ distance interaction [$F(2,46) = 4.42$, $P < 0.021$], since the distance effect was

⁸ Since the numerical distance effect aroused particularly early and was restricted to very few posterior electrodes in both numerical tasks, it could be accounted for by differences in perceptual properties of the numbers presented (11, 14, 16 and 19). This was confirmed by repeated measures ANOVAs including the variable size/position of the item, since this factor interacted significantly with distance on Oz and POz [$F(1,23) = 8.17$, $P < 0.009$] and with distance and electrode location on bilateral posterior sites [$F(4,92) = 8.05$, $P < 0.001$]. This size distance interaction was due to processing of number 11, which elicited a larger positivity than all other items. This was confirmed by the restriction of the distance effect, in both numerical tasks, to items smaller than 15 (i.e. 11 vs. 14) on electrodes Oz and POz [both $Fs(1,23) > 15.02$, $Ps < 0.001$] and on bilateral posterior sites [both $Fs(4,92) > 15.47$, $Ps < 0.0001$], while the distance effect was not significant for items larger/coming after 15 (i.e., 16 vs. 19) on both Oz and POz [both $Fs(1,23) < 2.19$, n.s.] and bilateral posterior electrodes (both $Fs < 1.16$, n.s.). On bilateral posterior sites, the distance effect for smaller numbers was restricted to electrodes O1/O2 [$F(1,23) = 12.62$, $P < 0.002$] in the quantity task, and PO5/PO6, PO7/PO8 and O1/O2 [all $Fs(1,23) > 7.06$, $Ps < 0.014$] in the order on numbers task.

again restricted to letter stimuli [$F(1,23) = 8.80$, $P < 0.007$; $F < 1$ for both numerical tasks].⁹

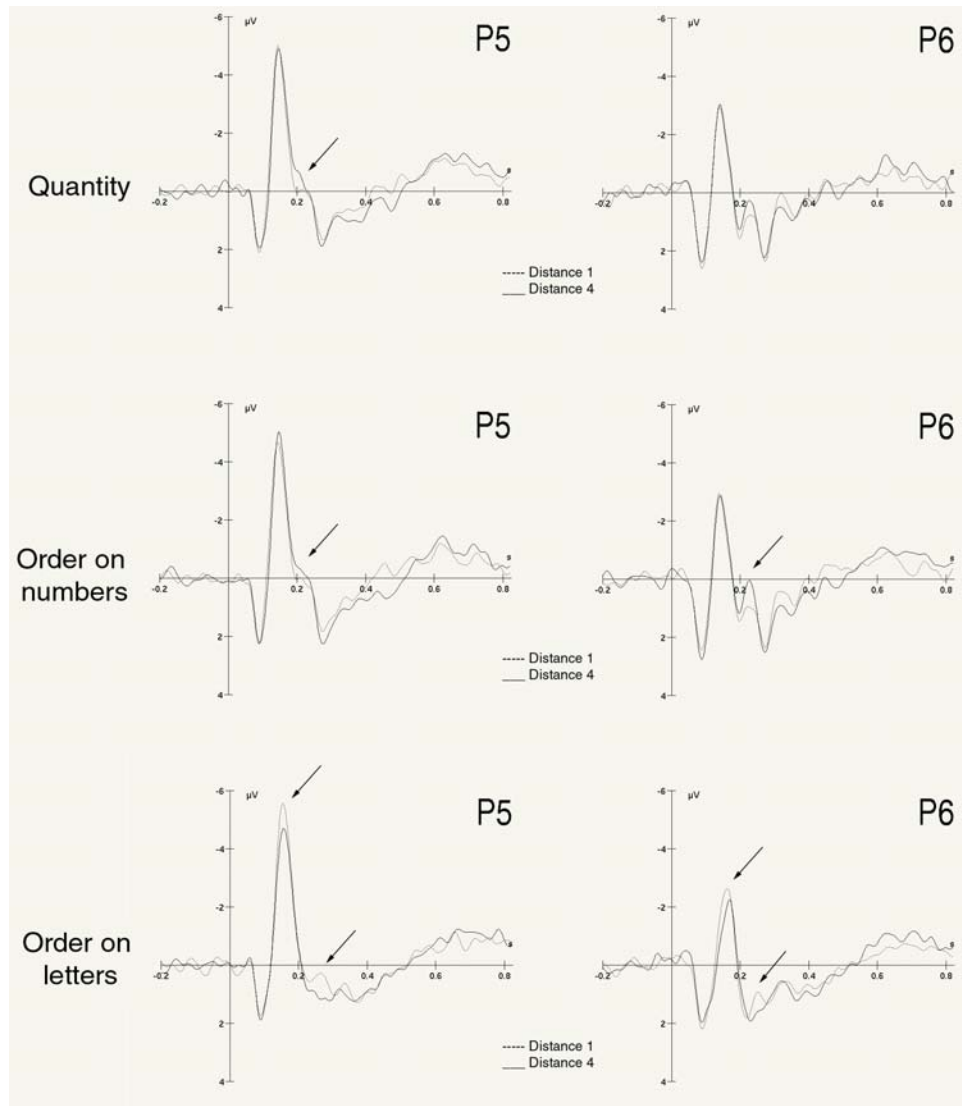


Figure 2. Distance effect for the three tasks over left (P5) and right (P6) parietal electrodes. Note that the first significant distance effect (indicated with an arrow) arises on N1 for the alphabetic task, but only later on the P2p component for both numerical tasks. Note that the asymmetry of N1 (larger N1 over the left hemisphere) is more pronounced with letter stimuli than numbers.

⁹ Repeated measures ANOVAs including the variable size/position of the item and restricted to the letter task showed no size/position effect (both $F_s < 1$) and no size/position distance interaction [both $F_s(1,23) < 2.4$, n.s.] on both bilateral posterior regions and fronto-central sites, thus reinforcing the semantic (rather than perceptual) nature of this distance effect.

3.2.3. Second posterior positivity: P2p (170–210 and 210–240 ms)

Following the N1, a second posterior positivity was observed over parieto-occipital sites for all tasks. This P2p component culminated around 190 ms for both numerical tasks (170–210-ms time window) and was delayed for the alphabetic task (peak around 225 ms, 210–240 time window), as a consequence of the delayed N1 for the same material. Accordingly, repeated measures ANOVAs on mean amplitudes of the P2p on bilateral parieto-occipital sites (P7/P8, P5/P6, P3/P4, PO7/PO8, PO5/PO6, PO3/PO4, O1/O2) showed a significant task/material effect in each time window [both $F(2,46) > 11.54$, $P_s < 0.0001$],¹⁰ with no difference between numerical tasks ($P = 1$ in all contrasts), but significant differences according to stimulus material (numbers vs. letters, $P < 0.006$ in all post-hoc comparisons). A similar task/material effect was reported on both Oz and POz in the first time window [$F(2,46) = 10.49$, $P < 0.001$] and marginally in the second [$F(2,46) = 3.11$, $P < 0.060$], and on the central negative counterpart of the P2p during both time windows [both $F(2,46) > 6.82$, $P_s < 0.003$], with the exception that order tasks differed only marginally in the second window ($P < 0.065$, all other $P_s < 0.005$). The asymmetry of the N1 continued to be perceptible on bilateral posterior sites for all tasks in the first time window (170–210 ms), as the P2p was larger over the right hemisphere [$F(1,23) = 5.19$, $P < 0.032$].

ANOVAs on the 170–210-ms window on bilateral posterior regions revealed a significant distance effect [$F(1,23) = 9.59$, $P < 0.005$], with items close to the standard eliciting a larger posterior positivity than items far from the standard. This effect was however modulated by both task and electrode location [$F(12,276) = 2.83$, $P < 0.017$], task and laterality [$F(2,46) = 4.46$, $P < 0.024$], and by electrode location and laterality [$F(6,138) = 2.89$, $P < 0.039$]. Separate ANOVAs on each electrode site for each task showed a significant distance effect when processing quantity [$F(1,23) = 8.96$, $P <$

¹⁰ Note that the task effect was modulated by tasks' order in the 210–240-ms time window [$F(10,36) = 2.72$, $P = 0.022$]. The effect of task/ material reached significance only for subjects who started with the order on numbers task (orders 3 and 4), though all other orders showed a similar trend (i.e., a larger positivity for the alphabetic compared to numerical tasks), which is consistent with the pattern of the task effect in this second time window.

0.006], but, as shown in Figure 3, this was restricted to left temporo-parietal [P3, P5, P7, PO5 and PO7, all $F_{s(1,23)} > 8.19$, $P_s < 0.009$] and bilateral occipital sites [O1 and O2 both $F_{s(1,23)} > 4.69$, $P_s < 0.041$]. In the order judgment on numbers task, the distance effect was also significant [$F(1,23) = 5.32$, $P < 0.031$] and involved a similar but smaller left-lateralized parietal network [P5, P7, PO5, PO7, all $F_{s(1,23)} > 4.72$, $P_s < 0.040$], as well as P8 [$F(1,23) = 5.37$, $P < 0.030$]. No distance effect was observed for the alphabetic task ($F < 1$). ANOVAs on the subsequent time window (210–240 ms) on posterior regions revealed that distance was again modulated by task [$F(2,46) = 5.61$, $P < 0.008$; $F(2,46) = 3.80$, $P < 0.031$, respectively, for bilateral and midline electrodes] and by laterality and electrode location [$F(6,138) = 2.90$, $P < 0.040$]. The distance effect was more than marginal in the quantity task [$F(1,23) = 3.22$, $P < 0.086$] but well significant when judging order on numbers [$F(1,23) = 16.97$, $P < 0.0001$], close numbers eliciting a larger positivity than far numbers. Separate ANOVAs showed that this numerical order distance effect was largely bilateral since it involved a main right hemispheric network [P4, P6, P8, PO4, PO6, PO8 and O2, all $F_{s(1,23)} > 10.40$, $P_s < 0.004$; see Figure 3],¹¹ a left-parietal network [P7, PO3, PO7, $F(1,23) > 4.74$, $P < 0.040$; and marginally P3 and PO5, $F(1,23) > 3.96$, $P < 0.059$] and central occipital sites [Oz and POz, $F(1,23) = 7.42$, $P < 0.012$]. Again, no distance effect was reported for the alphabetic task on the P2p ($F < 1.19$). ANOVAs on the negative central counterpart of the P2p showed no distance effect [$F_{s(1,23)} < 1.8$, n.s.] and no task x distance interaction [$F_{s(2,46)} < 2.36$, $P_s > 0.11$] in both time windows.

¹¹ Note that, when the marginal distance effect in the quantity task was analyzed separately on each electrode location, it was shown to be significant on a similar but much smaller right-parietal network [P4, P6 and PO8, $F_{s(1,23)} > 4.77$, $P_s < 0.039$; and marginally PO6, $F(1,23) > 4.04$, $P < 0.056$], and this result could not be explained by a carry-over effect of tasks' order [$F(30,108) = 1.09$, n.s.].

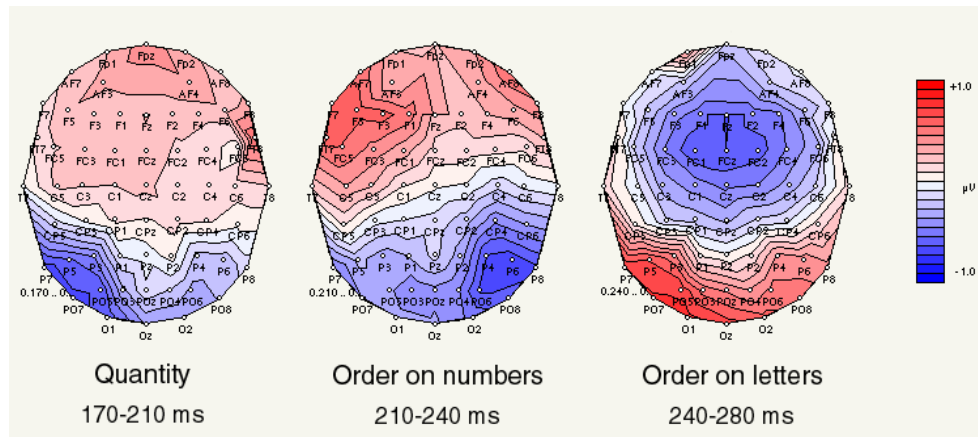


Figure 3. Topography of the distance effect (distance 4 - distance 1) over the early (170-210 ms) and late (210-240 ms) P2p and N2 (240-280) components, respectively for the quantity, order on numbers and order on letters tasks. Note that the distance effect is more pronounced over left parietal areas when processing quantity on numbers and over right parietal sites when processing order on the same numerical material. Order processing on letters elicits a bilateral parietal distance effect that is more pronounced over the left hemisphere.

3.2.4. Second fronto-central negativity: N2 (240–280 ms)

Following the P2p, a second negativity (N2) was observed for all tasks over fronto-central sites, and culminated on FCz at 269, 271 and 265 ms, respectively, for the quantity, order on numbers and order on letters tasks. This negative component was analyzed between 240- and 280- ms post-stimulus onset and was much anterior than the negative counterpart of the earlier P2p (culminating on CPz for numerical material).

Repeated measures ANOVAs on mean amplitudes of the N2 on FCz showed a task effect [$F(2,46) = 4.85$, $P < 0.023$], as the N2 was significantly larger when judging order on numbers compared to order letters ($P < 0.015$), while no difference was reported between numerical tasks, nor between quantity and alphabetic tasks. ANOVAs on the posterior positive counterpart of N2 on bilateral parieto-occipito-temporal sites (P7/P8, P5/P6, P3/P4, PO7/PO8, PO5/PO6, PO3/PO4, O1/O2), as well as on midline occipital electrodes (Oz and POz) showed an identical task effect [$F_s(2,46) > 6.01$, $P_s < 0.013$] with a larger positive counterpart of N2 when judging order on numbers compared to letters (both $P_s < 0.022$), and no difference between quantity and both order on numbers, and order on letters tasks.

A significant distance effect was observed on FCz for all tasks [$F(1,23) = 17.94$, $P < 0.0001$], with distance 4 eliciting a larger N2 than distance 1. The distance effect was also significant on bilateral posterior sites [$F(1,23) = 6.33$, $P < 0.019$], but interacted with task on these [$F(2,46) = 4.56$, $P < 0.019$] and midline posterior electrodes [Oz and POz, $F(2,46) = 4.24$, $P < 0.021$]. Hence, the distance effect was restricted to letter processing on both bilateral and midline posterior regions [both $F_s(1,21) > 9.53$, $P_s < 0.006$] and was not significant for numerical tasks (all $F_s < 1$). This alphabetic distance effect was significant bilaterally, on all electrode locations but was slightly more pronounced on the left [$F(1,23) = 19.29$, $P < 0.0001$; see Figure 3] than on the right hemisphere [all $F(1,23) = 9.30$, $P < 0.006$].

3.2.5. The late positive component

Repeated-measures ANOVAs on mean amplitudes of the P3 (310–510-ms window) on central sites showed a significant task x electrode location interaction [$F(2,46) = 23.41$, $P < 0.0001$]. The task/material effect was significant only on CPz [$F(2,46) = 8.56$, $P < 0.001$] with the letter judgments eliciting a smaller positivity than numerical judgments (both $P_s < 0.023$). As shown in Figure 4, the distance effect (i.e., items far from the standard eliciting a larger P3 than close items) was significant on central sites [$F(1,23) = 43.67$, $P < 0.0001$] for all tasks [$F_s(1,23) > 14.31$, $P_s < 0.001$] and did not interact with electrode location ($F < 1$).



Figure 4. Late P3 distance effect for the three tasks, with larger potentials elicited by far (distance 4) than close items (distance 1).



Figure 5. Subtraction waveforms of the distance effect for the three tasks over left (AF3), middle (FPZ) and right (AF4) prefrontal sites. The effect is observed for the three tasks but is significantly larger when processing order on numerical material. Note that the waveforms were lowpass filtered (16Hz) for the purpose of illustration only, and not for analysis.

Repeated-measures ANOVAs on mean amplitudes of the negative counterpart of P3 on prefrontal sites showed no task effect ($F < 1$) on both midline (FPz) and bilateral electrode locations (FP1/FP2, AF3/AF4, AF7/AF8), but a significant distance effect [$F(1,23) > 40.53$, $P < 0.0001$], with distance 4 eliciting a larger negative potential than distance 1. Distance interacted with task on bilateral [$F(2,46) = 5.12$, $P < 0.011$] and midline [FPz: $F(2,46) = 3.41$, $P < 0.046$] prefrontal regions. Because distance was significant in all tasks [both $F_s(1,23) > 11.58$, $P_s < 0.002$, $F_s(1,23) > 31.17$, $P_s < 0.0001$ and $F_s(1,23) > 5.25$, $P_s < 0.032$, respectively, for quantity, order on numbers and order on letters on bilateral sites and FPz] and on all locations for quantity [all $F_s(1,23) > 13.64$, $P_s < 0.001$] and order on numbers [all $F_s(1,23) > 19.96$, $P_s < 0.0001$], task x distance interaction was clarified by comparing the amplitude of the distance effect in pairs of tasks. Comparing quantity and order on numbers showed a significant triple interaction between task, distance and electrode location on bilateral prefrontal regions [$F(2,46) = 4.83$, $P < 0.022$], and finer-grained analyses reported task x distance interaction on electrode AF3 [$F(1,23) = 5.26$, $P < 0.031$], and marginally on FP1 [$F(1,23) = 3.63$, $P < 0.069$] and FPz [$F(1,23) = 3.75$, $P < 0.065$]. As can be seen in Figure 5, these results suggest that the distance effect was significantly larger when processing order, compared to quantity, on numbers. Contrasting order on numbers and order on letters tasks showed similar results, with a larger distance effect for numerical material on all electrode locations, as confirmed by task distance interactions on bilateral sites [$F(1,23) = 12.53$, $P < 0.002$] and FPz [$F(1,23) = 8.20$, $P < 0.009$]. Contrasting quantity and alphabetic tasks showed a very marginal task x distance interaction on bilateral sites [$F(1,23) = 3.6$, $P > 0.071$] and a non-significant difference on FPz ($F < 1$) with no further modulation by electrode location [$F(2,46) = 1.08$]. Thus, prefrontal regions showed a largely similar distance effect when processing quantity on numbers and order on letters, but were more recruited when processing order on numerical material.

4. Discussion

The aim of the present study was to clarify the relationship between numerical quantity and order processing and to test the hypothesis that they rely on (at least partially) dissociated mechanisms. Numbers were used to address this issue as they can be processed either according to their quantity meaning or to the relative position they refer to in the sequence, and letters were included as non-quantifiable ordered material. Although quantity and order processing show identical psychophysical characteristics on reaction times and accuracy (distance and SNARC effects [21, 28, 37, 61]), similar activated parietal and frontal regions [10, 54] and may show the same impaired or spared profile after brain lesion [11, 90], the hypothesis of dissociated mechanisms for quantity and order is supported by the fact that they have a differential developmental course [36, 97] and can be damaged selectively after cerebral lesions [26, 92]. Overall, our ERP results support this last hypothesis, as we disclosed significant differences between order and quantity processing on numbers, taking place after 200 ms following stimulus onset, at parietal electrode sites.

4.1. Behavioral results

Behavioral results showed a main effect of stimulus material, as processing order on letters (I to Q) lead to longer RTs than processing either quantity or order information on two-digit numerals (11 to 19). This stimulus material effect is consistent with previous studies [46, 65] and may be explained by a weaker knowledge of the alphabetic than numerical series (e.g., letters can hardly be recited backwards; [66]), which is even more pronounced for letters from the middle portion of the alphabet [45], as those we used in the present study.

With respect to numerical tasks, the present data suggest that they were of equivalent levels of difficulty since deciding whether a number was smaller or larger than a standard or whether it came before or after that standard took the same average time. What is more, the pattern of the behavioral distance effect was identical in the two tasks. Alphabetic order

judgments produced a similar distance effect (see Figure 1), though this was slightly more pronounced than in numerical order judgments. This may be explained, again, by weaker knowledge of the alphabetic (relative to the numerical) sequence and by the lack of an associated quantity meaning for letters (see Ref. [96] for a similar interpretation of children's more pronounced distance effect compared to adults in a number comparison task).

The classical distance effect (items far from the standard being processed faster than close items) observed in all three tasks was not modulated by the size/position of the item (smaller/before or larger/after the standard). This suggests that subjects solved quantity and order tasks on numbers and letters by using a comparison mechanism, and that they did not resort to a serial search (i.e., recitation) strategy, as confirmed by the absence of a reverse distance effect for items coming after the standard [46]. Hence, although the numerical distance effect has usually been interpreted as evidence that numerals activate a quantity representation (e.g., Refs. [20, 61]), the present data suggest that the distance effect can also be explained by the pure, sequential representation of the elements, which is the common feature of numbers and letters [96]. To further reinforce this hypothesis is the occurrence of a similar SNARC effect in the three tasks, with slower left-hand responses to items larger/coming after the standard, compared to smaller/before items. The SNARC effect is compatible with a mental representation of numbers and letters emphasizing their serial order and suggests that numerical and alphabetic series may receive a similar spatial abstract coding in the form of a left to right oriented continuum (see also Ref. [37]).

4.2. Electrophysiological results

Evoked potentials were affected by stimulus material and distance from the target. The former effect was mainly observed on early P1 and N1 components, and was reflected by differences in perceptual processing of two-digit numbers and letters. The latter effect had a specific time course and topography in each task. The first semantic distance effect was observed

on N1 for letter stimuli and had a bilateral posterior distribution. Quantity processing elicited the first numerical distance effect, which was significant on left parietal sites (P2p). Processing order on numbers showed a delayed bilateral distance effect and was followed by a likewise bilateral parietal effect for order processing on letters. Finally, all three tasks elicited a late distance effect on P3 on both midline parietal and prefrontal regions, these latter being more activated when judging order on numbers. Thus, ERPs showed different spatio-temporal patterns of the distance effect for quantity and order processing.

4.2.1. Differences in perceptual processing of two-digit numerals and letters

The amplitude of the first positive peak was modulated by stimulus material, with a larger P1 on midline occipital electrodes in the alphabetic than both numerical tasks. Task/ material modulation of this early visual potential is likely to be due to the physical differences between two-digit numerals and single letters, having different lengths and levels of complexity, and requiring specific visual processing mechanisms. Pinel et al. [70] reported a similar early notation effect, arising 120 ms after stimulus onset with a greater occipital P1 for Arabic than verbal numerals. Difference in stimulus length and visual eccentricity is one factor explaining P1 amplitude modulation in both studies as shorter stimuli (i.e., single-letters and single-digit Arabic numerals) elicited the larger responses. Enhanced task difficulty when processing letters, as suggested by longer RTs, may also account for the larger P1 in the alphabetic task. Indeed, no difference was reported between numerical tasks on both RTs, suggesting equivalent levels of difficulty, and the amplitude of P1, as expected by identical visual processes. A similar early task modulation was already reported during processing of faces with the task requiring more time and more attentional resources eliciting a larger P1 [76] (for a short review of task and attention modulation on the visual P1, see Ref. [87])¹²

¹² Specific visual features of numerical stimuli also affected P1, as shown by a significantly larger positivity on occipital electrodes for number 11 in both numerical tasks. Differences between 11 and

Both N1 latency and topography were also affected by stimulus material, as the first posterior negativity was bilateral for Arabic numerals, but delayed (parallel to RTs) and mainly left-lateralized for letters. These results confirm, on the one hand, that the left occipito-temporal region is involved in identifying both Arabic and verbal notations, as previously reported in ERP [16], fMRI (e.g., Ref. [70]) and studies of brain damaged patients [13], and, on the other hand, that the posterior left hemisphere plays a crucial role in the identification of letters, as supported again by electrophysiological [77, 79], neuroimaging (see Ref. [56]) and neuropsychological studies [30]. When directly comparing letter and number processing, fMRI studies reported greater activity in the left inferior occipitotemporal cortex during passive viewing of letter (vs. digit) strings [71, 72] (see also Ref. [2] for electrophysiological evidence consistent with this letter-number dissociation). Finally, studies of patients with callosal disconnection [13, 82] further confirm that the right hemisphere is poor at identifying alphabetic characters, while both hemispheres can identify digits (see also Ref. [12]). The right-hemispheric ability to identify and process Arabic numerals is consistent with both the present study and previous ERP [16, 69, 70] and functional imaging studies [67]. Delayed P2p for the alphabetic task can easily be explained as a consequence of the same task delay on the preceding N1. In fact, when ERPs are time-locked to stimulus onset, as in the present study, differences in duration of early stages of processing can highly affect later stages [16]. In a similar way, the right-lateralization of the P2p may also be a consequence of the earlier N1 asymmetry, and similar laterality effects were already reported in a number comparison task [16].

Finally, material effects were reported on the amplitude of N2 and P3 components that were larger for order judgments on numbers relative to order judgments on letters. This was found on fronto-central and parieto-occipital electrodes for N2 and on electrode CPz for P3. Enhanced amplitude of the rising part of P3 was already reported when comparing Arabic

other presented numbers involved both visual angle and physical features (11 is composed of the same repeated digit). However, since visual angle did not affect amplitude of early ERP components in the alphabetic task, the peculiar physical structure of number 11 might better explain amplitude modulation of P1 in numerical tasks.

numerals relative to written verbal numerals [16]. The production of larger potentials when judging order on numbers compared to letters may be further explained by the simultaneous activation of (automatic) quantity and (intentional) order information in numerical order judgments (see below for a discussion on this point). Late task effects (i.e., taking place after the activation of the P2p related semantic information) may thus be influenced by differences in the amount of information activated in each task: order and quantity in numerical judgments, and only order in the alphabetic task. This explanation may also account for the larger distance effect on prefrontal regions when judging numerical order relative to alphabetic order and numerical quantity.

4.2.2. Semantic processing of numbers and letters and the distance effect

The first distance effect was observed in the N1 time window and was restricted to the alphabetic order task, with letters close to the target ('M') eliciting a larger negativity than letters far from the target. This effect was significant on all bilateral parieto-occipital electrodes, as well as on the fronto-central positive deflection concomitant with N1. Because distance did not interact with position of the item (before/after the standard), this effect could not be explained by differences in the physical features of letter stimuli, which suggests that it had a semantic rather than perceptual origin. Previous ERP studies of number comparison reported a similar early distance effect on the N1 component on bilateral parieto-temporal sites [70, 89], with close items more negative than far items. The arising of an earlier distance effect for letters than numbers cannot be related to differential RTs, as they were longer in the alphabetic than numerical tasks. Results of a bin analysis on RTs did not either support the hypothesis of an earlier distance effect (i.e., on faster responses) in the alphabetic task, but showed that this effect was similar in all bins for all tasks.¹³

¹³ RTs for each item processed by each subject were ordered from the fastest to the slowest and divided into four groups, or bins. The distance effect was then analysed in each bin in order to test the hypothesis that it might arise earlier, thus on faster RTs, when processing letters relative to numbers. A Repeated-

One tentative explanation for this early distance effect is that the semantic representation of single letters was accessed earlier than that of two-digit Arabic numerals, because of a shorter perceptual identification stage. In fact, two-digit stimuli might take longer to be processed and their perceptual stage might not be terminated on N1, while that of single letters would be, causing earlier semantic access in the alphabetic task. Other ERP studies [16, 70] reported similar slower access to semantic (quantity) information by perceptually longer stimuli in number comparison tasks: written verbal numerals elicited a delayed distance effect compared to shorter Arabic numerals. Although stimulus length was confounded with notation (Arabic vs. verbal) in these studies and may have accounted for the delayed distance effect, a genuine effect of stimulus length was reported on N1 and appeared before the first effect of numerical distance [16].

4.2.2.1. Left-lateralized parietal network for quantity processing.

The earliest numerical distance effect was observed on the P2p component on posterior parietal regions and had the same profile as the earlier alphabetic distance effect, with close numbers eliciting a larger potential than far numbers (Figure 2). Although the behavioral distance effect was similar in the two numerical tasks, differences were reported in its time course and lateralization according to the processing mechanism, quantity or order, required by the task: the distance effect appeared earlier (170–210-ms window) and was left-lateralized when processing quantity, while it was slightly delayed (210–240-ms window) and bilateral, though more pronounced in the right hemisphere, when processing order on numbers (Figure 3). Previous electrophysiological studies of number comparison reported a similar numerical distance effect on the second posterior positivity, with a larger P2p for close than far digits, on the same parieto-occipito-temporal regions [16, 70, 89]. Likewise, functional imaging studies repeatedly showed activation of parietal areas in semantic number

measures ANOVA with variables task (3), distance (2) and bin (4) as within subject factors reported a significant distance effect in all four bins for the three tasks ($F(1,23) = 127.48$, $P < 0.0001$) and no task distance bin interaction ($F(6,138) = 1.8$, $P = 0.18$).

processing (e.g., Refs. [10, 28, 34, 68, 69, 70, 85]). ERP studies of Arabic number processing showed either a right-lateralized [16, 70] or a bilateral distance effect [90], while most studies using PET or fMRI techniques reported more prominent activations in the left parietal lobe when processing numbers [15, 28, 68, 69, 70, 74, 85, 98].¹⁴ Further evidence for a left-parietal dominance in numerical quantity processing comes from two fMRI studies of number comparison with single [69] and two-digit Arabic numerals [70] showing that the numerical distance specifically modulated the activation of bilateral intraparietal regions with a clear left-sided predominance. What is more, the left-parietal superiority for quantity processing is not restricted to the number domain, as it has also been reported when quantifying (vs. simply detecting) non-numerical visual stimuli [33]. Finally, the left intraparietal sulcus was shown to be exclusively and conjointly activated by quantitative comparison of symbolic (two-digit numerals) and non-symbolic (angles and lines) stimuli [34].

Converging behavioral, neuropsychological and developmental evidence reinforce the left-hemispheric superiority for quantity processing. Behavioral studies using visual half field stimulation reported faster comparison times when pairs of Arabic numerals were displayed in the right visual field [5]. Similar results were observed in a patient with callosal disconnection [13] who was fast and flawless in processing quantities (comparing single- and two-digit Arabic numerals) presented in the right visual field (left hemisphere), but significantly slower and less accurate with left visual field presentation (see also Ref. [14]). Furthermore, neuropsychological studies of patients with calculation disorders have repeatedly shown the dramatic effects of left-hemispheric posterior lesions on number and quantity processing (e.g., Refs. [11, 18, 86, 95]), while right-hemispheric lesions caused only moderate effects [38,44,51, 75,94]. One of the clearest neuropsychological evidence for a left-sided dominance in quantity processing comes from patients with Gerstmann's syndrome showing an inability to process quantities [4, 19, 22, 25, 55]. Finally, two studies on

¹⁴ One neuroimaging study reported larger right parietal activations in a number comparison task when this was contrasted with a digit naming task [10], but, when letter naming was used as control condition, a large bilateral intraparietal network was shown to be activated by magnitude comparison.

developmental dyscalculia further enhance the role of left parietal areas in processing numerical quantities [43, 52].

4.2.2.2. Bilateral parietal network for order processing on numbers and letters.

The present electrophysiological results showed that order processing on numbers and letters recruited, with a different temporal course, a bilateral parietal network. These data agree with previous neuroimaging studies: judging the order (vs. the identity) of two letters in a previously memorized array activated the left and right parietal cortices [54], and these same areas were shown to be engaged in numerical tasks [10]. Besides, performing a transitive inference task (i.e., selecting in a pair of items— visual shapes—the one coming later in a previously learned ordered sequence) was shown to recruit parietal areas in the two hemispheres, while performing a (visual quantitative) height comparison task (i.e., selecting the taller visual shape) on the same pairs of items only activated left parietal sites [1]. These latter data are consistent not only with the bilateral parietal involvement we reported in the present order tasks, but also with the left-lateralized distance effect observed in our (semantic) quantitative comparison task. Hence, the data of Acuna et al. [1] together with the present electrophysiological results (i.e., both the occurrence of a larger right-hemispheric distance effect when judging order on numbers and the recruitment of right-parietal areas when judging order on letters) point to the crucial role of right parietal areas in processing order information. This is corroborated by neuroimaging studies of time processing [73] and retrieval of temporal order information [9], showing right-parietal activation, and is consistent with electrophysiological recordings in humans reporting a right hemispheric bias, especially in the parietal cortex, for temporal processing [59]. Neuropsychological data give further emphasis to a right-hemispheric advantage in processing ordinal relations. In a recent study, Turconi and Seron [91] described the case of a patient with right parietal lesion who was impaired in processing the order of well-known sequences (numbers, letters, days and months) in various tasks, while showing better performance in processing quantity information. Similarly, Langdon and Warrington [51] reported that patients with right

posterior lesions were impaired in a reasoning test requiring the completion of numerical series, and concluded that the abstraction of (numerical) relations relies on the integrity of the right hemisphere (see also Ref. [75] for similar results).

In the present study, numerical quantity judgments also produced a small right parietal distance effect in the second P2p time window, i.e., concomitant with the larger right parietal effect reported for (numerical) order judgments. This result points to a potential automatic activation of order information when processing numerical stimuli and is consistent with a recent study reporting automatic activation of ordinal information in non-numerical series [37]. We thus make the hypothesis that the involvement of right parietal areas in (some) number processing tasks (e.g., number comparison [10], number detection [28]) could be explained by the automatic activation of numerical ordinal relations. With respect to the alphabetic task, following the early distance effect on N1, letter stimuli showed a later reversed effect on N2, with letters far from M eliciting a larger potential than close letters. The distance effect was found on bilateral posterior regions, but was more pronounced in the left hemisphere. Finding a major left-hemispheric involvement in semantic processing of letters is not surprising, since letter stimuli were mainly left-lateralized in our and other studies [13, 72] and left-hemispheric lateralization of linguistic functions has repeatedly been reported.

Similarly, the recruitment of left parietal areas during order processing on numbers could be interpreted as reflecting the involvement of a verbal strategy in this task (e.g., recitation of the counting sequence). However, the pattern of behavioral results does not support the use of a serial search process in the present order on numbers task (cf. behavioural results section). Hence, it seems more plausible to account for the left parietal distance effect in numerical order judgments by the automatic activation of quantity information. This is consistent with both the earlier left parietal distance effect observed in the quantity task and with several studies reporting automatic activation of magnitude information in numerical tasks (e.g., Refs. [17, 21, 32, 50]). In further agreement with this view is the production by numerical order judgments of a small left-parietal distance effect in the first

P2p time window that was concomitant with and had the same (though much restricted) topography as the quantity distance effect.

As explained in the introduction, order and quantity information are intimately related in the cognitive number domain. The present electrophysiological results suggest that processing numbers according to either quantity or order meanings may automatically activate the other dimension. Moreover, the temporal course of the distance effect on the P2p component further proposes that quantity information would be accessed faster than order. The question of why order information is accessed later than quantity remains open. Yet, since order processing specifically activated the right hemisphere, a tentative clarification may be proposed in light of the basic inability of the right hemisphere to process items in parallel. This hypothesis was put forward to account for the degraded speed and accuracy of right-hemispheric performance in word recognition with increasing word length, while word length did not affect performance by the left hemisphere [6, 29, 53]. In the number domain, a similar right-hemispheric delay was reported when processing two-digit numbers and pairs of single digits after callosal disconnection [13]. Hence, the right hemisphere was proposed to resort to a sequential (and thus slower) processing strategy, while the left hemisphere was thought to possess a more holistic parallel approach (see also Ref. [49]).

Finally, beyond peculiar mechanisms involved in each numerical task, the observed temporal course and topographical distribution of the distance effect suggest that processing numerical quantity or order information might rely on at least partially distinct mechanisms. Moreover, the present data also showed a different spatio-temporal pattern for order judgments on alphabetic and numerical material, and argue for dissociated processing of letters and numbers, as already reported in neuroimaging [72], electrophysiological [2] and neuropsychological studies [3, 12, 90].

4.2.2.3. Involvement of prefrontal regions in number and letter processing.

The late midline centro-parietal P3 component was larger for far than close items in all three tasks. A similar distance effect was consistently

reported in other ERP studies of number comparison [16, 40, 81, 93] and order judgment on letters [58]. Electrophysiological results of the present study further extend the distance effect to bilateral prefrontal regions. These were recruited by all three tasks, but significantly more when processing order on numbers, as suggested by the larger prefrontal distance effect in this task relative to the quantity and alphabetic order tasks. The enhanced involvement of prefrontal regions when judging order on numbers could be explained by the activation of both (intentional) order information and (automatic) quantity information in this task.

Recruitment of parietal and prefrontal areas has consistently been reported in neuroimaging studies of quantity (e.g., Refs. [10, 23, 28, 67, 70]; see also Refs. [39, 57] for the specific roles of these brain regions in numerical tasks) and order processing [1, 9, 54, 73]. Electrophysiological studies showed consistent results. On the one hand, dipole modelling of the late distance effect in a number comparison task was shown to engage both parietal and frontal sources [70]. On the other hand, parietal and frontal activations were specifically correlated with the manipulation of either spatial or temporal order information [80]. Neuropsychological case studies also stressed the importance of parietal and frontal areas in processing quantity (parietal: e.g., Refs. [22, 86, 95], frontal [31]), as well as temporal and serial order information (parietal [48, 83, 91], frontal [84]). Furthermore, investigation of abstract quantity processing in nonhuman primates was also shown to involve parietal [78] and prefrontal [62] regions.

4.2.3. Conclusion

In the present ERP study, we have reported different spatio-temporal patterns of the distance effect when instructions emphasized on either quantity or order processing on numerical and non-numerical material. Letter processing elicited an early (N1) and late (N2) bilateral parietal distance effect, while two-digit numerals elicited, on the P2 component, a left-lateralized parietal distance effect when quantitatively processed, and a delayed bilateral effect when coding for their relative position in the number sequence. Frontal areas were recruited by all three tasks, but significantly

more when judging order on numbers. Hence, these spatio-temporal differences suggest that distinct operational mechanisms are involved in quantity and order coding, in the parietal and prefrontal cortices.

Acknowledgements

We are grateful to Véronique Lambert for her help in data collection. This study was supported by the Belgian National Fund of Scientific Research (FNRS) for ET and BR, by a grant from the IAP P5/1/5—“Dynamic sensory processing, learning and visual cognition” Federal Office for Scientific, Technical and Cultural Affairs (Belgium) and a grant from ARC 01/06-267 (Communauté Française de Belgique-Actions de Recherche Concertées).

Reprinted from Cognitive Brain Research, Vol. 21, Turconi E., Jemel, B., Rossion, B. & Seron, X., Electrophysiological evidence for differential processing of numerical quantity and order in humans, Pages 22-38., Copyright (2004), with permission from Elsevier.

References

- [1] B.D. Acuna, J.C. Eliassen, J.P. Donoghue, J.N. Sanes, Frontal and parietal lobe activation during transitive inference in humans, *Cereb. Cortex* 12 (2002) 1312– 1321.
- [2] T. Allison, G. McCarthy, A. Nobre, A. Puce, A. Belger, Human extrastriate visual cortex and the perception of faces, words, numbers, and colors, *Cereb. Cortex* 5 (1994) 544– 554.
- [3] S.W. Anderson, A.R. Damasio, H. Damasio, Troubled letters but not numbers, *Brain* 113 (1990) 749– 766.
- [4] A. Ardila, M. Concha, M. Rosselli, Angular gyrus syndrome revisited: acalculia, finger agnosia, right– left disorientation and semantic aphasia, *Aphasiology* 14 (2000) 743– 754.
- [5] D. Besner, D. Grimsell, R. Davis, The mind’s eye and the comparative judgment of number, *Neuropsychologia* 17 (1979) 378–380.
- [6] D. Bub, J. Lewine, Different modes of word recognition in the left and right visual fields, *Brain Lang.* 33 (1988) 161– 188.
- [7] P.B. Buckley, C.B. Gilman, Comparison of digits and dot patterns, *J. Exp. Psychol.* 103 (1974) 1131– 1136.

- [8] B. Butterworth, *The Mathematical Brain*, Macmillan, London, 1999.
- [9] R. Cabeza, J. Mangels, L. Nyberg, R. Habib, S. Houle, A.R. McIntosh, E. Tulving, Brain regions differentially involved in remembering what and when: a PET study, *Neuron* 19 (1997) 863– 870.
- [10] F. Chochon, L. Cohen, P.F. van de Moortele, S. Dehaene, Differential contributions of the left and right inferior parietal lobules to number processing, *J. Cogn. Neurosci.* 11 (1999) 617–630.
- [11] L. Cipolotti, B. Butterworth, G. Denes, A specific deficit for numbers in a case of dense acalculia, *Brain* 114 (1991) 2619– 2637.
- [12] L. Cohen, S. Dehaene, Number processing in pure alexia: the effect of hemispheric asymmetries and task demands, *Neurocase* 1 (1995) 121– 137.
- [13] L. Cohen, S. Dehaene, Cerebral networks for number processing: evidence from a case of posterior callosal lesion, *Neurocase* 2 (1996) 155– 174.
- [14] M.C. Corballis, Can commissurotomy subjects compare digits between the visual fields? *Neuropsychologia* 32 (1994) 1475–1486.
- [15] S.F. Cowell, G.F. Egan, C. Code, J. Harasty, J.D.G. Watson, The functional neuroanatomy of simple calculation and number repetition: a parametric PET activation study, *NeuroImage* 12 (2000) 565–573.
- [16] S. Dehaene, The organization of brain activations in number comparison: event-related potentials and the additive factors method, *J. Cogn. Neurosci.* 8 (1996) 47–68.
- [17] S. Dehaene, R. Akhavein, Attention, automaticity, and levels of representation in number processing, *J. Exp. Psychol. Learn. Memory Cognit.* 21 (1995) 314–326.
- [18] S. Dehaene, L. Cohen, Two mental calculation systems: a case study of severe acalculia with preserved approximation, *Neuropsychologia* 29 (1991) 1045– 1074.
- [19] S. Dehaene, L. Cohen, Cerebral pathways for calculation: double dissociation between rote verbal and quantitative knowledge of arithmetic, *Cortex* 33 (1997) 219– 250.
- [20] S. Dehaene, E. Dupoux, J. Melher, Is numerical comparison digital? Analogical and symbolic effects in two-digit number comparison, *J. Exp. Psychol.: Hum. Percept. Perform.* 16 (1990) 241–626.
- [21] S. Dehaene, S. Bossini, P. Giraux, The mental representation of parity and numerical magnitude, *J. Exp. Psychol. Gen.* 122 (1993) 371– 396.

- [22] S. Dehaene, G. Dehaene-Lambertz, L. Cohen, Abstract representations of numbers in the animal and human brain, *Trends Neurosci.* 21 (1998) 355– 361.
- [23] S. Dehaene, E. Spelke, R. Stanescu, P. Pinel, S. Tsivkin, Sources of mathematical thinking: Behavioral and brain-imaging evidence, *Science* 284 (1999) 970– 974.
- [24] S. Dehaene, M. Piazza, P. Pinel, L. Cohen, Three parietal circuits for number processing, *Cogn. Neuropsychol.* 20 (2003) 487– 506.
- [25] M. Delazer, T. Benke, Arithmetic facts without meaning, *Cortex* 33 (1997) 697– 710.
- [26] M. Delazer, B. Butterworth, Dissociation of number meanings, *Cogn. Neuropsychol.* 14 (1997) 613– 636.
- [27] G. Deloche, X. Seron, C. Larroque, C. Magnien, M.N. Metz-Lutz, M.P. Noël, I. Riva, J.P. Schils, M. Dordain, I. Ferrand, E. Baeta, A. Basso, L. Cipolotti, D. Carlos-Salinas, D. Howard, F. Gaillard, G. Goldenberg, A. Mazzucchi, F. Stachowiak, A. Tzavaras, J. Vendrell, C. Bergego, P. Pradat-Dielh, Calculation and number processing: assessment battery; role of demographic factors, *J. Clin. Exp. Neuropsychol.* 16 (1994) 195– 208.
- [28] E. Eger, P. Sterzer, M.O. Russ, A.L. Giraud, A. Kleinschmidt, A supramodal number representation in human parietal cortex, *Neuron* 37 (2003) 719– 725.
- [29] A.W. Ellis, A.W. Young, C. Anderson, Modes of word recognition in the left and right cerebral hemispheres, *Brain Lang.* 35 (1988) 254– 273.
- [30] M.J. Farah, Patterns of co-occurrence among the associative agnosias: implications for visual object representation, *Cogn. Neuropsychol.* 8 (1991) 1 – 19.
- [31] L. Fasotti, P.A.T.M. Eling, J.J.C.B. Bremer, The internal representation of arithmetical word problem sentences: frontal and posterior-injured patients compared, *Brain Cogn.* 20 (1992) 245–263.
- [32] W. Fias, J. Lauwereyns, J. Lammertyn, Irrelevant digits affect feature-based attention depending on the overlap of neural circuits, *Cogn. Brain Res.* 12 (2001) 415– 423.
- [33] W. Fias, P. Dupont, B. Reynvoet, G.A. Orban, The quantitative nature of a visual task differentiates between ventral and dorsal stream, *J. Cogn. Neurosci.* 14 (2002) 646–658.
- [34] W. Fias, J. Lammertyn, B. Reynvoet, P. Dupont, G.A. Orban, Parietal representation of symbolic and nonsymbolic magnitude, *J. Cogn. Neurosci.* 15 (2003) 47– 56.

- [35] G.S. Foltz, G.R. Poltrock, G.R. Potts, Mental comparisons of size and magnitude: size congruity effect, *J. Exp. Psychol. Learn. Memory Cognit.* 10 (1984) 442– 453.
- [36] K.C. Fuson, *Children's counting and concepts of number*, Springer-Verlag, New York, 1988.
- [37] W. Gevers, B. Reynvoet, W. Fias, The mental representation of ordinal sequences is spatially organized, *Cognition* 87 (2003) B87– B95.
- [38] J. Grafman, D. Passafiume, P. Faglioni, F. Boller, Calculation disturbances in adults with focal hemispheric damage, *Cortex* 18 (1982) 37–50.
- [39] O. Gruber, P. Indefrey, H. Steinmetz, A. Kleinschmidt, Dissociating neural correlates of cognitive components in mental calculation, *Cereb. Cortex* 11 (2001) 350– 359.
- [40] K. Grune, P. Ullsperger, M. Molle, A. Mecklinger, Mental comparison of visually presented two-digit numbers: a P-300 study, *Int. J. Physiol.* 17 (1994) 47– 56.
- [41] J.M.E. Hamilton, A.J. Sanford, The symbolic distance effect for alphabetic order judgments: a subjective report and reaction time analysis, *Q. J. Exp. Psychol.* 30 (1978) 33–43.
- [42] K.J. Holyoak, The form of analog size information in memory, *Cogn. Psychol.* 9 (1977) 31– 51.
- [43] E.B. Isaacs, C.J. Edmonds, A. Lucas, D.G. Gadian, Calculation difficulties in children of very low birthweight: a neural correlate, *Brain* 124 (2001) 1701–1707.
- [44] M. Jackson, E.K. Warrington, Arithmetic skills in patients with unilateral cerebral lesions, *Cortex* 22 (1986) 611– 620.
- [45] J. Jou, Why is the alphabetically middle letter in a multiletter array so hard to determine? Memory processes in linear-order information processing, *J. Exp. Psychol. Hum. Percept. Perform.* 23 (1997) 1743– 1763.
- [46] J. Jou, Multiple number and letter comparison: directionality and accessibility in numeric and alphabetic memories, *Am. J. Psychol.* 116 (2003) 543– 579.
- [47] J. Jou, J.W. Aldridge, Memory representation of alphabetic position and interval information, *J. Exp. Psychol. Hum. Learn. Mem.* 25 (1999) 680– 701.
- [48] D. Kimura, N.V. Watson, The relation between oral movement control and speech, *Brain Lang.* 37 (1989) 565– 590.

- [49] S. Kosslyn, O. Koenig, A. Barrett, C. Backer Cave, J. Tang, J.D.E. Gabrieli, Evidence for two types of spatial representations: hemispheric specialization for categorical and coordinate relations, *J. Exp. Psychol. Hum. Percept. Perform.* 15 (1989) 723– 735.
- [50] S. Lang, B. Kotchoubey, Brain responses to number sequences with and without active task requirement, *Clin. Neurophysiol.* 113 (2002) 1734– 1741.
- [51] D.W. Langdon, E.K. Warrington, The abstraction of numerical relations: a role for the right hemisphere in arithmetic? *J. Int. Neuropsychol. Soc.* 3 (1997) 260–268.
- [52] L.M. Levy, I.L. Reis, J. Grafman, Metabolic abnormalities detected by H-MRS in dyscalculia and dysgraphia, *Neurologica* 53 (1999) 639–641.
- [53] A.K. Lindell, M.E.R. Nicholls, A.E. Castles, The effect of word length on hemispheric word recognition: evidence from unilateral and bilateral-redundant presentations, *Brain Cogn.* 48 (2002) 447– 452.
- [54] C. Marshuetz, E.E. Smith, J. Jonides, J. DeGutis, T.L. Chenevert, Order information in working memory: fMRI evidence for parietal and prefrontal mechanisms, *J. Cogn. Neurosci.* 12 (Suppl. 2) (2000) 130–144.
- [55] E. Mayer, M.D. Martory, A.J. Pegna, T. Landis, J. Delavelle, J.M. Annoni, A pure case of Gerstmann syndrome with a subangular lesion, *Brain* 122 (1999) 1107– 1120.
- [56] B.D. McCandliss, L. Cohen, S. Dehaene, The visual word form area: expertise for reading in the fusiform gyrus, *Trends Cogn. Sci.* 7 (2003) 293– 299.
- [57] V. Menon, S.M. Rivera, C.D. White, G.H. Glover, A.L. Reiss, Dissociating prefrontal and parietal cortex activation during arithmetic processing, *NeuroImage* 12 (2000) 357– 365.
- [58] H.J. Michalewski, A.W.M. Kamel, A. Starr, Brain potentials during mental distance judgments, *Int. J. Psychophysiol.* 6 (1998) 221–229.
- [59] W. Mohl, G. Pfurtscheller, The role of the right parietal region in a movement time-estimation task, *NeuroReport* 2 (1991) 309– 312.
- [60] R.S. Moyer, Comparing objects in memory: evidence suggesting an internal psychophysics, *Percept. Psychophys.* 13 (1973) 180– 183.
- [61] R.S. Moyer, T.K. Landauer, Time required for judgments of numerical inequality, *Nature* 215 (1967) 1519– 1520.
- [62] A. Nieder, E.K. Miller, Coding of cognitive magnitude: compressed scaling of numerical information in the primate prefrontal cortex, *Neuron* 37 (2003) 149– 157.

- [63] R. Nowagk, E. Pfeifer, Unix implementation of the ERP evaluation package (EEP 3.0), in: A.D. Friederici, D.Y. von Cramon (Eds.), Annual Report of Max-Planck Institute of Cognitive Neuroscience, Leipzig, Germany, 1996, pp. 124–126.
- [64] A. Paivio, Perceptual comparisons through the mind's eye, *Mem. Cogn.* 3 (1975) 635–647.
- [65] J.M. Parkman, Temporal aspects of digit and letter inequality judgments, *J. Exp. Psychol.* 91 (1971) 191–205.
- [66] M. Pesenti, Du rôle de l'analogique dans les représentations numériques: Numérosité et ordinalité, Unpublished Doctoral Thesis, Université Catholique de Louvain, Louvain-la-Neuve, Belgium, 1995.
- [67] M. Pesenti, M. Thioux, X. Seron, A. De Volder, Neuroanatomical substrates of arabic number processing, numerical comparison and simple addition: a PET study, *J. Cogn. Neurosci.* 12 (2000) 461–479.
- [68] M. Pesenti, L. Zago, F. Crivello, E. Mellet, D. Samson, B. Duroux, X. Seron, B. Mazoyer, N. Tzourio-Mazoyer, Mental calculation in a prodigy is sustained by right prefrontal and medial temporal areas, *Nat. Neurosci.* 4 (2001) 103–107.
- [69] P. Pinel, G. Le Clec'H, P.F. van de Moortele, L. Naccache, D. Le Bihan, S. Dehaene, Event-related fMRI analysis of the cerebral circuits for number comparison, *NeuroReport* 10 (1999) 1473–1479.
- [70] P. Pinel, S. Dehaene, D. Riviere, D. LeBihan, Modulation of parietal activation by semantic distance in a number comparison task, *NeuroImage* 14 (2001) 1013–1026.
- [71] T.A. Polk, M.J. Farah, The neural development and organization of letter recognition: evidence from functional imaging, computational modeling and behavioral studies, *Proc. Natl. Acad. Sci.* 95 (1998) 847–852.
- [72] T.A. Polk, M. Stallcup, G.K. Aguirre, D.C. Alsop, M. D'Esposito, J.A. Detre, M.J. Farah, Neural specialization for letter recognition, *J. Cogn. Neurosci.* 14 (2002) 145–159.
- [73] S.M. Rao, A.R. Mayer, D.L. Harrington, The evolution of brain activation during temporal processing, *Nat. Neurosci.* 4 (2001) 317–323.
- [74] T.C. Rickard, S.G. Romero, G. Basso, C. Wharton, S. Flitman, J. Grafman, The calculating brain: an fMRI study, *Neuropsychologia* 38 (2000) 325–335.
- [75] M. Rosselli, A. Ardila, Calculation deficits in patients with right and left hemisphere damage, *Neuropsychologia* 27 (1989) 607–617.

- [76] B. Rossion, S. Campanella, C.M. Gomez, A. Delinte, D. Debatisse, L. Liard, S. Dubois, R. Bruyer, M. Crommelinck, J.M. Guerit, Task modulation of brain activity related to familiar and unfamiliar face processing: an ERP study, *Clin. Neuropsychol.* 110 (1999) 449– 462.
- [77] B. Rossion, C.A. Joyce, G.W. Cottrell, M.J. Tarr, Early lateralization and orientation tuning for face, word and object processing in the visual cortex, *NeuroImage* 20 (2004) 1609–1624.
- [78] H. Sawamura, K. Shima, J. Tanji, Numerical representation for action in the parietal cortex of the monkey, *Nature* 415 (2002) 918– 922.
- [79] H.E. Schendan, G. Ganis, M. Kutas, Neurophysiological evidence for visual perceptual categorization of words and faces within 150 ms, *Psychophysiology* 35 (1998) 240– 251.
- [80] R. Schubotz, Instruction differentiates the processing of temporal and spatial sequential patterns: evidence from slow wave activity in humans, *Neurosci. Lett.* 265 (1999) 1 –4.
- [81] W. Schwarz, H.J. Heinze, On the interaction of numerical and size information in digit comparison: a behavioral and event-related potential study, *Neuropsychologia* 36 (1998) 1167–1179.
- [82] S.E. Seymour, P.A. Reuter-Lorenz, M.S. Gazzaniga, The disconnection syndrome: basic findings reaffirmed, *Brain* 117 (1994) 105– 115.
- [83] T. Shallice, *From Neuropsychology to Mental Structure*, Cambridge University Press, New York, 1988.
- [84] A.P. Shimamura, J.S. Janowski, L.R. Squire, Memory for the temporal order of events in patients with frontal lobe lesions and amnesic patients, *Neuropsychologia* 28 (1990) 803– 813.
- [85] O. Simon, L. Cohen, J.F. Mangin, D. LeBihan, S. Dehaene, Topographical layout of hand, eye, calculation and language related areas in the human parietal lobe, *Neuron* 33 (2002) 475– 487.
- [86] Y. Takayama, M. Sugishita, I. Akiguchi, J. Kimura, Isolated acalculia due to left parietal lesion, *Arch. Neurol.* 51 (1994) 286–291.
- [87] M.J. Taylor, Non-spatial attentional effects on P1, *Clin. Neurophysiol.* 113 (2002) 1903– 1908.
- [88] D.A. Taylor, J.O. Kim, P. Sudevan, Representation of linear orders, *J. Exp. Psychol. Learn. Memory Cognit.* 10 (1984) 61– 71.
- [89] E. Temple, M.I. Posner, Brain mechanisms of quantity are similar in 5-year-olds and adults, *Proc. Natl. Acad. Sci.* 95 (1998) 7836– 7841.

- [90] M. Thioux, A. Pillon, D. Samson, M.-P. de Partz, M.-P. Noel, X. Seron, The isolation of numerals at the semantic level, *Neurocase* 4 (1998) 371–389.
- [91] E. Turconi, X. Seron, Dissociation between order and quantity meanings in a patient with Gerstmann syndrome, *Cortex* 38 (2002) 911–914.
- [92] J. Tzelgov, D. Ganor-Stern, Automaticity in processing ordinal information, in: J. I. D. Campbell (Ed.), *Handbook of Mathematical Cognition*, Psychology Press, New York, 2004.
- [93] P. Ullsperger, K. Grune, Processing of multi-dimensional stimuli: P300 component of the event-related brain potential during mental comparison of compound digits, *Biol. Psychol.* 40 (1995) 17–31.
- [94] E.K. Warrington, J. Merle, C. Maciejewski, The WAIS as a lateralizing and localizing diagnostic instrument: a study of 656 patients with unilateral cerebral lesions, *Neuropsychologia* 24 (1986) 223–239.
- [95] J. Whalen, M. McCloskey, R.P. Lesser, B. Gordon, Localizing arithmetic processes in the brain: evidence from a transient deficit during cortical stimulation, *J. Cogn. Neurosci.* 9 (1997) 409–417.
- [96] H. Wiese, *Numbers, Language and the Human Mind*, Cambridge University Press, Cambridge, United Kingdom, 2003.
- [97] K. Wynn, Children’s acquisition of the number words and the counting system, *Cogn. Psychol.* 24 (1992) 220–251.
- [98] L. Zago, N. Tzourio-Mazoyer, Distinguishing visuospatial working memory and complex calculation areas within the parietal lobes, *Neurosci. Lett.* 331 (2002) 45–49.