

CHAPTER 2

When knowing that 3 is *smaller* than 5 doesn't tell you that 3 comes *before* 5: A dissociation between cardinal meaning and sequence knowledge after parietal damage

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INTRODUCTION

Numbers are highly flexible tools. The same number, say 10, can tell us as many different things as the number of Provinces in Belgium (cardinal meaning), the temperature of a late winter day (measure meaning), the last lane occupied by a runner in a hundred meter sprint (ordinal meaning), the subway line going from Boulogne to the Gare d'Austerlitz in Paris (nominal meaning), and so on. Hence, numbers refer to specific meanings when used in particular contexts. Fuson (1988, 1992) distinguishes numerical meanings (cardinal, measure, ordinal), sequence knowledge¹ and non-numerical (i.e. nominal) meanings. The distinction between cardinal (and ordinal) meaning and sequence knowledge will be crucial for the present study.

In a cardinal context, the number describes the numerosity (or numerical quantity) of a set of discrete objects and tells us “how many” objects there are. Cardinal numbers refer to sets (not to individual objects), they are well-ordered by magnitude², and thus allow us to judge not only numerical equivalence (i.e. whether or not two sets have the same numerosity), but also to identify the larger (or smaller) set in a pair (i.e. to process ‘cardinal order relations’, Fuson, 1988, see below). Cardinal meaning is thus accessed when

¹ Fuson speaks sometimes about “sequence meaning”, but we prefer “sequence knowledge” when referring, for instance, to sequence recitation, as this skill might not require any semantic elaboration.

² The sequential order of numbers is a crucial feature of cardinal assignments because it ensures that two sets having the same number of objects will end up having the same cardinality (see Wiese, 2003).

performing numerical (quantity) comparison tasks (e.g. 2 5, ‘which is larger?’) or when representing the value of Arabic numbers with dots or tokens.

In an ordinal context, the number describes the relative position (or rank) of one entity within a well-defined totally ordered set, in which the ordering relation has a specified initial point (Butterworth, 1999; Fuson, 1988; Wiese, 2003). There is no quantification involved in ordinal assignments since assigning one object a higher position, say 4, than another, 2, will only tell us that the former object ‘comes after’ the latter in the ordered set, but not that the object in position 4 is twice as larger as object in position 2 (think, for instance, about the position of runners at the end of a race). In a related vein, objects occupying positions 2 and 4 might not be equidistant to the object in position 3 (Wiese, 2003). Accordingly, any other ordered sequence with an initial point (e.g. the letters of the alphabet) could be used to provide meaningful ordinal assignments.

In the approach proposed by Fuson (1988), ordinal contexts are qualified as being characterised by the use of ordinal number words (first, second, third, and so on), which are isomorphic with cardinal numbers and support similar arithmetic principles. According to this view, ordinal contexts must be distinguished from sequence contexts, the latter referring to the mere recitation of the number words in their conventional order, with no external referents (whereas external referents are attached to number words in counting situations). In the present paper, we will adopt Fuson’s approach and consider ordinal meaning and sequence knowledge as distinct³. In sequence contexts, numbers do not refer to numerosities, and the conventional sequence of number words will be recited in much the same way as other familiar ordered series, like the letters of the alphabet, the months of the year and the days of the week (Fuson, 1992). In the present case-study we will mostly examine sequence knowledge and its relationship with cardinal number meaning; whereas the use of (ordinal) number words

³ Fuson’s (1988) sequence knowledge is close to what Wiese (2003) refers to as ‘ordinal assignment’, with the difference that numbers do refer to external entities in ordinal assignments. We decided to resort to Fuson’s terminology in the present paper, in order to avoid using the term ‘ordinal’ in a confusing manner, as this relates to slightly different meanings according to Fuson (1988) or Wiese (2003).

in ordinal contexts (as described by Fuson, 1988) will be given only limited attention.

With respect to sequence knowledge and cardinal meaning, it is crucial to understand that both will allow for the processing of order relations among numbers (Fuson, 1988). These relations will rely, however, on a different aspect of the number concept in each situation: in a sequence context, the order relation between numbers 3 and 5 will be expressed as '3 comes before 5' and refer to positions along the sequence (with no additional reference to cardinalities; this relation is called 'After/Before' relation by Fuson, 1988); in a cardinal context, the corresponding order relation will be expressed as '3 is smaller than 5' and refer to the cardinality of sets (this relation is called 'Greater Than/Smaller Than' relation by Fuson, 1988).

Adults easily shift from one number use to another in everyday life, but this is not the case for young children who take several years (from the age of 2 to around 6; Fuson, 1988) to construct a mature and flexible number concept. This construction follows a developmental sequence in which each numerical use is first learned separately, and remains context-dependent for some time, before being related to other uses of numbers and integrated into a full-blown number concept (e.g. Fuson & Hall, 1983). During this developmental course, learning to recite the sequence of number words appears to play a crucial role in the subsequent construction of numerical meanings, which will be later closely connected with sequence knowledge (Fuson, 1988). Fuson and colleagues (Fuson, Richards & Briars, 1982) have described children's acquisition and elaboration of the number word sequence, which they divided in five main stages. At the beginning, the sequence functions as a single connected serial whole from which internal words cannot be produced independently (string level). The subsequent elaboration of the sequence is a lengthy process of differentiating the words and constructing relations among them, up to the level of a bi-directional chain that can be recited automatically in the forwards and backwards directions. Each of the five levels is characterized by the achievement of specific skills, which will be described in detail in the Experimental section, together with our patient's performance in each level's particular tasks.

During the process of sequence elaboration, number words will initially

provide information about a number's relative position in the ordered list, without any related cardinal meaning. Hence, a child might know at this stage that 5 comes after 4, but not (yet) that 5 is larger than 4, nor which numerosity each number refers to. For the child to acquire cardinal meaning, he must not only be able to recite the sequence of number words, he also needs to understand the direct relationship between a word's position in the ordered list and the quantity it refers to (i.e., that the farther along a number word occurs in the list, the greater the numerosity it refers to; Wynn, 1990; 1992). Thus, a developmental distinction appears between the early ability to recite the sequence of number words, and the later knowledge of the numerosities these words refer to, together with their cardinal relationships.

Whether sequence knowledge and cardinal meaning remain partially distinct up to adulthood has been rarely investigated and remains largely unknown. Some neuropsychological evidence suggests, however, that this might be the case. Delazer and Butterworth (1997) described the case of a patient, SE, who showed impaired (automatic access to) cardinal number meaning, following a left frontal infarct, while his knowledge of the sequence of number words was largely preserved. SE was able to count from 1 to 20, both orally and in the Arabic code (while counting by 2 or 3 was impossible), he could count dots and name or write the number coming just after a given Arabic numeral between 6 and 20 (we know nothing, however, about his backwards recitation skills). In contrast, SE was unable to solve simple addition and subtraction problems with Arabic numerals (even in a multiple-choice procedure) and showed a reverse distance effect in number comparison (i.e., he was slower in comparing far than close numbers). Nonetheless, this patient did not appear to have damaged representations of cardinality, as he was still able to represent Arabic numerals with arrays of dots, and he could answer 'How many' questions. Yet, because he did it very slowly his impairment was thought to affect the automatic access, from Arabic numerals, to magnitude representations, thus forcing him to rely on sequence recitation to perform cardinal tasks. The patient's impairment was only transient, however, and the distance effect in comparison soon recovered its typical pattern (i.e., with slower processing for close than far numbers). This single-case study is crucial in that it is the first attempt to

describe a dissociation between different aspects of number meaning in adults, though it doesn't provide an answer, yet, as to whether sequence knowledge and cardinal meaning might rely on different representations, or on distinct processing mechanisms.

In a recent behavioural study, we (Turconi, Campbell, & Seron, 2005) have proposed that processing either quantity or order information on pairs of numbers might recruit distinct (and thus potentially dissociable) mechanisms. In the quantity comparison task, adult subjects showed a standard distance effect (i.e. faster responses for pair 2 5 than pair 2 3) when choosing the larger (or smaller) of two Arabic numerals. In the order task, telling whether (or not) a pair of numbers was presented in the counting, ascending, order elicited a reversed distance effect on close ascending pairs (i.e. the order of numbers was processed faster in pair 2 3 than in pair 2 5). This peculiar effect was proposed to reflect the specific involvement of a serial search (i.e. sequence recitation) strategy in numerical order judgments. Taken together, developmental, neuropsychological and behavioural studies suggest that number processing might recruit different mechanisms (or different representations) when used in different contexts (cardinal, sequence), or according to specific instructions (quantity, order).

Up to now, however, neuropsychological models of number processing have only taken into account the cardinal aspect of numbers (also referred to as numerosity, magnitude, or numerical quantity; Butterworth, 1999)⁴, ignoring the processing of order or sequence information. In the model of McCloskey (1992), for instance, an amodal semantic representation is proposed to underlie transcoding as well as calculation procedures; this representation is a cardinal one and specifies the basic quantities in a number with their associated powers of ten (e.g. 13 is represented as {1}10EXP1, {3}10EXP0). The order of numbers in the sequence should be derived from the lexicon in this kind of (base-ten) representation. Other models (e.g.

⁴ Some authors have suggested that the representation of magnitude underlies the development of cardinal meaning (e.g. Gallistel & Gelman, 1992), but magnitude and cardinality are not equivalent. The cardinality of a number is exactly defined and refers to a set of entities (e.g. the number 5 refers to a set with exactly 5 elements); whereas a number's analogue magnitude is only approximate and refers to a segment on the number line (a portion of the continuum either around, or up to the target number, depending on the models).

Dehaene, 1992) have resorted to the ‘number line’ metaphor to describe the semantic representation of numbers. The number line is considered as an analogue representation of magnitude and is proposed to underlie the processing of numerosity and to mediate the quantity (or cardinal) meaning of numbers. Yet, while the latter models again do not explicitly represent sequence order, some kind of order information can be derived from the organization of the number line. Number line models can be categorized in two main classes: place-coding and magnitude-coding. In place-coding models (Dehaene, 1992; Verguts, Fias & Stevens, 2005) a number will maximally activate its corresponding position on the number line, and this activation will spread to neighbouring numbers with decreasing strength. Hence, when presented with number 5, its corresponding position will be maximally activated on the number line together with the positions of numbers 4 and 6, and, to a lesser extent, those of numbers 3 and 7. Some kind of ordering can thus be derived from this representation, but only for numbers around the target, and not for the entire sequence. Magnitude-coding models (e.g. Meck and Church, 1983; Zorzi & Butterworth, 1999) provide a more direct representation of cardinality and its inclusion property (i.e. the fact that the numerical quantity 4 is included in the quantity 5). In this type of coding, a number will activate a segment on the number line that comprises the complete range of numbers up to the target number (much like a thermometer or an accumulator), and activation will not be restricted to a region around the target number. Magnitude-coding thus allows for an exhaustive representation of the order of numbers up to the target number (because all smaller numbers are concomitantly activated), but this order is purely derived from magnitude information. Yet, if number ordering were implicitly derived from magnitude representations, we might expect damaged magnitude representations to entail concurrently impaired sequence knowledge, but this was not the case in patient SE (Delazer & Butterworth, 1997).

With respect to sequence knowledge, some authors (e.g. Delazer & Butterworth, 1997) have suggested that it could be based on the auditory-

verbal code of the Triple-Code model (Dehaene & Cohen, 1995)⁵. However, this verbal code is merely employed in the recitation of automated verbal routines, such as arithmetic facts, the number sequence and other verbal sequences, and does not encompass what Fuson (1988) refers to as ‘sequence knowledge’. There is more to sequence knowledge, in fact, than the automatic recitation of the verbal number sequence as this knowledge allows for the additional processing of the ordered list (e.g. answering ‘What comes next/before?’ questions). In the Triple-Code model (Dehaene & Cohen, 1995), such additional processing might require the further involvement of the analogue magnitude code (i.e. the place-coding number line described above), which is directly linked to the verbal code. However, while this could be the case for the sequence of number words, it is unclear, though, how the model would account for the processing of non-numerical sequences, beyond automatic sequence recitation. Moreover, with respect to analogue magnitudes, they might only provide some approximate answer to questions that would, instead, require a precise elaboration of the sequence (e.g. finding the number between 13 and 15 might require more than an approximate representation of magnitudes). Thus, taken together, models of number processing (e.g. Dehaene & Cohen, 1995; McCloskey, 1992; Verguts & al., 2005; Zorzi & Butterworth, 1999) don’t provide a clear answer to the way and locus sequence, and more generally order, is coded and processed, on numerical and non-numerical material.

Likewise, neuroimaging studies of number processing were primarily devoted to a better understanding of the core neural substrate for numerical quantity, neglecting other aspects of the number domain, like sequence knowledge. These studies reported the consistent activation of intraparietal areas when processing numerical quantity. In a recent review, Dehaene, Piazza, Pinel, and Cohen (2003) proposed that three circuits might coexist in parietal cortex, each being selectively involved in specific aspects of number processing. Among these, the bilateral horizontal segment of the intraparietal

⁵ Beside the analogue-magnitude code (i.e. place-coding number line) and the auditory-verbal code, the third code proposed by Dehaene & Cohen (1995) in their model is a visual-Arabic code that would support multidigit processing and parity judgment tasks. This code will not be discussed here as does not imply numerical meaning by itself, but only through the activation of the analogue-magnitude component.

sulcus (HIPS) was proposed to be the neural substrate underlying the abstract semantic representation of number magnitude (i.e., the ‘number line’ representation, Dehaene, 1992); this locus was found to be increasingly activated as the task put greater emphasis on quantity processing, with a right-hemispheric advantage for number comparison and tasks requiring the abstraction of numerical relations (e.g. Chochon, Cohen, van de Moortele, Dehaene, 1999; Langdon & Warrington, 1997; Rosselli & Ardila, 1989). Activations in the HIPS were further found to be category-specific (e.g. greater for numerals than for animal names, Thioux, Pesenti, Costes, De Volder, & Seron, 2005), but it is unclear, yet, whether this neural substrate is specific to numbers, or whether it extends to other categories that have a strong spatial or serial component (e.g., the ordered series of letters, days, months). The second identified circuit is the left angular gyrus that, in connection with other left-hemispheric perisylvian areas, was proposed to support the manipulation of numbers in the verbal form (i.e., the auditory-verbal code in the Triple-Code model, Dehaene & Cohen, 1995) and to contribute to tasks making strong demands on the verbal coding of numbers (e.g. multiplication and arithmetic fact retrieval, Cohen & Dehaene, 2000). The angular gyrus might be a potential locus for the storage of sequence knowledge (see Hubbard, Piazza, Pinel, & Dehaene, 2005), as long as automatic recitation is required in sequence processing tasks. This region was also found to be involved in verbal working memory tasks⁶. The third circuit, recruiting bilateral posterior superior parietal areas, supports spatial attentional orientation and is not specific to the number domain. Activation of these regions during counting (i.e. the sequential enumeration of objects) and spatial working memory tasks, suggests that they might be involved in the selection of locations in space. Hence, they might be a good candidate for the processing of proximity relations of elements along an ordered (spatial) continuum (e.g. the ‘number line’). The relationship between space and number was further reinforced by neuropsychological evidence, with the description of neglect patients having an equivalent right-shift when

⁶ Because the order of items is a crucial feature of working memory, angular gyrus recruitment in working memory tasks might lend further support for the potential involvement of this region in processing the order of numbers.

performing line bisection and numerical bisection tasks (e.g. responding 6 when finding the middle number between 3 and 7; Zorzi, Priftis, & Umiltà, 2002). Yet, whether this attention-orienting process is involved in sequence processing (e.g. which number comes after, 3 or 7?) is still an open question.

The major role of intraparietal areas in numerical quantity processing is further confirmed by neuropsychological evidence. Gerstmann's syndrome, which is characterized by acalculia, agraphia, finger agnosia and right-left confusion (Gerstmann, 1940; see Butterworth, 1999, and Simon, Cohen, Mangin, Le Bihan, & Dehaene, 2002, for opposite explanations for the co-occurrence of these symptoms) is probably one of the most striking evidence for impaired quantity representation following lesions to the intraparietal sulcus in the left (language-dominant) hemisphere (e.g. Mayer, Martory, Pegna, Landis, Delavelle, & Annoni, 1999; Takayama, Sugishita, Akiguchi, & Kimura, 1994). Lesions to inferior parietal areas were consistently associated with deficits in number processing (see Dehaene, Dehaene-Lambertz, & Cohen, 1998, for a review), and the impairment could either affect number comprehension, production and calculation altogether (e.g. Cipolotti, Butterworth, & Denes, 1991), or be selective for calculation (Dehaene & Cohen, 1997; Takayama, Sugishita, Akiguchi, & Kimura, 1994). It has been proposed (Dehaene & Cohen, 1995, 1997), however, that the core deficit in number processing following parietal damage did not much affect calculation processes *per se*, but involved a disorganisation of the semantic representation of numerical quantities, as that found in Gerstmann's syndrome.

With respect to numerical order meaning and sequence knowledge, they still have not been specifically investigated with neuroimaging techniques. Yet, as regards the three parietal circuits involved in number processing (Dehaene & al., 2003), as discussed above, all could be potential candidates but none appears to be a definitive one. Order is however not specific to numbers and neuroimaging studies in non-numerical domains might be relevant. In a verbal working memory task, judging the order (vs. the identity) of two letters in a previously memorized array was found to activate bilateral parietal areas (Marshuetz, Smith, Jonides, DeGutis, & Chenevert, 2000), and these same areas were shown to be engaged in

numerical tasks (e.g. number comparison; Chochon, & al., 1999). Besides, performing a transitive inference task (i.e., selecting the item coming later in a pair, according to a previously learned ordered sequence) was also shown to recruit bilateral parietal regions (Acuna, Eliassen, Donoghue, & Sanes, 2002). Yet processing the order of items in a temporary encoded sequence (like the order of letters in a working memory task) is quite different from processing the order of numbers or letters (overlearned series held in long-term memory, and that might also hold semantic information). To our knowledge, our event-related potentials study (Turconi, Jemel, Rossion, & Seron, 2004) was the only one to examine brain regions involved in processing the order of numbers and letters. In this study, we found that parietal areas were equally recruited in numerical and alphabetic order judgments, as in numerical quantity processing, but with a different time course. The involvement of prefrontal areas was also consistently reported in studies of order processing.

Yet, because parietal areas were found to underlie both numerical quantity and order processing, a lesion to this site is expected to impair not only quantity, as consistently reported (Dehaene & al., 1998), but also order knowledge. However, sequence knowledge and ordinal number meaning were rarely studied in acalculic patients, thus leaving this issue mostly unresolved. In the present study, we will describe a detailed investigation of sequence knowledge and address the question of whether numerical order can be disrupted after parietal lesions. Furthermore, whether impaired sequence knowledge entails impaired cardinal (or quantity) meaning is also an open question that we will address here. This question leads to the issue of whether sequence knowledge and cardinal number meaning can be selectively damaged after cerebral lesion, which would imply that they rely on (at least partially) distinct representations or processing mechanisms. This would corroborate, in adults, the developmental distinction reported in children between the elaboration of the number word sequence and the acquisition of a cardinal number meaning.

In the present paper, we describe the case of a patient, CO, whose knowledge about the sequence of number words was found to be

considerably impaired after bilateral parietal damage. On the contrary, his understanding and processing of numerical quantity was largely preserved. The fact that CO was able to process numbers according to the quantity they refer, but not according to their relative position in the sequence (i.e., their rank) challenges the idea that numerical quantity and numerical rank address the same mental representation, and/or rely on a common processing mechanism. Furthermore, this dissociation was not restricted to the number domain, but extended to other ordered series (the letters of the alphabet, the days of the week and the months of the year) and to non-numerical quantities. We thus make the hypothesis that, because they were acquired at different stages during development and because they refer to distinct numerical contexts, sequence knowledge and cardinal number meaning might rely on (at least partially) distinct representations and/or processing mechanisms, that could be selectively spared or impaired after cerebral (parietal) lesions.

CASE REPORT

CO was a right-handed (as confirmed by the Edinburgh Handedness Inventory) French-speaking former accountant, born in 1928. He was 72 years old in February 2001, when we started the present investigation. His medical history revealed that he presented in May 1992 with a CVA in the left posterior parietal region causing oral and written language impairment, apraxia and spatial orientation disorders. The quasi-complete recovery of his language impairment was established in February 1993 after a one-year speech therapy.

CO was first seen at the Neuropsychological Rehabilitation Unit of St Luc University Hospital (Brussels) in April 1999. At that time, he complained of memory disorders, together with reading, writing and calculation difficulties. He also reported difficulties in following a well-known familiar itinerary and in planning a sequence of actions. Dealing simultaneously with two or more tasks was also difficult. CO was well oriented in time and place and co-operative. The neuropsychological

investigation performed at that time showed slightly reduced working memory and long-term memory in the verbal and visual modalities. Spontaneous speech was fluent and non-apahasic. Reading was laborious for non-words, long sentences and texts. Writing words and sentences under dictation was impaired and slightly apraxic. Picture naming was good (88/90; Bachy-Langedoc, 1988). With respect to the number domain, the patient was able to read aloud Arabic numbers, but he made errors in writing numerals under dictation. Mental and written calculation was largely impaired.

In August 2000, CO newly complained of gait and balance disorders, word finding difficulties and problems in planning certain tasks. The CT scan revealed the occurrence of a new cerebral infarct at the level of the right parieto-occipital junction, besides the sequels of the former left parieto-occipital CVA. The neuropsychological examination performed in September 2000 confirmed the cognitive profile of April 1999 and the hypothesis of a degenerative disorder was excluded. The patient was conscious of his impairments, anxious and depressed. He was addressed to us in January 2001 and underwent a new comprehensive neuropsychological assessment (January-August 2001), detailed below.

Neuropsychological investigation

CO was well oriented in place but slightly disoriented in time. His verbal short-term memory was within normal range at the forwards digit span (he repeated correctly sequences of 4 digits; controls: 4.07), but impaired at the backwards span. At this latter task, he could repeat 2 digits in the reverse order, but proved unable to reverse the order of 3-digit sequences and produced order errors on all trials (e.g. 6 2 9 was repeated 2 6 9). He had a reduced visuo-spatial span of 2 at the Corsi task (normal range: 4-6; taken from Wechsler, 1997). At a French adaptation of the Grober and Buschke verbal long term memory test the patient was found to have preserved encoding and recall abilities. Visual long-term memory was impaired (the patient's performance was below the fifth percentile at the "Doors and People" test; Baddeley et al., 1994). Selective attention was impaired (9/60,

controls: 46.73, SD: 8.2) at the "Three Matrices" test. Executive functions were tentatively evaluated with the Stroop (Stroop, 1935) and the Trail Making tests, but performance at the Stroop test was already impaired in colour naming (8 errors), thus reading and interference tasks were not proposed; at the Trail Making test, the patient was slow in performing Part 1 (below the 10th percentile) and unable to perform Part 2 (linking alternatively a number with a letter in the increasing/alphabetical order) because of comprehension problems. At a verbal fluency test (Benton & Hamsher, CO produced, in 2 minutes, 10 animal names, which was within normal limits (- 1.6 SD), but only 4 words starting with the letter P, which was below the normal range (- 2.3 SD) and suggests impaired executive functions. Nonetheless, CO performed well at another test of executive functions inspired from Luria's graphic series. Performance in drawing on oral command and in copying geometric figures showed a mild constructive apraxia and planning difficulties, for more complex figures. CO's performance at the clock test was largely impaired: he was able to draw the circle, but placed "reference points" (corresponding to the digits) in a pseudo-random manner inside the circle and indicated the digits 1 to 11 outside the circle in uneven places. No signs of unilateral neglect were observed at a clock cancellation task (32/35 correct responses) nor at a line bisection task. The indication of body parts (except for fingers) on verbal command was flawless with (15/16) and without visual control (eyes closed: 16/16).

Because of CO's bilateral parietal lesions, we looked for the clinical features of Gerstmann's syndrome (finger agnosia, right-left confusion, agraphia and acalculia) and investigated each feature in detail. We will first present the assessment of agraphia and language in general, we will then turn to finger agnosia and right-left confusion, and finally to CO's number processing and calculation impairment, which was the main focus of the present case study.

Language

The extensive language screening was performed with the *Batterie d'évaluation du langage* (Cliniques Universitaires St-Luc), which comprises a large set of subtests aiming at assessing sublexical, lexical, semantic and morpho-syntactic processing in the different speech modalities. This screening essentially revealed writing and reading difficulties.

Written language. Writing was severely impaired, at both the graphic (due to apraxia) and the linguistic levels. The patient was barely able to write his name and address. Writing under dictation of letters and words was very slow and marked by frequent letter substitutions causing the production of neologisms. Oral spelling was impossible. Reading isolated letters was preserved (36/36) and so was the identification of letters among digits, truncated letters and spatially incorrect letters (52/54). To the contrary, the sequential processing of letters was dramatically impaired: in a letter-sequence matching task the patient was unable to find among four 6-letter sequences, the one that corresponded to a given target. Reading showed a dissociation between preserved lexical and impaired non-lexical pathways: CO was able to read irregular words (37/40), but impaired in reading non-words (11/40). Semantic processing was good as assessed with a written word-picture matching task (62/64; LEXIS: De Partz, Bilocq, De Wilde, Seron, & Pillon, 2001). Morpho-syntactic processing showed preserved processing of number (17/18), good understanding of irreversible active (4/4), reversible active (3/4) and passive (4/4) sentences, while relative reversible sentences were more error-prone (2/4).

Oral language. At a functional level, expressive and receptive communicative abilities were judged normal. The patient's spontaneous speech was fluent and his automatic speech was preserved: he could count from 1 to 20, recite the series of days and months and he was flawless in completing idiomatic expressions (42/42). Repetition of isolated sounds, syllables, words, non-words and short sentences was perfect, while repeating longer sentences was impaired likely because of his short-term memory deficit. Oral naming was normal in two picture-naming tasks (60/64; LEXIS: De Partz, Bilocq, De Wilde, Seron, & Pillon, 2001; 87/90; Bachy-

Langedock, 1988). The patient was able to elaborate sentences with predetermined target words. His oral comprehension was in the normal range (31/36) at a shortened version of the Token Test (De Renzi and Faglioni, 1978), with all errors made on complex sentences that tapped on the comprehension of relations between figures and spatial transformations (e.g., "place the red circle between the green square and the black square"). Good oral comprehension was confirmed by a semantic designation task (62/64; LEXIS: De Partz, Bilocq, De Wilde, Seron, & Pillon, 2001) the patient choosing the correct picture corresponding to a target oral word among four (visuo-semantic, semantic, visual and neutral) distractors.

Finger agnosia

Finger agnosia was tested following the procedure proposed by Mayer et al. (1999). We first tested input and output modalities in nine situations (S1 to S9), which combined three types of stimulation (verbal, tactile, visual) and three modes of response (verbal, pointing on one's own hand, pointing on a diagram of a hand). The importance of visual control (VC) was also assessed by comparing situations with and without visual feedback (see Mayer et al., 1999, for a detailed presentation of each situation). The results are shown in Table 1 and reveal impaired performance. No errors were elicited on the thumb in all situations and about 50% of the errors (20/41) were made on the ring finger. Comparative analysis showed that performance was worse without VC (situations S2, S5, S7, S8, 56/80, 70% correct) than with VC (situations S3, S4, S6, S9, 65/80, 81.3%; $\chi^2(1) = 2.77$, exact one-tailed $p < 0.05$).

We then tested the integration with three situations from the procedure used by Mayer et al. (1999) and originally proposed by Kinsbourne and Warrington (1962). First (situation 10 in Mayer et al., 1999), two fingers were simultaneously touched and the patient had to indicate the number of fingers between the ones touched. This task was very laborious (9/24 correct) and the patient produced the same response, 2 fingers, on most occasions (22/24). Second (situation 11), the patient had to decide whether 2 simultaneous touches were made on the same or different fingers. He was

good with the right hand (23/24), but impaired with the left hand (15/24). All the errors were "same" responses, though two different fingers were touched, and were distributed over all five fingers. Third (situation 15), the patient was asked to raise the same finger as the one rose by the examiner, but he was not allowed to see his hands. CO performed better with the left (7/10) than with the right (4/10) hand.

Table 1. Finger agnosia: number of correct responses in each situation.

Responses	Verbal	Pointing to own hand without VC	Pointing on a diagram of a hand with VC
<i>Stimulation</i>			
Verbal	S1: 3/5	S2: 10/20	S3: 19/20
Visual	S4: 15/20	S5: 15/20	S6: 18/20
Tactile	S7: 11/20	S8: 20/20	S9: 13/20
Total	29/45 (64.4%)	45/60 (75%)	50/60 (83.3%)

These results clearly reveal the presence of finger agnosia in this patient. In fact, as reported by Mayer et al. (1999), five neurologically intact subjects aged between 53 and 70 did not make a single error in any of the conditions reported above. As shown in Table 1, CO's performance was good with visual and verbal stimulations when vision was allowed and a pointing response was required, but more impaired when visual control was prohibited and when a verbal response was expected. Tactile stimulation was more error-prone, unless when the patient simply had to touch on his hand the same finger as the examiner, just after her. When testing the integration, CO was unable to give the number of fingers between two fingers touched by the examiner. With his left hand, he was also impaired in discriminating simultaneous touches to the same or to two different fingers. Finally, CO was impaired in raising the same finger as the examiner, in a situation without VC.

Finger agnosia was confirmed by another test in which the patient was asked to close his eyes (no visual control) and place a hand, palm down, on

the table; the examiner touched either one or two fingers (successively or simultaneously) on that hand and the patient was asked to indicate, with his other hand, the fingers touched by the examiner on either a homologous or a symmetrical drawing of the hand touched. The patient was impaired in this task (see the results in Table 2), though not significantly more when two fingers were touched (simultaneously or successively) instead of one ($\chi^2(1) = 1.94$, *n.s.*). Performance was better when indicating the finger(s) touched on a homologous, relative to a symmetrical drawing of the hand ($\chi^2(1) = 5.49$, $p < .019$). The patient's performance in this task was not better than that of 6-year old children.

Table 2. Correct responses in the second finger agnosia assessment

	Homologous hand drawing	Symmetrical hand drawing	Total correct
Single touch RH LH	9/10 8/10	6/10 6/10	15/20 14/20
2 successive touches RH LH	13/20 14/20	11/20 10/20	24/40 24/40
2 simultaneous touches RH LH	13/20 14/20	11/20 11/20	24/40 25/40
Total RH LH overall	35/50 36/50 71/100	28/50 27/50 55/100	63/100 63/100 126/200
Norms for 6 years-old	68/100	60/100	132/200

Note: RH is for Right Hand, LH is for Left Hand

Right-left discrimination

Right-left discrimination was also tested using the procedure proposed by Mayer et al. (1999). First, CO was given an oral command requiring him to point to his right or left ear, eye, cheek, shoulder, etc. The patient performed well in this task, whether visual control was allowed (15/16) or

not (16/16). However, when instructions further specified the (left or right) hand with which the patient had to point to these body parts, his performance fell in both conditions: with VC (12/16) and without VC (9/16; overall with vs. without specification of the hand to be used: $\chi^2(1) = 10.26$, $p < .001$). When pointing had to be made on a line-drawing model of the body facing the patient (incongruous position), performance fell to 8/16 when the hand was not specified and to 4/16 with further specification of the hand to be used. When pointing had to be made on a line-drawing model of the body facing away from the patient (congruous condition), performance was slightly better either without (11/16) or with (10/16) specification of the hand to be used (overall congruous vs. incongruous conditions: $\chi^2(1) = 5.07$, $p < .024$).

These data suggest that CO was impaired in right-left discrimination, since control subjects don't make a single error in any of the above-mentioned situations (see Mayer et al., 1999). Besides, we found an increase in error rate according to when the hand to be used was specified and when the line-drawing position with respect to the patient was incongruous (vs. congruous), whereas the presence or absence of visual control did not affect performance ($\chi^2(1) < 1$). As for Mayer & al. (1999)'s patient, CO was also influenced by the number of mental processes necessary to resolve the different tasks ($\chi^2(1) = 13.55$, $P < .001$).

In sum, CO was shown to have agraphia, finger agnosia and right-left confusion. These, together with calculation difficulties reported in neuropsychological assessments and detailed below, constitute the features of Gerstmann syndrome. We now turn to the experimental investigation of CO's number processing abilities.

EXPERIMENTAL INVESTIGATION OF NUMBER PROCESSING

The patient was tested during a period of two years (February 2001 - February 2003) on an average basis of two 45-minute sessions per week. Our investigation of CO's number processing abilities was not restricted to a detailed examination of cardinal meaning and quantity processing. We also placed particular emphasis on examining the patient's capacities to process the sequence of number words, after bilateral parietal damage. Yet, we tested sequence knowledge and order relations not only on the number sequence, but also on non-numerical ordered series. As we will see, CO had largely preserved abilities to process quantity and cardinal meaning, while showing impaired sequence processing. To clarify this potential dissociation, we directly compared the patient's performance in similar tasks testing order relations either in sequence or in (equivalent) cardinal situations.

The experimental investigation is reported in 5 main sections. In line with the existing numerical models, we first examined CO's abilities to handle numbers in the Arabic and verbal (written and oral) codes using transcoding and matching tasks; these will be reported in Section 1, together with the patient's abilities to carry out simple calculations. In Section 2, we examined the patient's cardinal number meaning and more general quantity processing abilities on numerical and non-numerical material. In Section 3, we first assessed CO's level of elaboration of the sequence of number words, following the 5 stages proposed by Fuson (1988), and then turned to his capacities to process sequence order relations, on numerical and non-numerical ordered series. In Section 4, we compared CO's performance in processing order relations in similar sequence (e.g. 'Does 3 come before or after 5 in the conventional sequence of number words?') and cardinal contexts (e.g. 'Is 3 smaller or larger than 5?'), and tested whether they relied on common or partially distinct mechanisms. Finally, in Section 5 we present CO's abilities to process spatial order relations in non-numerical contexts.

Some of the tasks we used (mainly in Sections 1 and 4) were taken from the “Batterie longue du calcul” (Seron & al., 2001, UCL), a standardized number processing and calculation battery. CO’s performance in these tasks will be compared to that of 12 control subjects matched for age (mean age = 71.7 years; SD = 6.65) and education (mean years of formal education = 10.6; SD = 0.8). Other tasks were specifically devised for the purpose of the present investigation; some of these tasks were proposed to 5 neurologically intact subjects matched as closely as possible to CO for age (mean age = 75.4 years; SD = 8.4) and education (mean years of formal education = 13.6 years; SD = 2.6). Impairment in performance will be determined by computing modified t-tests (Crawford and Garthwaite, 2002) on CO’s scores compared to performance in the appropriate control group. When performance will be compared to other groups of controls, it will be clearly mentioned. Finally, note that in all these tasks, the patient was under no time pressure and stimuli remained visible until he gave his response (with the exception of one subitizing task).

Section 1: Basic numerical abilities

Test 1: Transcoding

Method. CO was presented with six number transcoding tasks: he was asked to read aloud Arabic numerals (AN) or written verbal numerals (WVN), to write Arabic or verbal numerals under dictation, and to transcode AN into WVN and vice versa. Two categories of items were used: (1) the lexical primitives (LP) of the French verbal number system (the units 1-9, the teens 11-16, the tens 10-90 and the multipliers 100 and 1000), and (2) complex 3 to 6-digit numerals, for a total of 16 or 17 items according to the task. All tasks with complex numerals were taken from the “Batterie Longue du calcul”.

Results. As show in Table 3, CO had a flawless performance in reading simple (i.e. LP) Arabic and written verbal numerals. Writing these numerals under dictation in the Arabic code was also largely preserved, though CO made 2 lexical errors (e.g. he wrote 13 for 15). Writing LP in the verbal code

was more impaired, due to severe agraphia and to several code intrusion errors (e.g. /quatorze/ “fourteen” was written *latoze*; see Thioux, Seron, Turconi & Ivanoiu, 1999, for a detailed presentation of this kind of transcoding errors). Transcoding the LP from the Arabic into the written verbal code and vice versa was largely impaired. Some were lexical errors (e.g. transcoding *treize*, thirteen, into 30), but most of the patient’s productions consisted in copying the entry (Arabic or WV) numeral, which might be explained by his attentional and executive impairment.

Performance with more complex numerals was impaired in all tasks (see Table 3). Reading Arabic and verbal numerals, as well as writing AN, led to both lexical (e.g. 107 was read *cent septante*, “one hundred and seventy”) and syntactic errors (e.g.: 1009 was read *dix-neuf cents*, “nineteen hundred”). Writing complex verbal numerals under dictation was interrupted after 6 items because of CO’s severe agraphia. Most of his productions were recognizable words, if one ignores spelling and graphic errors. Transcoding AN into WVN showed similar errors as those reported with the LP.

Table 3. CO’s number of correct responses and the corresponding percentage in transcoding tasks.

	CO				Control subjects	
	Lexical Primitives		Complex numerals		Complex numerals	
	<i>N</i> = 26	%	<i>N</i>	%	Mean <i>N</i>	SD
Reading AN	26	100	7/16*	44	16.92	0.29
Reading WVN	26	100	9/17*	53	17	0
Writing AN	24	92	14/17*	82	16	0
Writing WVN	20	77	5/6 (Agraphia)		17	0
Transcoding AN into WVN	11	42	9/16*	56	15.92	0.29
Transcoding WVN into AN	17	65	Not tested		16.83	0.08

Note: AN is for Arabic numerals; WVN is for written verbal numerals.

* Difference significant at $p < .05$ compared to mean scores obtained in controls; modified t-tests (Crawford and Garthwaite, 2002) were used when the Standard Deviation was different from 0.

Comment. CO could read and write under dictation the lexical primitives in the Arabic and written verbal codes, although producing WVN was very laborious because of agraphia. Reading complex numerals was more error prone whatever the input code. Transcoding AN into WVN or vice versa was altered. Note that because of impaired reading of complex numerals, when such stimuli were presented to the patient in subsequent tasks, they were always simultaneously read aloud by the experimenter. Furthermore, because of severe agraphia, the patient was not asked to produce numerals in the written verbal code in the forthcoming tasks.

Test 2: Matching

Method. CO was presented with a verbal numeral and asked to select the corresponding Arabic numeral among four alternatives. Twenty-four verbal numerals were given orally (9 units, 6 teens and 9 tens), 26 were written on cards (the multipliers *hundred* and *thousand* were added to the previous list).

Results and comment. CO had a nearly flawless performance (24/24 and 24/26, respectively in the oral and written modalities) attesting good comprehension of Arabic numerals.

Test 3: Arithmetical facts

Method. CO performed four calculation tasks. Addition was tested using all problems from $0 + 0$ to $9 + 9$ ($N=100$). Subtraction was examined with 95 problems of the form $p - q = r$: in 36 problems p was larger than 1 and q smaller than 9, in 40 problems p was comprised between 11 and 20 and q between 1 and 9, and the remaining were rule-based problems of the form $p-0$ or $p-p$. Multiplication was tested with 100 problems from 0×0 to 9×9 . Finally, division was evaluated with 80 problems, of which 64 were of the form $p \div q = r$ (where p is the result of a multiplication between 2×2 and 9×9 and q is comprised between 2 and 9) and 16 were rule-based problems of the form $p \div 1$ or $p \div p$. All the problems were presented in the Arabic code and simultaneously read aloud by the experimenter; the patient gave his response orally.

Table 4. CO's correct performance in Arithmetical Facts.

<i>Addition problems ($p + q = r$)</i>			<i>Subtraction problems ($p - q = r$)</i>		
Total correct		81/100* (81%)	Total correct		51/95* (53.7%)
Rules	$p + 0$ and $0 + q$	17/19	Rules	$p - 0$ and $p - p$	17/19
Facts	p and $q \in \{1; 5\}$	23/25	Facts	p and $q \in \{1; 9\}$	27/36
	p or $q \in \{6; 9\}$	31/40		$p \in \{11; 20\}$ and $q \in \{1; 9\}$	7/40
	p and $q \in \{6; 9\}$	10/16			
<i>Multiplication problems ($p \times q = r$)</i>			<i>Division problems ($p \div q = r$)</i>		
Total correct		32/100* (32%)	Total correct		28/80* (35%)
Rules	$p \times 0$ and $0 \times q$	1/19	Rules	$p \div p$ and $p \div 1$	8/16
	$p \times 1$ and $1 \times q$	15/17	Facts	$q \in \{1; 5\}$	10/32
Facts	p and $q \in \{2; 5\}$	7/16		$q \in \{6; 9\}$	10/32
	p or $q \in \{6; 9\}$	7/32			
	p and $q \in \{6; 9\}$	2/16			

Note:

* Difference significant at $p < 0.05$ compared to mean scores obtained in controls (modified t-test; Crawford and Garthwaite, 2002).

Results. As shown in Table 4, CO was impaired in all tasks. Addition was nonetheless better performed than subtraction ($\chi^2(1) = 16.62$, $p < .0001$) that was in turn less impaired than multiplication and division (both $\chi^2(1) > 6.12$, $p < .013$), these latter two tasks being equally altered ($\chi^2(1) < 1$). Performance in addition was influenced by the size of the operands, the patient making more errors on large (both operands between 6 and 9) than small problems (both operands between 1 and 5; $\chi^2(1) = 5.406$, $p < .02$).

Nonetheless, CO's errors were often close to the correct sum (mean distance between error and expected response was 1.8), suggesting good approximation of the magnitude of the result. Note that CO always tried to resolve addition problems by retrieving the answer from memory. When unable to do so, he knew he could use his fingers to resolve the problem, and sometimes tried to do so, but he always failed, not knowing anymore how to do. Performance in subtraction was also influenced by the size of the operands ($\chi^2(1) = 25.34, p < .0001$) with most errors made on large problems (first operand between 11 and 20). All errors were plausible responses (i.e., they were smaller than the first operand). Rule knowledge was preserved in addition and subtraction. In multiplication problems, on the 48 non rule-based errors, 46 were the answer to another multiplication problem and 35 of these belonged to the table of one of the operands (e.g., $6 \times 5 = 35$)⁷. The patient appeared to have forgotten the rule $p \times 0 = 0$ as he responded "p" in most cases (13/18), while he still knew the rule $p \times 1 = p$. There was no size effect in multiplication ($\chi^2(2) = 4.5, p < 1$). Performance for division showed preserved knowledge of the rule $p:p=1$, but not for the rule $p:1=p$ as the patient responded 1 in most cases (7/8). Over the remaining 44 errors, 16 (36.4%) consisted in repeating the divisor and 8 (18.2%) were table errors. There was no size effect.

Comment. Results showed a better preservation of addition and, to a smaller extent, subtraction. The patient was able to provide a good approximation of the results for addition problems, as suggested by the small distance between his erroneous response and the expected answer. With respect to multiplication and division, the absence of a size effect is explained by the fact that even very simple problems were impaired (CO failed more than half of the multiplication problems with operands between 2 and 5). Besides, most errors in multiplication were within-table responses, suggesting that the patient was impaired in retrieving rote arithmetic facts.

⁷ Note that CO was unable to recite multiplication tables. For the table of 2 he couldn't start recitation on his own and with the help of the experimenter he produced "2 by 2, 4", then "4 by 4, 16", and when redirected to the table of 2, he proved unable to continue recitation.

Test 4: Exact numerical (encyclopaedic) knowledge

Method. The patient was asked 52 questions that tapped his knowledge about exact number facts. Each question required a precise numerical answer (e.g., "How many weeks are there in a year?").

Results. The patient made 11 errors in this task, which is in the normal range (mean number of errors: 10.89; SD: 4.5), when compared to 37 control subjects of about the same age (62 to 86 years old; mean age = 71.5).

Test 5: Parity judgment

Method. Knowledge of the odd or even status of numbers was tested in a parity judgment task with 1- to 3- digit numerals (range 1-871) presented in the Arabic, spoken verbal or written verbal codes (N=22, in each code).

Results. Performance was flawless in this task (100% correct in the three codes).

Summary of Section 1

CO was able to read and write simple numbers in the Arabic and verbal codes. Arithmetical facts were impaired: the patient was unable to retrieve rote arithmetic tables, while he could give an approximation of the result of addition problems. Knowledge of exact number facts and parity were preserved.

Section 2: Processing of numerical and non-numerical quantity

Three sets of tasks were used to test CO's abilities to process quantity information and cardinal meaning: (A) dot tasks, (B) Arabic and verbal numeral tasks, (C) non-numerical tasks.

A. Dot tasks

These tasks aimed at assessing the patient's performance in processing

numerical quantity without involving linguistic abilities, and at investigating whether CO could access and process the cardinality of dot arrays.

Test 1: Comparison and seriation of dot patterns.

Method. Three comparison and one seriation tasks were proposed. In task 1, the patient was asked to compare the numerosity of two 1 to 9 non-canonical dot patterns randomly arranged on pairs of sheets, and to indicate the pattern (right- or left-hand) that contained more dots. Twenty pairs were devised; in each pair, one pattern contained between 3 and 7 dots, and the other set displayed the same number of dots either +1, +2, -1 or -2 (e.g., a 4 dot-pattern was alternatively compared to patterns of 2, 3, 5 and 6 dots). In task 2, patterns of small (8), medium (15) and large (30, 55) numerosities had to be compared to simultaneously presented patterns with a small (+3), medium (+15) or large (+50) distance (N=12). In task 3, CO was shown pairs of large random dot patterns presented on separate cards. In each pair, one pattern (the standard) had a fixed number of dots (either 20 or 40; 24 cards each) and the other contained 2, 4, 6 or 8 dots more or less the standard set. In task 4 (seriation) CO was asked to arrange three non-canonical 1- to 9-dot patterns presented on separate cards, according to the number of dots.

Results. CO's performance was fast and flawless in task 1 (20/20, 100%) and almost perfect in task 2 (11/12, 92%); the only error concerned the large set/small distance pair (i.e., pair 55-58), an error shared by 66% of young control subjects (N=29, mean age = 26; Pesenti, unpublished data). In task 3, the patient performed well when the standard was 20 (22/24, 92% correct); he made a few errors when the standard was 40 (18/24, 75% correct), but his performance was still above the average of young controls (controls' mean correct performance = 70%; N = 16, mean age = 28). Finally, CO was almost flawless in the seriation task (19/20, 95%) and his performance was not statistically different from controls (modified t-test: $t < 1$).

Comment. CO was able to compare dot patterns and arrange them according to their numerosity, showing preserved knowledge of non-symbolic quantities. Yet, these achievements (e.g. recognizing that five dots is more than four dots) don't necessary entail the understanding of the cardinality meaning conveyed by the corresponding Arabic numerals (e.g.

knowing that 5 is more than 4); this ability will thus be tested in the following section.

Test 2: Cardinality judgments

Method. Two tasks were devised. Task 1 examined Arabic-to-dot matching abilities. CO was presented with 60 pairs comprising an Arabic numeral and a dot pattern, in which small dots had a value of 1 and large dots had a value of 10. The AN was either presented with the corresponding dot pattern (target set), with a close distractor, or with a far distractor. The patient had to decide, for each pair, whether or not the dot pattern corresponded to the AN. Task 2 tested the comprehension of cardinal inclusion. CO was presented simultaneously, on 5 occasions, with an AN (e.g. 8) and 5 dot patterns (e.g. patterns containing 3, 5, 8, 9 and 16 dots) and asked (1) to point to the dot pattern which cardinality corresponded exactly to the numerosity of the AN (the pattern with 8 dots in the e.g.) and (2) to point to all patterns containing "at least" that numerosity (patterns with 9 and 16 dots in the e.g.).

Results. The patient performed well in task 1 (58/60, 97%) and in task 2 (cardinality matching: 4/5, inclusion: 4/5). His errors were due to impaired coordination of pointing and counting procedures (e.g. in task 2, he counted 6 dots instead of 8 and discarded that set as containing at least 8 dots). CO's performance was good, but still below that of controls in task 1 (modified t-test: $t = -3.65$, $p < 0.022$) and task 2 (none of the controls made a single error in this task).

Test 3: Accessing cardinality through quantification procedures

Method. We tested CO's abilities to access the cardinality of dot patterns (i.e. tell how many dots there are) through subitizing, counting and numerosity estimation. The patient was presented successively with 1 to 9 dot-patterns in a random order on a computer screen and asked to tell how many dots are in each pattern. In the subitizing/estimation task, patterns were presented for 500 ms and the patient's RT was recorded. In the counting task, the pattern remained on the screen until the patient gave his response.

Each magnitude was presented in different arrangements, 12 times in the subitizing/estimation task, 14 times in the counting task.

Results. In the subitizing/estimation task, CO showed the expected difference between faster RT in the subitizing range (mean RT for 1 to 3 dot patterns: 619 ms) compared to the estimation range (mean RT for 4 to 9 dot-patterns: 1304 ms; $F(1,47) = 23.22$, $p < .0001$); he was also more accurate but far from perfect for small (29/36, 81% correct responses for 1 to 3 dot patterns; he made no error for 1-, three errors for 2- and four errors for 3-dot patterns) than large sets of dots (20/72, 28%; $\chi^2(1) = 26.97$, $P < .0001$), for which his response was always close to the expected answer (mean distance: 1.5). Counting was partially correct up to 3-dot patterns (overall: 39/42, 93% correct), although CO made 2 errors on 2-dot patterns (14%) and 1 error on a 3-dot pattern (7%). Besides, his performance was gradually more impaired with the increasing number of to-be-counted dots (5, 6, 7, 11, 12 and 4 errors, respectively for 4 to 9-dot patterns). Yet the patient's response was always close to the expected answer (mean distance between CO's response and the number of dots in the array was 1.3 and it never exceeded 2) and impaired counting of larger sets could be explained by the patient's impaired coordination of the pointing and counting procedures (e.g. he sometimes counted the same dot twice).

Comment. CO was able, most of the time, to correctly subitize and count the numerosity of small dot patterns. This suggests that he had preserved understanding of the core principles of counting (e.g. he correctly used a counting strategy to answer 'How many' questions), but his performance was impaired for larger sets because of a procedural inability to correctly match oral counting and finger pointing (probably due his finger agnosia). Yet, when counting larger sets, his performance was less accurate, and this can be explained by impaired coordination of the pointing and counting procedures, not by impaired understanding of cardinal meaning. With respect to estimation abilities, they appeared to be only partially preserved.

Comment for dot tasks

CO had preserved dot-pattern comparison and seriation abilities. He was also able, most of the time, to match an AN with the dot pattern displaying

the corresponding cardinality, and to identify dot-patterns which numerosity was included in the target AN. The few errors he made in these tasks can be largely explained by impaired coordination of the pointing and counting procedures. This impairment was also found to elicit an increasing number of errors when counting large sets of dots, while subitizing and counting small sets was mostly preserved. Overall, CO's ability to match Arabic numerals with arrays of dots and to answer 'how many' questions shows a genuine understanding of cardinality.

Having established that CO had largely preserved abilities to process numerical quantity represented by non-symbolic material (dot patterns) we now turn to his performance with symbolic stimuli (Arabic and verbal numerals).

B. Tasks with Arabic numerals and number words

Test 1: Comparison tasks

Method. a. Paper and pencil task. In this task, that was taken from the "Batterie longue du calcul" (Seron & al., 2001, UCL, unpublished document), twenty-nine pairs of 3 to 6-digit numerals (ranging from 102 to 800.000) were presented in the Arabic and verbal (written and oral) modalities, at two different occasions. CO was asked to point to the larger number of the pair.

b. Computerized task. The patient was presented with 8 pairs of Arabic numerals, four consecutive (Distance 1: 2-3, 3-4, 6-7, 7-8) and four far pairs (Distance 3: 2-5, 3-6, 4-7, 5-8) in the ascending (e.g. 2 3) or the descending (e.g. 3 2) order, and asked to choose the larger number in magnitude. Size congruity was also manipulated and pairs could be either congruent (the numerically larger number was also physically larger), neutral (both stimuli had the same, intermediate, physical size) or incongruent (the numerically larger number was the physically smaller). Pairs were presented randomly (3 times each) in the centre of a computer screen and the patient had to respond by pressing the left- or right-hand key according to the position of the larger number on the screen. Reaction Times and error rates were recorded (see Turconi, Campbell, & Seron, 2005, Experiment 1, for a detailed description

of the method, the only difference being that stimuli remained on the screen until the patient responded).

Results for the paper and pencil task. The patient made 3 reading errors with AN (e.g. 5301 was read *five thousand and one* and judged smaller than 5072). These errors were removed from the analysis. His performance on the remaining items was mostly correct (53/55, 96%; note that control subjects don't make a single error in this task). Comparing written verbal numerals (WVN) lead to a few errors in the first presentation of the task (22/29, 76%), but these could be mostly explained by impaired reading abilities. Thus, on the second presentation of the task, written verbal numerals were presented to CO and simultaneously read aloud by the examiner; his performance was flawless (29/29, 100%). Finally, when comparing large orally presented numbers without any written counterpart, CO made a few errors (22/29, 76%) that could be due to poor working memory abilities. Thus, on the second presentation of the task, the patient was asked to first repeat the numbers of the pair and to give his response only after that; his performance was slightly improved (25/29, 86%)⁸, but remained just below the performance of age-matched controls (modified t-test: $t = -2.42$, $p < 0.034$).

Results for the computerized task. Performance was almost flawless (140/144, 97%) and did not differ from that of young controls (mean control performance = 138/144; SD = 6.9; N = 24, mean age = 20.2). Correct RTs after removing outliers were analysed through a repeated-measures ANOVA with distance (1, 3), pair order (ascending, descending) and size congruity (congruent, neutral, incongruent) as within-subjects factors. Results showed a significant distance effect, with close number pairs processed slower (2229 ms) than far pairs (1846 ms; $F(1,9)=7.23$, $p<.025$), and a significant pair-order effect, with faster responses to ascending (1931 ms) than descending pairs (2144 ms; $F(1,9)=6.39$, $p<.032$). With respect to size congruity, the overall effect did not reach significance ($F(2,18)=2.35$, $p>0.12$), though congruent pairs were processed significantly faster (1914 ms) than

⁸ Note that 2 of the errors occurred on items involving *hundred* in a product relationship with a quantity between 11 and 19, a syntactic structure mostly used in French to denote historical dates (e.g. *onze cents* - *mille trois cents*, i.e. 1100 – 1300).

incongruent pairs (2216 ms; one-tailed t-test: $t(38) = -1.84$, $p < .037$). No interaction was significant. Note that once CO had selected the correct response, he was slow in pressing the corresponding key; such non-automatic response-key association contributes to the lengthening of RTs.

Test 2: Number positioning on an analogue scale

Method. CO was presented with 24 numbers and asked to point to their position on a vertical scale going from 0 to 100 or from 0 to 1000 (12 items each). On each scale, there were 4 intermediate marks, one of which corresponded to the target number. The numbers were presented in the Arabic and oral verbal codes (12 items each). This task was taken from the “Batterie longue du calcul” (Seron & al., 2001).

Results. Performance was perfect (24/24, 100%).

Test 3: Give a number smaller/larger than the target

Method. Presented with one AN, the patient was asked to orally give any smaller or larger numeral. Thirty-five numerals were presented in a random order (9 units, 15 two-digit numerals and 11 three-digit numerals).

Results. CO was flawless in giving a smaller number (35/35, 100%) and made 2 errors in giving a larger numeral (33/35, 94%), with both errors made on 3-digit numbers. Control subjects hardly make a single error in this task.

Comment on tasks with Arabic numerals and number words.

Performance in these tasks suggest that the patient was able to access and process the quantity meaning of symbolic numerals: he could select the larger in magnitude of two Arabic or verbal numerals, position them on an analogue scale, and produce a number smaller or larger than a given target. Overall, these preserved abilities suggest that CO relies on a preserved representation of analogue-magnitude (i.e. the so-called ‘number line’; Dehaene, 1992) to compare, order, and produce numbers according to their corresponding quantity. Furthermore, the presence of a distance effect on

RTs in the computerized comparison task, together with the better performance for physically congruent compared to incongruent pairs, suggest that magnitude information was accessed when processing small AN (Henik & Tzelgov, 1982). Performance in these tasks appears nonetheless to be better preserved for small than large numbers. A difference that can be explained by reduced working memory and impaired reading abilities, causing errors to appear on more demanding, larger, numerals. Finally, faster processing for ascending (e.g. 2 3) relative to descending pairs (3 2) in the computerized comparison task might reflect the contribution of automatic number sequence recitation when processing small number pairs that follow the direction of counting (see Turconi et al., 2005 for a discussion on this point).

We have shown that CO could process quantity information in numerical contexts, with non-symbolic and symbolic material. We now turn to quantity processing in non-numerical contexts.

C. Non-numerical quantity tasks

Test 1: Size comparison

Method. Two tasks were used to assess CO's abilities to process quantity information in non-numerical domains. In the first task (size judgment) the patient was orally presented with 70 pairs of words and asked to choose the one corresponding to the largest item in real size. The two members of a pair belonged to the same semantic category (animals, plants or manufactured objects) and were matched for frequency and familiarity. For the second task, we selected 4 pairs from task 1 (e.g. elephant-dog) and devised, for each pair, 4 sentences involving size relations (e.g. a dog is bigger than an elephant). The patient was asked to tell whether each sentence was true or false.

Results. CO was almost flawless in tasks 1 and 2 (respectively 69/70, 99%, and 15/16, 94%) and his performance did not differ from that of controls (modified t-test, $t < 1$).

Test 2: Comparison of quantity and frequency adverbs.

Method. CO was orally presented with pairs of words (adverbs or adjectives that were matched for frequency) tapping either quantity (8 pairs, e.g. many-few) or frequency knowledge (6 pairs, e.g. often-rarely) and asked to select the word that represented "more" than the other (respectively *many* and *often* in the examples).

Results. The patient had a preserved performance in this task for both quantity (7/8, 88%) and frequency adverbs (5/6, 83%). His performance did not differ from that of matched controls (modified t-test: $t = -1.747$, $p = 0.22$; $t = -2.494$, $p = 0.13$, respectively for quantity and frequency adverbs).

Test 3 : Ferocity judgments

Method. An animal name was displayed on the centre of a computer screen and the patient was asked to judge whether the animal was more or less ferocious than a dog. Eight different animal names (4 less ferocious than a dog and 4 more ferocious) that were matched for frequency were presented 12 times each in a random order (see the paper by Thioux, & al., 2005, for a detailed description of the task).

Results. Performance was almost perfect (95/96, 99%).

Comment for non-numerical quantity tasks

The patient showed preserved abilities to process quantity information conveyed by non-numerical material that could be object or animal size, quantity or frequency adverbs, or animal ferocity.

Summary of section 2

CO was largely preserved in processing quantity information conveyed by numerical (symbolic and non-symbolic) and non-numerical material. Overall, the collected data suggest that CO's cardinal number meaning (Fuson, 1988) was preserved, and that his understanding of quantity extended beyond the category of numbers, as it was also preserved in non-numerical contexts. Yet, performance was better for small numbers, for

which magnitude information was found to be automatically activated, than for larger numerals that could be more subject to reading and working memory impairments. Similarly, counting larger sets of dots was found to be more affected by impaired coordination of the counting and pointing procedures.

Section 3: Sequence recitation and processing sequence relations

In the present section, we will first examine CO's recitation skills for the number word sequence, and for non-numerical ordered series, and assess his knowledge of the sequence, according to the five stages of sequence elaboration described by Fuson (1988). We will then turn to the patient's abilities to process sequence relations. Finally, semantic knowledge about ordered series (e.g. knowing that July is a summer month), which is independent from sequence order, will also be assessed.

A. Sequence recitation: Five levels underlying the elaboration of the sequence

Fuson (1988; Fuson & al., 1982) described five stages in the elaboration of the number word sequence in children, that are marked by increasingly complex sequence abilities, both with respect to sequence production ('forward and backward sequence skills'), and with respect to the comprehension and production of relations on the words in the sequence. The achievement of each level is characterized by the child's acquisition of specific skills that can be assessed through particular tasks. This framework was used in the present section to drive our analysis about CO's sequence skills, and to identify a potential level of elaboration reflecting his preserved and impaired abilities to process sequence relations. Yet, recitation of the non-numerical ordered series of letters, days and months will also be examined, using similar tasks as those devised for the number sequence.

1. String level

At the string level, number words are forward-directed, connected, and undifferentiated. At this stage, the sequence is a unidirectional structure that can only be recited starting from the beginning, much like a song, and has no numerical meaning.

Method and results. CO was asked to count orally from 1 and was stopped at 20. He counted flawlessly.

2. Unbreakable list level

At this stage, the words are separated, but the sequence still exists in a forward-directed recitation form and can only be produced by starting at the beginning. Yet, the ability to recite the sequence from the beginning up to a given item also appears at this stage. Note that the sequence can be used at this stage to find the relations “comes just after”.

Method. CO was asked to recite the number sequence from 1 to 31, both orally and in the Arabic code, and sequence recitation from 1 to 20 was tested on many occasions. Recitation was tested for 4 additional ordered series: the ordinal number words (first, second, third, etc.), the letters of the alphabet, the days of the week and the months of the year. CO was asked, on several occasions, to orally recite each series from the first element, respectively ‘first’, A, Monday and January, up to ‘thirty-first’, Z, Sunday, and December, respectively.

Results. Reciting the number sequence from 1 to 31 was flawless in the Arabic and oral verbal codes. Sequence recitation from 1 to 20 was also always fast and flawless. Recitation of ordinal number words was correct from *first* to *tenth* on the three occasions it was tested, but CO made some omission errors above *tenth* (*eighteenth* on one occasion, *twelfth*, *thirteenth* and *fourteenth* on another, and he jumped from *twenty-first* to *twenty-ninth* on a third occasion). Reciting the alphabet from A to Z was tested on 7 occasions and was fully correct on only one of these. On the remaining occasions, CO always correctly recited the alphabet from letter A to letter D, but after D he omitted either 1 letter (E), 2 letters (F and G), 3 letters (E, F, G on 2 occasions) or even 6 letters (E, F, G, H, I, J). On later portions of the

alphabet, he omitted the letter V twice. Reciting the days of the week from Monday to Sunday was fast and flawless on all occasions (8/8). Reciting the months of the year was correct most of the time, but the patient omitted one month on 3/9 occasions (August, November, or December) and he once omitted two months (August and November).

3. Breakable chain level

At this level, the connecting links between the words in the sequence are understood and parts of the chain can be produced starting from arbitrary entry points (counting up from *a*), rather than always starting at the beginning. The ability to recite the number sequence from a lower number (*a*) to an upper number (*b*) is also acquired at this stage, and so is the ability to produce the sequence backwards. Yet, producing backward sequences is a very difficult task for young children and this ability was found to lag behind the production of forward sequences by about 2 years (Fuson & Secada, 1983).

Method. CO was asked to recite the number sequence starting from 3, 6, 8, 12 and 16, and he was stopped at 20. Counting from *a* to *b* was tested on 5 occasions and involved numbers up to 23 (e.g. count from 9 to 15). Backwards recitation of the number sequence was tested on several occasions (either from 22 or from 10 to 1). Alphabet recitation was also tested from a different letter than A (respectively from C, D, H, K, M, Q) up to Z. The patient was asked to recite the days of the week from Tuesday, Wednesday, Thursday or Friday until Sunday, and to recite the months of the year from February, March, May or July, up to the end of the sequence.

Results. Reciting the number sequence up to 20 starting from an arbitrary entry point was flawless (5/5 correct) and so was recitation from a lower to an upper number (5/5). To the contrary, the patient was unable to recite the sequence backwards from 22, and backwards recitation from 10 was almost impossible too. CO did not make it on a first occasion; on a second occasion, he was able to recite the series in the reverse order but only when primed with the first three numbers of the recitation by the experimenter who said *ten, nine, eight* and the patient continued *seven, eight, nine*, then said *no it's the other way round* and tried again, *ten, eight, ... No, ten, nine, eight, seven,*

etc. and makes it at last; he laboriously produced the correct reverse series on a third occasion, but omitted the number word *five*. Note that aged matched controls don't make a single error in these tasks (norms taken from the 'Batterie Longue du calcul', Seron & al., 2001).

With respect to the alphabet, starting recitation from a letter different than A was laborious (2/6 correct): the patient could recite the sequence from letters M and Q, as well as from letter K (but he omitted letter L), while recitation from letters C and H needed to be primed by the experimenter with three letters, and alphabet recitation from letter D showed sparse omissions (in brackets): D [E] F G [H I J] K L [M] N O P Q R S T U V W X Y Z. Reciting the days of the week from another day than Monday was perfect (4/4) and the equivalent performance over the months of the year was mostly correct (3/4). Although CO omitted the month of August when he started recitation from February. A peculiarity with the series of months is that CO seemed to know quite well the calendar number associated with each month: he knew that June is the sixth month of the year, April the fourth, May the fifth, July the seventh, August the eighth, November the eleventh, December the twelfth, and, of course, January the first.

4. Numerable chain level

The words are abstracted still further and become units in the numerical sense; thus sets of sequence words can themselves represent a numerical situation and can be counted or matched to a set of items of known numerosity (e.g. five fingers). The abilities to count up a specified number '*n*' from a given number *a*, to count from *a* to *b* to find out the number of words between them, and to count by '*n*', appear at this stage. Parallel skills also develop for the backward sequence, but appear some time later however. In tasks like counting up or down '*n*' from one number to another, one must remember the word to which he is counting, produce the sequence, and simultaneously keep track (e.g. on the fingers) of the number of words already being produced (Fuson & al., 1982).

Method. The abilities specific to this level were tested on the number sequence only. CO was asked to orally count '5' after 67, 197 and 3997. Oral counting by 3 and by 10 was also examined. These tasks were taken

from the 'Batterie Longue du calcul' (Seron & al., UCL, 2001).

Results. When asked to orally count 5 steps after a target number, CO was somehow impaired: his counting sequence from 67 was correct, but he only counted 4 steps (68, 69, 70, 71), when starting from 197 his counting sequence was incorrect, but he correctly counted 5 steps (198, 199, 200, 201, 203) and finally, when starting from 3997 he both produced an erroneous sequence and counted 6 steps after the target instead of 5 (3997, 3998, 3999, 400, 401, 402, 403). Counting by 3 was impaired on a first occasion, and very slow on a second: it took the patient about 5 minutes to count 3, 6, 9, 12 (then he said 18, 24 and stopped). In counting by 10, he omitted number 70. Age-matched controls don't make a single error in these tasks.

5. Bidirectional chain level

The sequence is strongly automatized in the forward and backward directions at this level and words can be produced easily and flexibly in either direction. The ability to change direction rapidly without directional intrusions also appears at this stage. Because of CO's total inability to recite the number sequence backwards from 22, and his non-automatic backwards recitation from 10 to 1, more complex backwards recitation tasks, or shifting from forwards to backwards recitation, were not proposed.

Comment on the elaboration of the sequence

CO's forwards recitation skills for the number sequence included the ability to recite the series from the beginning, from a number other than 1, and from a lower to an upper number. Yet, counting '5' after a given number was somehow impaired (the patient did not keep track of the number of items counted, and he was impaired when crossing a *thousand* boundary) and counting by 3 or by 10 was very laborious. Examination of backwards recitation skills showed that counting backwards from 22 was virtually impossible, and counting from 10 to 1 was far from being automatic, as it needed to be primed with at least 3 numbers. Note that similar non-automatic backwards recitation skills were reported by Fuson & al. (1982) in children whose sequence skills corresponded to the 'Breakable chain level': these

children recited the sequence backwards by first producing a small portion of the sequence forwards, then inverting it and repeating these two operations. Overall, the above analysis suggests that CO's forwards production skills were flawless up to the 'Breakable chain level', with an only partial achievement of the skills expected at the 'Numerable chain level'. In fact, CO's inability to recite the sequence backwards from 22 and his laborious production of the numbers from 10 to 1 suggests that backwards recitation skills were only partially preserved and yet far from being automatized, thus not reaching the skills expected beyond the Breakable chain level.

With respect to the other series, CO was not flawless in reciting the sequence of ordinal numbers, even from the beginning, suggesting that this sequence was less automatized than that of 'cardinal' numbers. Hence, ordinal numbers did not appear to be easily derived from the corresponding cardinal numbers, and distinct abilities were found for each series. Alphabet recitation was rarely entirely correct since CO often omitted one or more letters. Recitation from another letter than A was correct when it started with a letter from the second portion of the alphabet (M and Q), otherwise the patient appeared unable to start recitation without help and he sometimes omitted one or more letters. The series of days was correctly recited from the beginning, as well as from an intermediate element. With respect to the series of months, CO correctly recited it most of the time, yet he sometimes omitted one or two months, whether he started recitation from the beginning or from an intermediary month. Hence, CO's recitation skills for the non-numerical sequences of days and months also achieved the 'Breakable chain level'. With respect to the alphabet, correct recitations were only occasionally produced, even from the beginning of the series, thus suggesting that the patient's recitation skills for this sequence did not even fulfil the requirements of the 'Breakable chain level'. Alphabet recitation appeared to be far from automatized.

B. Processing sequence relations

Fuson and colleagues (1983) have suggested that during the process of sequence elaboration, children also progressively understand sequence

relational meanings and become able to process specific, and increasingly complex, sequence relations. Yet, if processing specific sequence relations (e.g. ‘Just After’) rely on particular sequence recitation abilities (‘count up from *a*’), we make the hypothesis those sequence relations that involve CO’s preserved sequence recitation skills will be spared, whereas it might not be the case for order relations that require more elaborate sequence knowledge that is damaged in this patient (e.g. automatized backwards sequence recitation). Again, sequence relations will be examined using numerical and non-numerical series. Because most tasks will involve the concepts “before” and “after”, we first tested the patient’s understanding of these concepts.

Test 1: Definition and understanding of the concepts “before” and “after”

Method. Definition. The patient was asked, on several occasions, to give an oral definition of the concepts “before” and “after”, and to give examples of these concepts.

Understanding in experimental situations. CO was also presented with a horizontal line with a small square in the middle, and asked to indicate the portion of the line “before the square” and “after the square”. The small square was then replaced by number 5 and the patient was asked to point to the portion of the line coming “before 5” and “after 5”.

Understanding in everyday life situations. The patient was shown written sentences (N=14) orally read by the experimenter; each sentence involved two everyday life actions that were related in time (e.g. “In the morning, you get up before you get dressed”) and the patient had to tell whether the sentence was true or false.

Results. CO had a good knowledge and understanding of the concepts “before” and “after”. He gave the following definition for “before”: “something that anticipates an action, that precedes, that is anterior, and not posterior, to something else”. For the concept “after”, he only gave a synonym: “ulterior to”. Nonetheless, he could not provide spontaneous examples of these concepts, unless he was given a clue: when asked “what do you do after you get up in the morning?”, he responded “I shave myself”; when asked “what do you do before you go to bed?” he said “I recite my

prayer, and before each meal too". When asked if "before" a definite moment is "sooner" or "later" than that moment, he correctly responded "sooner". Similarly, he hesitated but then pointed correctly to the left side of the line to indicate the portion "before the square" and to the right side of the line to indicate the portion "after the square". He also responded correctly when the square was replaced by the number 5. Finally, his understanding of 'before' and 'after' applying to everyday life situations was also correct (12/14, 86%).

Comment. The patient had largely preserved understanding of the concepts "before" and "after", but he was unable to give spontaneous examples of these concepts.

Test 2: What comes Just After/ Just Before?

The sequence relation 'Just After' is the first acquired by children (Fuson, 1988), since the ability to produce the next element in the sequence relies on the forwards sequence recitation skills that are achieved as soon as the 'Breakable chain level'. Giving the element 'Just Before', instead, is a more complex process that develops about two years later in children than the 'Just After' relation, and requires good backwards recitation skills⁹.

Method. Presented with one number, letter, day or month, CO was asked to produce the previous (e.g. "What comes just before 18 in the counting sequence?") or the next element in the sequence (e.g. "What comes just after L in the alphabet?"). Cardinal numbers were single and two-digit numerals presented in a random order (N=30 for numbers, N=20 for all other series).

Results. As shown in Table 5, CO was impaired in all series when asked to give the element coming just before the presented target. Most of his errors consisted in giving the element coming just *after* that target in the sequence (proportion of such errors for numbers: 100%; letters: 68%; days: 100%; months: 86%). Note that these errors cannot be explained by perseveration of the strategy used in "what comes next" questions, since CO

⁹ The sequence relations 'Comes After/ Comes Before' also appear at the Breakable chain level.

started the task answering “what comes before” questions. When the patient was asked to give the element coming just after the target in the sequence he showed a far better performance, that was almost perfect for days and months. CO made only two errors with numbers (one of which was a decade error: 29 → 40), but his performance was still slightly impaired compared to that of aged-matched controls who hardly make an error. Performance with the series of letters was impaired. Note that the patient never recited any series from the beginning to find the answer in these tasks. With respect to the alphabet, he sometimes recited a portion of the sequence to find the letter coming just after the target, but he seemed unable to use this strategy to find the correct response (e.g. to find the letter coming just after H, he recited G, H, and then stopped), and erroneously produced twice (33%) the just preceding letter (as in the example given).

Table 5. Give the number, letter, day or month coming just before/ just after the target in the sequence.

		Patient CO				Control subjects			
		Just before		Just after		Just before		Just after	
		<i>N</i>	%	<i>N</i>	%	<i>Mean</i>	<i>SD</i>	<i>Mean</i>	<i>SD</i>
Numbers	(N=30)	7*	23	28*	93	29.5	0.58	29.5	0.58
Letters	(N=20)	1*	5	14	70	19.33	1.15	20	0
Days	(N=20)	10	50	19	95	20	0	20	0
Months	(N=20)	13*	65	19	95	19.67	0.58	20	0

* Difference significant at $p < 0.05$ compared to mean scores obtained in controls (modified t-test; Crawford and Garthwaite, 2002). Note that modified t-tests could not be applied when the SD was 0.

Comment. CO’s impaired ability to give the item ‘Just Before’ can be related to his impaired backwards sequence recitation skills. In the same way, his mostly preserved performance in giving the next item in the sequence of days, months, and numbers can be explained by his preserved forwards sequence recitation skills up to the ‘Breakable chain level’. Yet,

impaired performance for ‘Just After’ questions applied to letters was expected given CO’s inability to recite the alphabet starting from an arbitrary entry point. Furthermore, erroneously producing the item coming ‘Just After’ the target on most ‘Just Before’ questions, for all series, suggests that CO was relying on a forwards sequence recitation strategy, that he could not inhibit to perform this task. Hence, CO appeared to automatically activate (forwards) sequence recitation when processing ordered series. Yet, impaired performance could not be explained by the misunderstanding of the concepts “before” and “after”, since the patient proved able to define them, and, more crucially, because performance was found unchanged when the words “before” and “after” in the instructions were replaced with other words conveying equivalent meaning (e.g. replacing “before” with “preceding” or “sooner than”).

Test 3: Find the n^{th} element in a sequence

The ability to use sequence recitation to find the n^{th} entity in an array is initially acquired at the ‘Unbreakable list level’ and is specific to ordinal contexts. When this ability is applied to arrays of dots it may require minimal involvement of sequence knowledge (i.e., ordinal numbers recitation from ‘first’ and simultaneous pointing to the dots). On the contrary, finding the n^{th} element of a linguistic series (e.g. the tenth letter of the alphabet) may necessitate to recite the sequence up to the requested position, and simultaneously keep track (e.g. on fingers) of the items already counted in order to derive the element corresponding to the given ordinal position. This task requires more elaborate sequence skills (e.g. count ‘ n ’ from a), that might be specific to the ‘Numerable chain level’. Besides, good working memory (WM) capacities might also be necessary.

Method. We first examined the patient’s understanding and processing of ordinal positions using concrete material. He was presented with 10 (Part 1) or 20 (Part 2) aligned wooden tokens and asked either to touch the token corresponding to a given ordinal position (e.g. “Touch the fourth token”; Part 1) or to tell the position of the token touched by the experimenter (Part 2). We then examined CO’s abilities to process ordinal positions over linguistic series: he was either asked to retrieve the item corresponding to a

given ordinal position (e.g. “What is the third letter of the alphabet?”; Part 1) or to retrieve the ordinal position of a given item within its corresponding sequence (e.g. “Which month of the year is April?”; Part 2). Each part of the task was tested separately, but questions about tokens were randomly intermixed with questions about the series of letters, days and months. Finally, because performing Part 1 may request, in addition to good recitation skills, preserved WM capacities (which is not the case for CO), we examined whether reducing the WM load in Part 2 (by allowing the patient to use a written presentation of the ordered series) entailed an overall better performance.

Results. Part 1. CO was almost flawless with tokens (9/10, 90%); he made one error because of incorrect coordination of oral counting and pointing. To the contrary, his performance was truly impaired with the series of letters (7/18, 39%), days (8/15, 53%) and months (11/19, 58%). He gave more correct responses for the beginning (up to the fourth letter, third day and fourth month), and the end of the series for days and months (seventh day, eleventh and twelfth months); he rarely (i.e. twice for each series) resorted to recitation to perform the task. Note that aged-matched controls make very few errors in this task (overall mean: 96%; SD = 3.5).

Part 2. Performance was partially preserved with tokens (18/20, 90%) and months (10/12, 83%), but truly impaired with the series of letters (11/26, 42%) and days (4/7, 57%). The patient rarely resorted to oral recitation and he hardly used the written series presentation (e.g. by counting the items up to the target) to find the answer. He appeared nonetheless to sometimes resort to a counting strategy with the series of letters (on 18 out of 26 occasions), though this didn’t prevent him from making errors (12/18). Some of these errors were due to incorrect coordination of the pointing and counting procedures, but others reflected the patient’s inability to relate the counting result (e.g. counting up to 6, for the letter F) to the requested answer (i.e., sixth position in the alphabet). With the series of days and months, the patient more frequently tried to directly retrieve the answer from memory. This resulted in the correct response for months, as well as days at the beginning of the week (up to the fourth) while answers for the last 3 days were incorrect because the patient was confused about the length of the

series (he thought there were 10 days in a week and he thus said that Friday is the eighth day, Saturday the ninth and Sunday the tenth). Aged-matched controls don't make a single error on any series.

Comment. Good performance with tokens suggests that CO could understand the meaning of ordinal numbers and count up to the corresponding element in the series (part 1). Besides, CO could also, most of the time, identify the ordinal position of a given element in the sequence, by reciting the number word sequence and simultaneously pointing to the tokens (part 2). Using counting to find out 'what position' is acquired already at the unbreakable chain level. Impaired performance with linguistic series suggests that he did or could not resort to such recitation strategy for memorized sequences. This might be due to an inability to orally recite the series and simultaneously keep track (e.g. on his fingers; but see Fuson & al., 1982 for other keeping-track methods) of the items counted until reached the requested position, which might be expected as the patient had poor WM and impaired ability to use his fingers in counting (finger agnosia). Nonetheless, performance was not improved when the patient could rely on the written series (comparing performance for letters and days in Part 1 vs. Part 2: both $\chi^2(1) < 1$), although WM load was reduced and finger counting could be replaced by pointing to the items in order to keep track of already recited elements. CO appeared unable to use the written sequences to perform this task. More generally, he rarely resorted to a recitation strategy, with the exception of letters in Part 2, and when he tried to count up to the item to find its position in the series, he sometimes proved unable to convert the counting result (e.g. 6) into the corresponding ordinal position (sixth), suggesting impaired count-to-ordinal shift (Fuson, 1988). Overall, he more frequently resorted to a direct memory retrieval strategy in this task. A strategy that led to correct responses for items at the beginning and at the end of the series, as these probably have a stronger association with their relative position in the sequence (e.g. we know that Sunday is the seventh day of the week, without reciting the sequence, presuming we know there are 7 days in a week). Besides, the use of such direct retrieval strategy coupled with CO's preserved knowledge of most (9/12) months' position in the sequence can explain why he performed well with months in Part 2,

without having to use recitation. Correspondingly, using a direct retrieval strategy with letters led to a very poor performance, as their order in the alphabet can hardly be processed otherwise than through recitation (letters are not numerically ordered like months might be); and this probably also explains why CO used recitation more often with letters than other series. Overall, the pattern of performance found in this task might be explained by CO's impaired ability to use elaborate sequence recitation abilities (e.g. count 'n' from a) in ordinal contexts (e.g., finding the n^{th} element in a sequence).

Test 4: Order verification tasks

The ability to verify whether or not a pair of items (e.g. G L) is in the correct sequence order might need elaborate sequence recitation skills.

Method. Two tasks (a paper and pencil and a computerized task) were devised in which the patient was not asked to produce an element of a sequence but simply asked to verify the order of a pair of elements.

a. In the paper and pencil task, CO was asked to judge, for each pair of ordinal numbers (ranging from first to nineteenth), letters, days and months, whether the elements were presented in the ascending sequence order (e.g. B-C) or not (C-B). Pair distance was varied between 1 (consecutive elements) and 10 for numbers, 5 for the other series. In the first part of the task, pairs of all series were mixed and shown in a random order; in the second part, each series was tested separately.

b. In the computerized experiment, the patient was first presented with a numerical task, identical to the one presented in number comparison (Section 2, B, Test 1), but with order instructions: presented with a pair of AN (consecutive: 2-3, 3-4, 6-7, 7-8; non-consecutive: 2-5, 3-6, 4-7, 5-8), he was asked to decide whether numbers were presented in the ascending (i.e. forwards counting: 2 3) order, or not (3 2). He was then proposed the corresponding alphabetic task, with number pairs replaced by their corresponding letter pairs (B-C, C-D, F-G, G-H and B-E, C-F, D-G, E-H, respectively) and asked to tell whether or not the letters were presented in the alphabetical order. Each pair was shown 9 times on the centre of a computer screen. The patient gave his response orally because he could not

associate the response side (left, right) with the expected answer (no, yes, respectively). We recorded RTs and error rates. The method for this task is described in detail elsewhere (Turconi, Campbell, & Seron, in press, Experiment 1), the only differences being the mode of response and the fact that stimuli remained on the screen until the patient responded.

Results for the paper and pencil task. Performance in Part 1 was impaired for all series and did not differ from chance (ordinal numbers: 26/51, 51%; letters: 21/35, 60%; days: 14/23, 61%; months: 13/30, 43%; all Binomial tests: $p > .31$; overall mean performance of control subjects: 98.5%; SD = 2.3). Performance was equally impaired in Part 2, it did not differ from Part 1 (all $\chi^2(1) < 2.2$, $p > .14$) and was again not better than chance in all series (ordinal numbers: 25/49, 51%; letters: 23/34, 68%; days: 12/20, 60%; months: 17/27, 63%; all Binomial tests: $p > .060$). With respect to the strategy used, if the patient resorted to recitation, we would have expected better performance for consecutive (e.g. March April) than non-consecutive pairs (e.g. March July). This was not the case ($\chi^2(1) < 2.016$, n.s.) and is consistent with CO's claim that he never used recitation to perform the task.

Results for the computerized task. Performance was impaired in the numerical task (84/144, 58%), but just above chance level ($\chi^2(1) = 4$, $p < .046$). The error analysis suggested that the patient was biased towards answering 'no' (i.e., the number pair is not in the counting order; 116/144, 81% of his responses). Nonetheless, when he responded 'yes', he did so more often for consecutive (23/28, 82%) than for more distant number pairs (5/28, 18%), whatever their order. RTs were not analysed in this task because of the response bias and the high error rate. When the patient had to verify the order of letter pairs, he was also impaired (76/144, 53%) and his performance wasn't better than chance ($\chi^2(2) < 1$). RTs were not analysed, but exploring the error pattern highlighted the same response bias towards answering 'no' (116/144, 81% of total responses). When the patient correctly responded 'yes' (i.e., the pair is in the alphabetical order, 16/144), he did so on almost all occasions for consecutive (15/16) pairs. This pattern might be explained by the activation of (counting or alphabetic) sequence recitation when processing consecutive elements.

Comment. These data suggest that the patient was unable to recognize pairs of stimuli that were presented in the conventional sequence order, compared to pairs that were in the reverse order, and this was true for all tested ordered series (cardinal numbers, ordinal numbers, letters, days and months). CO performed at chance in both the paper and pencil task and the computerized alphabetic order task, and he additionally resorted to a response bias in the two computerized experiments. The patient's comments further illustrate his inability to understand the meaning of sequence order: for instance, when presented with the pair '8 9' he said that numbers were not in the correct order, and when asked what is their order in the counting sequence, he said (without counting) that 8 didn't come before, but after 9 when counting (but he did not count to verify his answer). The patient did not appear to intentionally resort to a recitation strategy in these order verification tasks, as suggested by the absence of an improved performance for consecutive relative to non-consecutive pairs (i.e., of a reverse distance effect). However, the pattern of correct 'yes' responses in computerized tasks might suggest that sequence recitation (i.e., counting or alphabet recitation) was sometimes automatically activated and contributed then to correct response selection. Note that CO did not either appear to resort to a quantity strategy in the case of numerals, as no standard distance effect was found, and performance was equally impaired with numbers than with other series.

Comment about CO's order processing abilities on ordered series.

The patient proved able to understand the concepts "before" and "after". He could find the next element in an ordered series, but was impaired in producing the previous one. These abilities can be related to preserved forwards and impaired backwards recitation skills. Furthermore, the patient appeared to automatically use forwards recitation when answering 'Just Before' questions. Finding the ordinal position of a given token or the token corresponding to a given ordinal number was largely preserved. Yet, processing ordinal relations on linguistic ordered series was impaired, and this could not be simply explained by poor WM capacities. CO often used a direct memory retrieval strategy in this task, instead of resorting to sequence

recitation, which could reflect a basic inability to use elaborate sequence meaning in ordinal contexts. Recognizing pairs of items presented in the conventional sequence order was impaired as well, and again, CO didn't resort to intentional sequence recitation to perform these tasks.

C. Lexical and semantic knowledge about ordered series

Method. In a first task (category fluency), the patient was asked to produce, in a random order during 2 minutes, as many different words as possible belonging to each of 5 ordered series (numbers, letters, days, months, musical notes). In a second task, he had to answer a series of questions that tapped semantic knowledge about the series of days, months and letters (e.g. "Which day of the week do we usually eat fish?").

Results. Performance was good in both tasks. In the category fluency task, when repetitions of the same word were discarded (no other error was observed) the patient proved able to produce all the elements for the series of days (7), months (12) and musical notes (7), as well as 18 different number words (ranging from *ten* to *eighty-five*) and 18 different letters. Nonetheless, producing the elements of a sequence in a random order proved to be difficult and the patient could not prevent from making clusters in his productions (e.g., X, Y, Z). Performance in the semantic task was also preserved (18/21, 86% correct). The patient made 1 error with days (5/6) and 2 with months (13/15) (e.g. "What month a new school-year begins with?" CO responded January instead of September). His performance was not statistically different from that of age-matched controls' (modified t-test: $t = -4.025$; $p = 0.06$).

Comment on CO's knowledge about ordered series. The patient had largely preserved lexical and semantic knowledge about the ordered series tested in the present section: he could produce most of the elements of each series in a fluency task, though he sometimes failed to inhibit automatic sequence recitation, and he showed preserved non-order semantic knowledge about the series of days, months and letters. Hence, impaired performance in sequence order processing tasks may not be explained by (non-impaired) lexical and semantic knowledge.

Summary of Section 3.

We have shown in this section that CO had preserved forwards recitation abilities up to the ‘Breakable chain level’ for the series of numbers, days and months. Yet, reciting the letters of the alphabet was more error-prone, even from the beginning of the sequence. Besides, a major impairment was observed for backwards recitation skills. The subsequent investigation of sequence order relations revealed that CO had preserved capacities to produce the element ‘Just After’ a given target in the sequence, while he was unable to produce the element ‘Just Before’. This pattern of performance can be explained by CO’s preserved forwards recitation skills in the face of impaired backwards recitation abilities. Similarly, the patient’s inability to find the item occupying the n^{th} position in an ordered series could also be accounted by impaired elaborate sequence knowledge. More specifically, because CO was unable to count n from a (‘Numerable chain level’ skill), he might have been equally unable to find the n^{th} position in a sequence starting from the first element. The patient’s impaired performance in pair-order verification tasks might be due to his failure to explicitly resort to a sequence recitation strategy. Overall, CO appeared to be largely unable to intentionally use sequence recitation to process sequence order relations. CO tried instead to directly retrieve the answer from memory, which elicited correct responses for the initial portion of each series, but otherwise high error rates. Finally, lexical and semantic knowledge of these ordered series was largely preserved.

Finally, understanding the concepts “before” and “after” in non-sequential contexts was also slightly impaired, and so was ordering the hours of the day. Whereas processing the temporal order of everyday life personally experienced events appeared better preserved.

Section 4: Direct comparison of order relation processing in sequence and cardinal contexts

We have established, in Section 2, that CO had largely preserved abilities to process numerical (and non-numerical) quantity using symbolic and non-symbolic material. Assessing sequence knowledge in Section 3 showed preserved forwards recitation skills for the series of numbers, days, months, and to lesser extent, letters, whereas impaired backwards recitation abilities. Besides, CO was found unable to intentionally use his sequence recitation skills to process order relations in sequence contexts (e.g. giving the number *coming before* the target). However, the question of whether CO would be able to process similar order relations in cardinal contexts (e.g. giving a number *smaller* than the target) remains open and theoretically challenging. Yet, comparing performance in Sections 2 and 3 suggests that processing quantity meaning or sequence knowledge may rely on partially distinct mechanisms that can be selectively spared or impaired after cerebral lesion. This is further evident when comparing performance in the computerized Arabic number comparison task (Section 2) with the corresponding computerized order verification task (Section 3) that involved the same number pairs. The patient was very good in identifying the larger of two numbers and RTs showed a standard distance effect, suggesting preserved activation of magnitude information in this task. On the contrary, CO was unable to process the order of numbers in these same pairs and showed a biased response pattern in the order verification task. Such a difference in processing the same items with quantity or order instructions could reflect a dissociation between their underlying mechanisms. Nonetheless, we must ascertain that this potential dissociation cannot be merely explained by the differential contribution of non-specific cognitive functions to each kind of task (e.g. WM and executive functions could be more recruited in the sequence tasks). For this reason, we devised new experiments in which the type and load of non-specific cognitive functions were matched as well as possible, so that equivalent tasks differed only with respect to the instructions and the corresponding underlying mechanism, that

is quantity¹⁰ or sequence processing. In a first set of computerized experiments, the patient was presented with a number and asked to decide whether it was smaller or larger than a fixed standard (quantity instructions), or whether it came before or after that standard in the counting sequence (sequence instructions). In a second set of tasks, the patient was shown a numeral and either asked to give any number smaller/larger than the target, or to give the target numeral $-1/+1$ (quantity instructions); or, he was asked to give any number coming before/after the target numeral, or to give the number coming just before/just after that target (sequence instructions). In a third set of tasks, the patient was required to give a number between two limits, again using quantity (give a number that is larger than x and smaller than y) or sequence instructions (give a number that comes after x and before y). In a final set of tasks, we presented the same pairs as in the third set and asked CO to simply select the smaller or larger element (quantity instructions), or the element coming before or after in the pair (sequence instructions). The sequence tasks presented in these four sets were also proposed with the non-numerical ordered series of letters, days and months, to test whether impaired sequence processing extended to non-numerical series. Because of their particular status and low frequency of occurrence, ordinal numbers will not be used in the present section. Consequently, numerical stimuli will be identical whether sequence or quantity instructions are used.

Test 1: Computerized tasks

Numbers

Method. CO was presented with an Arabic numeral between 1 and 9 (except for 5) and asked to tell whether it was smaller or larger than the standard 5 (quantity instructions), or whether it came before or after 5 in the counting sequence (sequence instructions). He gave his response by pressing on the corresponding response key (left-hand key for “smaller” or “before”

¹⁰ The general term ‘quantity’ refers here to the use of numbers in cardinal contexts (Fuson, 1988).

responses; right-hand key for “larger” or “after” responses). Both speed and accuracy were emphasized. Each numeral was displayed on the centre of a computer screen until the patient responded. Numbers were presented 15 times in random blocks. The quantity task was performed first.

Results. CO performed well with quantity instructions (117/120, 98% correct), while he made significantly more errors with sequence instructions (105/120, 88%) $\chi^2(1) = 8.65, p < .003$. Note that in a similar behavioural task, young control subjects ($N = 24$, mean age = 24.6) made 2.6% errors on average, whatever the instructions (see Turconi, Jemel, Rossion, & Seron, 2004, for a detailed presentation of the results). Hence, CO had a preserved ability to process the quantity of small numbers (his performance accuracy was equivalent to that of young controls), whereas he was more impaired in processing their sequence order.

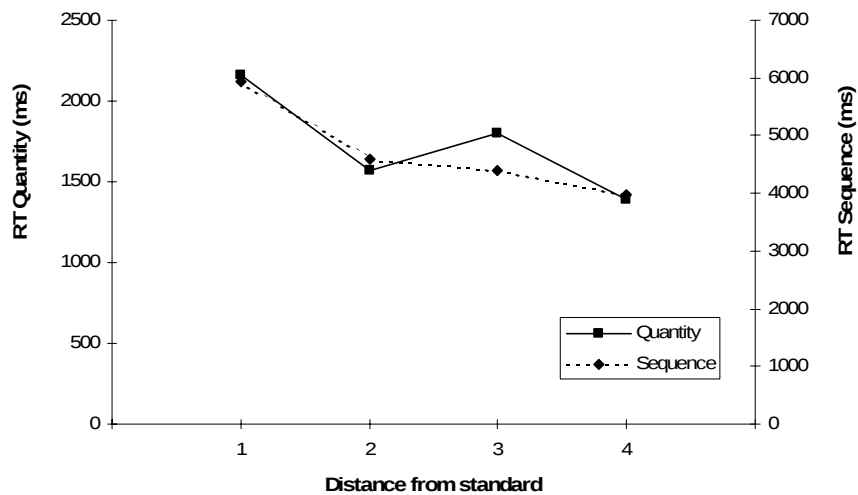


Figure 1. Distance effect in processing order relations with Quantity or Sequence instructions.

RT analysis further showed that the patient was significantly slower when processing sequence order (mean of median correct RTs: 4720 ms) than quantity (1730 ms; $t(87) = -14.2, p < .0001$). Separate repeated-measures ANOVAs were computed for each task on correct RTs, after the exclusion of outliers, with Response (smaller/before or larger/after) and Distance from the standard (1, 2, 3, 4) as within-subject factors. Response did not affect

performance with quantity (Smaller: 1540 ms, Larger: 1919 ms; $F(1,12)=1.75$; $p>.2$) or sequence instructions (Before: 4643 ms After: 4797 ms; $F<1$). While distance from the standard significantly affected RTs in the quantity ($F(3,36)=12.46$; $p<.0001$) and sequence tasks ($F(3,36)=5.64$; $p<.026$). As shown in Figure 1, this effect was similar in the two tasks (Task x Distance interaction: $F(3,48) = 1.2$, *n.s.*) with slower RTs for close (Distance 1, quantity: 2165 ms; sequence: 5923 ms) than far numbers (RTs for Distance 2, 3 and 4 with quantity instructions: 1566 ms, 1798 ms and 1390 ms; with sequence instructions: 4592 ms, 4398 ms and 3967 ms). The interaction between response and distance was not significant in either tasks ($F < 1$). Furthermore, error analysis for the sequence task showed a significant distance effect ($\chi^2(3) = 22.17$, $p< .0001$) as most of the errors were made on Distance 1 (11/15, 73%; 8 errors on the number before 5, 3 errors on the number after 5).

Non-numerical ordered series

Method. The patient was either presented with a letter (from A to Z, except for the standard M), a day of the week (from Monday to Sunday, except for the standard Thursday) or a month of the year (from January to December, except for the standard June) and he was asked to tell whether the item presented on the screen came before or after the standard in the corresponding sequence. The item remained on the centre of the screen until the patient responded. Each series was tested separately. Letters were each presented 5 times, days 10 times and months 12 times, in random blocks. Pauses were allowed between blocks.

Results. CO was impaired in the letter task (overall 63.2% correct) and inspection of his response pattern revealed that he resorted to a response bias in the last two blocks, for which he gave the response “before” in 44 out of 50 (88%) trials. Response analysis in the remaining 3 blocks showed that his performance was significantly better than expected by chance (49/75, 65%; Binomial test: $p = 0.011$). There was no effect of response: 39% (14/36) errors were made on letters coming before M and 31% (12/39) on letters coming after M ($\chi^2(1) < 1$). The distance effect was tested by grouping letters into 4 levels (letters J, K, L, N, O, P, were grouped to form “Distance

1”, letters G, H, I, Q, R, S constituted “Distance 2”, and so on). Distance did not affect performance (error rate for Distance 1, 2 3 and 4, respectively: 6/18, 6/18, 7/18 and 7/21; $\chi^2(3) < 1$)¹¹ and this was true whatever the expected response (before or after M, both $\chi^2(3) < 1.4$). RTs were not analysed because of the high proportion of errors. Performance with the series of days and months was also impaired and the patient performed at chance level with both series: 31/60 (52%) correct with days, 70/132 (53%) correct with months; Binomial tests: $p > 0.543$. In the days' task, the patient was biased towards answering “after” (57/60, 95% responses) and the opposite response bias was found in the months' task, the patient answering “before” more often (88/132) than “after” (44/132; $\chi^2(1)=29.33$, $p < .0001$). Correct RTs and error rates were not analysed in the tasks with days and months because the patient performed at chance level.

Comment for Test 1. When presented with an Arabic number between 1 and 9, the patient was almost perfect in telling whether it was smaller or larger than 5; RTs showed a standard distance effect, suggesting automatic activation of (intact) magnitude representation of small numbers. When asked to tell whether the same AN came before or after 5 in the counting sequence, he was much slower and made more errors, suggesting that processing of order relations in a sequence context was far less automatic, than in a cardinal context. Anyhow, CO still showed a standard distance effect, on both RTs and error rate with sequence instructions. Presence of a similar distance effect in cardinal and sequence contexts could suggest that the patient resorted to an equivalent (magnitude) comparison strategy in the two tasks, and thus exploited the quantity meaning of numbers when processing order relations in certain sequence contexts. Yet, using a magnitude-based strategy in a sequence context appeared to be particularly slow and error prone. Finally, telling whether a letter, day or month came before or after the standard in the corresponding sequence was largely

¹¹ Statistical analysis of the distance effect without grouping the letters was not possible because of insufficient observations (expected count less than 5 for all cells in the Chi square analysis). Anyhow, inspection of the number of errors for each single distance showed no trend towards a distance effect (number of errors per distance on a total of 6 observations, -3 for distance 13-, for distances 1 to 13: 3, 2, 1, 3, 1, 2, 2, 2, 3, 4, 2, 0, 1).

impaired. The patient performed at chance-level with days and months, and slightly above with letters. These data suggest that his abilities to process order information was limited to cardinal numbers (i.e. quantitative stimuli), for which he probably relied on magnitude information.

Test 2: Give an item smaller/larger or before/after the target

Numbers

Method. We devised a list of 32 Arabic numerals comprising the lexical primitives of the French verbal system (8 units, 6 teens and 9 tens) and 9 two-digit numerals (from 19 to 95). Numerals were presented in random order, on separate cards. They were written in the Arabic code and simultaneously read aloud by the experimenter. The patient was asked (1) to give *any* number smaller or larger than each target numeral, and (2) to subtract or add 1 unit to the target numeral (quantity instructions). Performance in each task was compared, respectively, with the patient's ability to (1) give *any* number coming before or after the same target numeral, and (2) to give the numeral coming *just* before or *just* after that target (sequence instructions). Quantity and sequence tasks were proposed in separate sessions. Results are presented in Table 6.

Table 6. Give any number smaller/larger, -1/+1, just before/after, any before/after than a target number

	Quantity instructions				Order instructions			
	Any smaller	Any larger	- 1	+ 1	Any before	Any after	Just before	Just after
Numerals (N=32)	31	32	15	30	9	29	6	30
% correct	97	100	47	94	28	91	19	94

Results. Performance was flawless when producing a number larger than a given item, and almost so when producing a smaller number. Subtracting 1 from the target number showed impaired performance, and about half of the errors (47%) consisted in the just following number in the sequence (e.g. 7

→ 8). Adding 1 to the target elicited an almost perfect performance, thus significantly better than subtracting 1 (comparing +1 and -1: $\chi^2(1)=17.4$, $p < .0001$).

Performance with sequence instructions was largely impaired when giving any number coming *before* the target numeral (only 1 error out of 23 consisted in the just following number in the sequence: 19 → 20), while it was significantly better when giving any number coming *after* that target ($\chi^2(1)=26.7$, $p < .0001$). When the patient had to give the numeral coming *just before* the target, he was again largely impaired, but this time the vast majority of errors (18/26, 69%) consisted in the next number in the sequence (e.g. 73 → 74). Giving the number coming *just after* was almost preserved (both errors consisted in giving the next ten in the sequence: 30 → 40 and 90 → 100), and thus significantly less impaired than giving the number just before ($\chi^2(1)=40$, $p < .0001$).

Comparing results in the quantity tasks with the corresponding sequence tasks showed that the patient performed far better in the former than the latter. He was better able to give a number smaller, than a number coming before the target numeral ($\chi^2(1)=69$, $p < .0001$), as well as he was less impaired in subtracting 1 from the target than in giving the just preceding number ($\chi^2(1)=5.74$, $p < 0.017$). Similarly, the patient had a slightly better performance when asked to give a number larger than the target numeral, relative to a number coming after that numeral ($\chi^2(1)=3.15$, exact one-tailed $p = 0.038$); whereas performance was identical when adding 1, or giving the number just after a given target.

Comment. The patient had a preserved performance in quantity tasks, with the exception of the subtraction by 1, which is consistent with his general impairment in subtraction and in counting backwards. With respect to sequence instructions, performance in giving the successor number was equivalent to the corresponding quantity instruction (+1); giving any number after was slightly below the corresponding cardinal relation, but performance was nonetheless largely preserved. On the contrary, severe impairment was found when CO was asked to give any number before or the number just before a given target. Yet, the kind of errors produced in these two tasks suggests that CO was using a different strategy: when asked to give the

preceding number, he gave the next one, thus using a forwards recitation strategy (which is consistent with his impaired backwards recitation), while this was not the case in the task ‘give a number before’.

Non numerical ordered series

Method. CO was presented, in a random order and separately for each series, with a target letter, day or month and asked to provide (1) the element coming *just* before or just after it in the corresponding series, and (2) *any* element coming before or after that target in the sequence. Targets were written on separate cards and simultaneously read aloud by the experimenter. All elements of each series, except for the first and last, were used as targets and presented once for the letter series (N=24), twice for months (N=20) and four times for the days of the week (N=20). The task was proposed on two occasions: on the first occasion, the patient had to give his response without external help; on the second occasion, he was allowed to use the written series presented in front of him. The purpose of this second presentation was to test the patient’s order processing ability once WM load was reduced.

Table 7. Give a letter, day or month (just) before/after the target item

	FIRST PRESENTATION				SECOND PRESENTATION (reduced WM load)			
	Any before	Any after	Just before	Just after	Any before	Any after	Just before	Just after
Letters (N = 24)	6	13	3	11	13	8/11	11	11
% correct	25	54	13	46	54	73	46	46
Days (N = 20)	10	8	5	18	12	16	13	20
% correct	50	40	25	90	60	80	65	100
Months (N = 20)	10	17	1	16	16	20	12	19
% correct	50	85	5	80	80	100	60	95

Results. Note that aged-matched controls don't make a single error in this task, except when asked to give the item just preceding the target letter (Mean = 23.2/24; SD = 1.39) or the target month (Mean = 19.67/20; SD = 0.58) in the sequence. CO's results are presented in Table 7. The patient was impaired with all series on the first presentation of the task. This was mostly the case when he had to give the element *just* preceding the target in the corresponding series (percentage correct did not exceed 25%). Giving *any* element preceding that target was impaired to the same extent for letters ($\chi^2(1) < 1.2$), but to a smaller extent for days ($\chi^2(1) = 2.67$, exact one-tailed $p = 0.05$) and months ($\chi^2(1) = 10.16$, $p < 0.001$). Performance was better when producing the element coming just after the target in the sequence (all $\chi^2(1) < 6.45$, $p < 0.011$ when comparing "just after" with "just before" tasks), or any item coming after the target, for letters and months (comparing "any after" with "any before" tasks: both $\chi^2(1) < 4.27$, $p < 0.039$; days: $\chi^2(1) < 1$). Comparing performance when CO had to give the item *just* after, or *any* item after the target in the sequence showed no difference for letters and months (both $\chi^2(1) < 1$); while giving the next day in the week appeared easier than giving any day after the target ($\chi^2(1) = 10.99$, $p < 0.001$).

When the patient was allowed to use the written series, performance was significantly improved in giving the element *just* before (all $\chi^2(1) > 6.45$, $p < 0.011$) or *any* element before the target for letters and months (both $\chi^2(1) > 3.96$, $p < 0.047$; days: $\chi^2(1) < 1$). The same was true when giving *any* day ($\chi^2(1) = 6.67$, $p < 0.01$) or month after the target ($\chi^2(1) = 3.24$, exact one-tailed $p = 0.036$), while performance was not improved when CO had to give the item *just* after the target in the sequence (for all three series: $\chi^2(1) < 2.11$, *n.s.*). Comparing "before" and "after" instructions on this second task presentation showed again a better performance in giving the *just* following, relative to the just preceding, day or month (both $\chi^2(1) < 7.03$, $p < 0.008$; no difference for letters); when giving *any* item after the target, the advantage remained present for months only ($\chi^2(1) = 4.44$, $p < 0.035$; for letters and days: both $\chi^2(1) < 1.9$). However, although CO performed better with the written series, his performance was still impaired, compared to normal controls, with "before" instructions (correct performance did not exceed

80%; modified t-tests: all $t < -5.48$, $p < 0.05$) and “after” instructions for letters, as well as days when giving *any* item after the target (modified t-tests could not be performed since control subjects perform at ceiling in these tasks). Conversely, performance was almost flawless with days and months when he used the written series to produce the next item in the sequence, or any item after the target, for the months of the year.

Table 8. Error distribution for tasks “Give a letter, day, month before/after the target”.

Task		Errors	Letters		Days		Months	
			<i>N</i>	%	<i>N</i>	%	<i>N</i>	%
First task presentation	Just before	just following item	13/22	59	15/15	100	15/19	79
		an item before	4/22	18	0		1/19	5
		an item after	4/22*	18	0		3/19	16
	Any before	just following item	7/18	39	5/10	50	4/10	40
		an item after	11/18	61	5/10	50	6/10	60
	Just after	just preceding item	5/13	38	0		1/4	25
		an item before	0		1/2	50	1/4	25
		an item after	8/13	62	1/2	50	2/4	50
	Any after	just preceding item	2/11	18	4/12	33	3/3	100
		an item before	9/11	82	8/12	67	0	
Second task presentation	Just before	just following item	7/13	54	7/7	100	7/8	88
		an item before	4/13	31	0		1/8	12
		an item after	2/13	15	0		0	
	Any before	just following item	5/11	45	7/8	88	2/4	50
		an item after	6/11	55	1/8	12	2/4	50
	Just after	just preceding item	10/14	71	0		0	
		an item before	0		0		0	
		an item after	4/14		0		1/1	100
	Any after	just preceding item	2/8	25	1/4	25	0	
		an item before	6/8	75	3/4	75	0	

Analysis of the errors in "give a letter, day, month before/after the target". CO never produced an element from a different sequence than the target's. As shown in Table 8, when asked to give the element *just* before the target, he mostly produced the next element in the sequence (e.g. Friday → Saturday). Other errors consisted in items coming well after the target (e.g. July → October), and in only very few cases the patient gave an item (letter

or month) coming well before the target in the series (e.g. J → F). This was true whether an external help was provided or not. When the patient could give *any* element coming before the target in the sequence, about half of his erroneous responses consisted in producing the next item in the sequence (and almost all of them for days, when an external help was provided). When asked to give the item *just* after the target, the patient sometimes mistakenly gave the just preceding one, and this happened quite often for letters when using the written series. Note that CO almost never produced an item coming before the target in this task, but usually gave an item coming well after that target. Finally, errors in giving *any* element coming after the target were, most of the time, an item coming well before it, and only on few occasions (but on all of them for months), the just preceding item.

Comment. The patient's impaired performance in this task suggests that he was unable to process the order of well known sequences. This impairment persisted (though to a smaller extent) once WM load was reduced, thus discarding the explanation of CO's impairment in terms of low WM capacities. The patient was again better in giving an item coming after, than an item coming before the target. Moreover, when asked to give the just preceding element, CO was impaired because of impaired backwards recitation abilities, and the fact that most of his errors consisted in giving the next item in the sequence suggests that the patient resorted to (automatic) forwards recitation instead. And better performance in giving *any* item before the target, relative to the item *just* before, could be explained by the automatic activation of forwards sequence recitation when presented with instructions in the latter, but not in the former task. Yet, CO's performance in giving an item coming after the target was better, but nonetheless also slightly impaired, relative to age-matched controls. Thus, impaired sequence processing may not be fully explained by CO's inability to recite the series backwards.

Summary of Test 2.

The patient performed again better with quantity than with sequence instructions on numerical material. Impaired sequence processing was not restricted to numbers, but extended to the well-known series of letters, days

and months. In all sequence tasks, producing an item coming before a given target was more impaired than producing an item coming after. This might be explained by the contribution of automatic sequence recitation, that elicited correct responses in the latter task and errors in the former, and which is consistent with the pattern of errors found in sequence tasks (and more specifically with 'Just Before' instructions). However, the patient's impairment cannot be simply explained by a mere inability to recite the series backwards and to inhibit forwards sequence recitation, since his performance was also below that of controls when he had to produce an item coming after the target in the sequence. The patient appeared to have a more general impairment in processing order relations in sequence contexts. On the contrary, processing the same order relations in cardinal contexts was largely preserved, with the exception of the subtraction task that could be explained by impaired backwards recitation.

Test 3: Give an item between two limits

The sequence relation 'Between' develops at the 'Breakable chain level' by a combination of "Comes Before" and "Comes After" relations, and also through the ability to recite a portion of the sequence, both forwards and backwards (Fuson & al., 1982). Again, this kind of order relation may be processed either in a quantity or in a sequence context, according to the instructions. Analysis of the type of errors produced in either contexts might also be informative as to the kind of strategy used by the patient.

Numbers

Method. The patient was presented with two numbers, x and y , and either asked (1) to give any number that is larger than x and smaller than y , for pairs in the ascending order (e.g. 1-9), and any number that is smaller than x and larger than y , for pairs in the descending order (e.g. 9-1; quantity instructions), or (2) to give any number coming after x and before y , for ascending pairs, and any number coming before x and after y , for descending pairs (sequence instructions). We replicated in this task part of the material used in a number bisection experiment (Zorzi & al., 2002). The patient was

presented with a list of 32 number intervals, in a random order. The list comprised all possible pairs of units, and of 2-digit numbers (up to 19), that had a length of one (e.g., 1-3), three (e.g., 1-5), five (e.g., 1-7) or seven (e.g., 1-9). Number pairs were shown separately, first in the ascending order, then in the descending order; they were presented in the Arabic code, on separate cards, and simultaneously read aloud by the experimenter. Quantity and order tasks were presented on separate occasions.

Results. As shown in Table 9, the patient performed better with quantity (overall 81% correct) than with sequence instructions (61% correct; $\chi^2(1)=6.43$, $p < 0.011$). Control subjects performed almost at ceiling in this task, thus, when comparing the patient's results with those of controls using Crawford & Garthwaite's (in press) revised t-test for dissociations, we found that CO was impaired with both quantity ($t(4) = -5.93$, $p < 0.002$) and sequence instructions ($t(4) = -10.87$, $p < 0.0002$), but significantly more so in processing sequence order than quantity ($t(4) = -4.01$, $p < 0.016$).

Table 9. Give a number between two limits (percentage correct)

<i>Interval length</i>	Quantity instructions		Order instructions	
	Ascending pairs	Descending pairs	Ascending pairs	Descending pairs
1 (N=14)	64	57	57	21
3 (N=10)	100	90	70	70
5 (N=6)	100	100	83	83
7 (N=2)	100	100	100	100
<i>Number size</i>				
Units (N=16)	94	88	81	63
2-digit numbers (N=16)	75	69	56	44
Total (N=32)	84	78	69	53

Analysing the patient's results showed a better performance for single than two-digit numbers in each task (both $\chi^2(1) < 3.22$, exact one-tailed $p < 0.037$). The length of the interval also affected performance in both tasks (both $\chi^2(3) > 11.3$, $p < 0.01$), with more errors made on shorter than longer intervals (see Table 8). Conversely, direction of the pair (ascending,

descending) did not affect performance with either instructions (both $\chi^2(1) < 1.6$), but it did influence the kind of errors. In most cases, errors consisted in a number smaller than the lower limit (e.g. pair 14-16, response 12), with both quantity (10/12 errors, 83%) and sequence instructions (18/25 errors, 72%), but among these errors the patient produced the *just* preceding number most of the time on descending pairs (overall with quantity and sequence instructions: 11/18 occurrences, e.g. pair 8-6, response 5), while it was not the case for ascending pairs (overall 2/10 errors; $\chi^2(1)=5.26$, $p < 0.022$, for the effect of pair direction on the kind of errors). The patient only rarely produced the next number in the sequence in this task, whatever the direction of the pair (ascending: 20% of the errors; descending: 14%).

Non-numerical ordered series

Method. The patient was presented separately with a pair of letters (N=48), days (N=56) or months (N=68) and asked to produce an element of the corresponding sequence falling in between the two items of the pair. Ascending and descending pairs were tested in separate random lists. Pairs could have a length of 1, 2, 3 or 4; they were written on separate cards and simultaneously read aloud by the experimenter.

Table 10. Give a letter, day, month between two limits (percentage correct)

<i>Interval length</i>	Letters		Days		Months	
	Ascending Pairs (N=24)	Descending Pairs (N=24)	Ascending Pairs (N=28)	Descending pairs (N=28)	Ascending pairs (N=34)	Descending pairs (N=34)
1	12.5	17	30	10	30	10
2	0	17	37.5	50	22	33
3	40	33	50	50	50	37.5
4	0	33	25	75	29	29
Total	12.5	25	36	39	32	26.5

Results. Control subjects didn't make a single error with the series of days and months and performed almost at ceiling with letters (overall: 96% correct). The patient was thus truly impaired in these tasks (29% correct overall; see Table 10). His performance was not affected by direction of the

pair in either series (all $\chi^2(1) < 1.23$, *n.s.*), nor by interval length for letters ($\chi^2(3) = 3.13$, *n.s.*) and months ($\chi^2(3) = 2.47$, *n.s.*), while more errors were made on small than large intervals for days ($\chi^2(1)=4.1$, $p < 0.044$). Most errors consisted in an element coming after the upper limit (letters: 28/39, 72%; days: 20/35, 57%; months: 31/48, 65%); some of these productions were the just following item in the sequence for letters (6/28, 21%) and months (9/31, 21%), and it was the case for all errors with the series of days (20/20, 100%; e.g. answering Thursday for the interval Monday-Wednesday). Note that CO never explicitly recited the series to find the answer in these tasks.

Comment for Test 3. CO was impaired with all series in this task, and significantly more so when processing sequence order than quantity. Among the order tasks, the best performance was found with numbers, whereas performance with letters, days and months was drastically impaired. The kind of errors was different with numbers, for which CO mostly produced a number smaller than the lower interval limit, relative to all other series, for which he usually produced an item coming after the upper limit, suggesting the involvement of a forwards sequence recitation strategy.

Test 4: Select the smaller/larger or before/after element of the pair

In this test, we prevented the patient from producing the elements of ordered series and asked him instead to select the correct response among the items of a pair.

Numbers

Method. The lists with 32 ascending and 32 descending pairs of Arabic numerals presented above (Test 3, this section) were assembled into one mixed list, that was presented 4 times to the patient. He was asked to select in the pair: (1) the smaller number, (2) the larger number (quantity instructions), or (3) the number coming before, (4) the number coming after (sequence instructions).

Table 11. Select the smaller/larger or before/after cardinal number of the pair (percentage correct)

<i>Direction of the pair</i>	Horizontal pair		Horizontal pair		Vertical pair	
	Smaller	Larger	Before	After	Before	After
Ascending (N=32)	100	100	100	100	50	97
Descending (N=32)	100	100	19	22	84	28
Total (N=64)	100	100	59	61	67	63

Results. As shown in Table 11, the patient was flawless (and fast) with quantity instructions, whether he had to select the smaller or the larger numeral of the pair. Performance with sequence instructions was highly affected by the direction of the pair ($\chi^2(1) = 84.78, p < 0.0001$), as all errors were made on descending pairs. This was explained by the use of a response bias in both sequence tasks: when asked to choose the number coming before in the pair, CO nearly always selected the left-hand item (91% of the trials); conversely, when he had to choose the number coming after, he selected the right-hand item on 89% of the trials. This was much more than expected by chance (Binomial test: $p = 0.0001$). The patient thus appeared to associate the response “before” with the right side of the horizontal pair, and the response “after” with its left side. In order to reduce the verbal-spatial association, the same sequence tasks were proposed with a vertical alignment of the pairs. The patient was again resorting to a response bias, that was the same whether he had to choose the number coming before or the number coming after in the pair: he selected the number below more often than expected by chance (67% for “before” responses, Binomial test: $p = 0.008$; 83% for “after” responses, Binomial test: $p = 0.0001$; see Table 10). Control subjects perform at ceiling in these tasks.

Comment. The patient was flawless in choosing the smaller or the larger number of a pair of AN. To the contrary, when asked to select the number coming before or the number coming after in these same pairs, he was totally impaired. When numbers were horizontally presented, he appeared to associate the response “before” with the left-hand number of the pair and the response “after” with the right-hand number; but he also resorted to a response bias when pairs were vertically aligned.

Non-numerical ordered series

Method. The lists with ascending and descending pairs of letters, days and months proposed in the previous test (this section) were compiled into one mixed list (separately for each series) and shown to the patient in a random order. CO was asked to select in each pair the element coming before, or the element coming after in the sequence.

Table 12. Select the item coming before/after in the pair (percentage correct)

<i>Direction of the pair</i>	Letters		Days		Months	
	Before (N=48)	After (N=48)	Before (N=28)	After (N=28)	Before (N=34)	After (N=34)
Ascending	46	88	79	71	59	100
Descending	79	21	50	29	88	6
Total	63	54	64	50	74	53

Results. Control subjects perform at ceiling in these tasks, whereas CO was truly impaired (60% correct overall; see Table 12). His performance wasn't better than chance for the series of letters and days (Binomial tests: $p > 0.13$). Analysis of CO's response pattern revealed that he selected the right-hand element of the pair more often than the left, when processing months (55/68; Binomial test: $p = 0.0001$) and letters (40/48; Binomial test: $p = 0.0001$) and when selecting the day coming after in the pair (20/28; Binomial test: $p = 0.036$). Besides, most of his left-hand responses were found when selecting the element coming before in ascending pairs (overall 32/55, compared to 14/55, 7/55 and 10/55, respectively when selecting the item before on descending pairs, the item after on ascending and on descending pairs; all $\chi^2(1) > 12.11$, $p < 0.001$), which produced a correct response. This could explain why performance was better on ascending than on descending pairs for days or months (both $\chi^2(1) < 7.65$, $p < .006$). Finally, when the patient was proposed to use the written series to perform these tasks, his performance was found unchanged ($\chi^2(1) < 1$ in all three series).

Comment. The patient was flawless when processing numerical quantity, but truly impaired when processing sequence order on numerical and non-numerical material. Choosing the cardinal number coming before or after in a pair was affected by a spatial-verbal association (before-left, after-right), and a response bias was also found with a vertical number alignment. CO performed at chance for the series of letters and days and he resorted to a response bias when processing months.

Summary of Section 4.

In Section 4, we have examined CO's ability to process equivalent order relations, using the same material, either in a sequence context or in the corresponding cardinal context. Altogether, the data reported in this section clearly speak in favour of a dissociation between impaired sequence processing, on both numerical and non-numerical series, in the face of largely preserved cardinal, quantity, processing. CO always had a far better performance when processing quantity meaning, relative to sequence knowledge on the same numerical material. Processing numerical quantity was found unimpaired for small numbers, as suggested by the patient's good performance in comparing numbers between 1 and 9 to the standard 5, and by the standard distance effect this task generated. Besides, the ability to produce a number smaller or larger than a target 1- and 2-digit numeral was almost perfect. Selecting the smaller or larger number of a pair was fast and flawless, while producing a number between two limits with quantity instructions was slightly worse than controls' performance. On the contrary, processing the sequence order on the same numbers was found impaired, though to a lesser extent than processing the order of non-quantitative series. The patient had a slightly impaired performance and was very slow in deciding whether a number between 1 and 9 came before or after the standard 5 in the counting sequence. Yet, performance in this task was fare better than in the remaining sequence tasks in this section. To explain this, we make the hypothesis of a contribution of a magnitude comparison strategy, as suggested by the presence of a distance effect, on both RTs and error rates. Nonetheless, using this quantity-based strategy in a sequence

context appeared time-consuming and error-prone. CO could hardly produce a number coming before (or just before) a target numeral in the sequence, while his performance was improved when producing a number coming after that target. Giving a number between two limits with sequence instructions was truly impaired, and performance was at chance when the patient had to select the number of a pair coming before or after in the counting sequence. Sequence processing was even more impaired for non-numerical material since performance wasn't better than chance in several tasks (deciding whether a day or a month comes before or after a standard item in the corresponding sequence; selecting in a pair of letters or days the item coming before or after in the ordered series), while other tasks were performed resorting to a response bias (deciding whether a letter comes before or after M in the alphabet; selecting in a pair of months the one coming before or after during the year). Overall, performance in sequence tasks was profoundly impaired, considering that aged-matched controls perform at ceiling in almost all the tasks in this section. With respect to the strategies used by the patient, he appeared to rarely resort intentionally to a recitation mechanism, yet, forwards sequence recitation appeared to be sometimes automatically activated (e.g. when giving the number coming just before a given target). Besides, reducing WM load by allowing the patient to use a written presentation of the series during some of the sequence tasks, slightly improved performance (e.g. in Test 2), but performance was still impaired. This, together with the fact that WM load was kept equal in the quantity and sequence tasks, suggest that impaired order processing in a sequence context could not be simply explained by CO's reduced WM capacities. A more basic inability in processing order relations in sequence contexts must be invoked. This inability may be partly related to the patient's low level of elaboration of the number word sequence, and to his impaired backwards recitation skills. Yet, the presented data suggest that quantity and sequence processing may rely on at least partially distinct processing mechanisms.

Section 5: The relationship with space

We have seen in Section 4 that the patient appeared to sometimes associate the concept “before” with the left-side of a horizontal line and the concept “after” with its right-side. Yet, a relationship between numbers and space has been consistently reported in the literature (see Hubbard, & al., 2005, for a recent review). For instance, the SNARC (Spatial Numerical Association of Response Codes) effect that is, faster left- than right-side responses to small numbers and the reverse for large numbers (e.g. Dehaene, Bossini & Giraux, 1993), has been taken as evidence for the activation of a spatial representation of numbers in the form of a left-to-right oriented number line. However, the SNARC effect is not restricted to numbers and has also been reported with non-numerical ordered series, such as letters, months and days (Gevers, Reynvoet, & Fias, 2003, 2004), which share with numbers the property of sequential order. This might suggest that sequence (and only number) and space processing are closely connected. An attempt towards testing this hypothesis was undertaken in the present case study. Hence, because CO had impaired sequence processing, we asked whether he was equally impaired in spatial processing tasks and tested his abilities with both numerical and non-numerical material¹².

Test 1: Oral and spatial before-after choice tasks

Method. The patient was shown a horizontal line with an item above the middle mark of the line (e.g. 13), he was then presented with an oral target (e.g. 14) and asked (1) whether the oral target comes before or after the written item in the corresponding sequence (after, in the example; oral response), and (2) to indicate the target's spatial position (right or left side) on the horizontal line with respect to the written item (right side, in the example; spatial response). The ordered series of cardinal numbers (range 1-100), letters, days and months were tested separately. The distance between

¹² Note that searching for a SNARC effect in computerized order processing tasks would have been one way to investigate the relationship between sequence order processing and space. However, CO's extremely slow RTs in these tasks precluded any interpretation.

the written item and the oral target was either 1 (consecutive items), or it varied from 2 to 5 (and up to 10 for numerals; non-consecutive items). The results are shown in Table 13.

Results. Control subjects didn't make errors with numbers, and very few with the other series (overall 96% correct); performance was identical for oral and spatial responses. On the contrary, CO was impaired with all series, whatever the modality of response (modified t-tests: all $t < -5.81$, $p < 0.05$). Performance was overall better when he gave a spatial (77% correct) than an oral response (67%; $\chi^2(1)=11.20$, $p < 0.001$), but when series were tested individually, this effect was restricted to cardinal numbers ($\chi^2(1)=5.38$, $p < 0.020$), and days ($\chi^2(1)=5.33$, $p < 0.021$). Position of the target also affected performance, since more errors were found for targets coming before (55% correct, overall), than targets coming after the written item (88%; $\chi^2(1)=151.7$, $p < 0.0001$); this effect was significant on each individual series (all $\chi^2(1) > 17.07$, $p < 0.0001$), remained so when oral and spatial responses were tested separately (both $\chi^2(1) > 54.13$, $p < 0.0001$), and also when this analysis was computed on individual series (all $\chi^2(1) > 8.4$, $p < 0.004$; for oral responses with months: $\chi^2(1) > 2.68$, exact one-tailed $p < 0.05$). Distance (i.e., whether target-item pairs were consecutive or not) did not overall affect performance (69% and 74%, respectively for consecutive and non-consecutive pairs; $\chi^2(1)=2.5$, *n.s.*). Non-consecutive pairs were nonetheless found to elicit a better performance for the series of months ($\chi^2(1) > 9.07$, $p < 0.003$). Comparing performance among the series showed that letters were the most impaired (all $\chi^2(1) > 6.84$, $p < .009$)¹³, numbers were more impaired than the series of days ($\chi^2(1) = 4.20$, $p < .040$) and months ($\chi^2(1) = 12.11$, $p < .001$), that did not differ ($\chi^2(1)<1$). Impaired performance with letters could be explained by the use of a response bias: the patient gave the response "after" and indicated the right side of the line on most trials (consecutive letter pairs: 72%; non-consecutive pairs: 89%; both Binomial tests: $p < 0.0001$).

¹³ Letters also elicited the highest amount of errors in control subjects, but CO was disproportionately impaired in this task (modified t-test: $t = -9.98$; $p < 0.01$).

Table 13. Oral and spatial before-after choice task (percentage correct).

		Cardinal numbers	Letters	Days	Months	Total
Consecutive items		N=28	N=26	N=22	N=20	N=96
<i>Oral response</i>	Before	39	35	50	50	44
	After	93	77	77	90	84
<i>Spatial response</i>	Before	71	42	82	55	63
	After	93	89	100	100	96
Non consecutive items		N=38	N=26	N=20	N=28	N=112
<i>Oral response</i>	Before	58	12	65	87	56
	After	71	100	95	96	91
<i>Spatial response</i>	Before	53	19	60	80	53
	After	97	96	100	100	98
<i>Overall</i>		72	59	79	82	73

Comment. CO was impaired with all series in this task. For numbers and days, he was better able to indicate the spatial position of the target with respect to the written item (left or right side), than to provide the corresponding oral ("before"/"after") response. This effect was not found for letters, because of a response bias, nor for months that were overall better processed, especially in non-consecutive pairs. Performance was more impaired for targets coming before, relative to targets coming after the item, in all series, and whatever the modality of response. The fact that non-consecutive pairs were sometimes processed better than consecutive pairs goes against the hypothesis that the patient resorted to a recitation strategy in these tasks.

The patient was also proposed two tasks involving spatial prepositions, and not ordered sequences, to more deeply investigate his spatial processing abilities. Two kinds of spatial relations were tested: "in front of" vs. "behind" and "above" vs. "below".

Test 2: "In front of" vs. "behind" relations

Method. CO was presented with a picture-sentence verification task. He was shown pictures in which a smaller object (e.g. a car) is in front of, or behind, a larger object (e.g. a house) and simultaneously presented with a sentence describing the spatial relation between these two objects (e.g. on this picture, the car is in front of the house); he was asked to tell for each sentence, whether it was true or false, according to the picture. Objects were well visible in all pictures. The patient was orally presented with 4 sentences for each of the 8 pictures.

Results. Before starting the task, CO was asked to match each object's name with its visual counterpart on the picture and he did it flawlessly. Performance was nonetheless impaired in this task (20/32), and this was mostly the case when the larger object was presented first in the sentence (e.g. the house is behind the car; 6/16), than when it was given after the smaller (e.g. the car is in front of the house, 14/16). There was no effect of the position adverb used (in front of: 10/32; behind: 10/32) and the patient appeared unable to define them: he said, for both adverbs "it's a position defined with respect to a reference point".

Test 3: "Above" vs. "Below" relations

Method. The patient was presented, on three occasions, with 3 objects entertaining spatial relations. On the first occasion, the objects were geometrical figures (a triangle, a circle and a square) vertically aligned on a sheet of paper. On the second occasion they were replaced by the picture of a church showing more concrete objects (a cloud, the church tower and the church window); real objects were used on the third occasion (a sheet of paper, a pair of scissors above it, and a pen below it). Thirteen sentences (12 on the third occasion) were devised to qualify the spatial relations of these objects, two by two (e.g. the triangle is above the circle), and the patient was asked to verify the truth of each sentence and answer "yes" or "no".

Results. Before starting each task, CO was asked to name each presented object, and he did it perfectly. He was nonetheless impaired on each occasion (4/13, 9/13, 8/12 correct, respectively for occasions 1, 2 and 3),

with the worst performance on geometrical figures (both $\chi^2(1) > 3.22$, exact one-tailed $p < 0.036$). The patient appeared unable to define the concepts "above" and "below". For "below" he said: "it's with respect to a reference point", and for "above": "it's the same kind, but the reverse, and always with respect to a reference point".

Comment. CO's impairment in these tasks cannot be explained by the procedure we used, since he showed a good performance in a similar task (sentence verification) that involved object's size relations (e.g. a dog is bigger than an elephant; Section 2, C, Test 1). Hence, altered performance in the present tasks suggests that the already reported impairment in processing order relations could be extended to a more general inability to process spatial relations.

Summary of Section 5

CO was generally impaired in systematically associating the position of items in the sequence (before/after a given target), with their spatial counterpart (left/right position on a horizontal line). Yet, in Section 3 (Test 1) CO was found able to merely associate 'before' with 'left' and 'after' with 'right'. In the present section, we found that this association was yet not systematic, as he sometimes responded 'after' and showed the left side of the line. Impaired right-left discrimination might contribute to this pattern of performance. Spatial responses were more often correct than oral responses, and 'before' answers were more error-prone. Letters were again the most impaired series, and days and months the better preserved. CO did not resort to any recitation strategy in this task. Examination of spatial processing in non-numerical contexts showed a general inability to process relative positions of objects in space (e.g. 'in front of/behind' and 'above/below'). Hence, the collected data might suggest that processing relative positions in a sequence and processing locations in space could be somehow related.

DISCUSSION

We have described the case of a patient, CO, who showed the four symptoms of Gerstmann syndrome (acalculia, agraphia, finger agnosia and right-left confusion) after bilateral parietal lesions. His acalculia was the focus of the present study. The deficit in number processing usually reported after parietal damage is thought to reflect a disorganisation of the semantic representation of numerical quantities (e.g. Dehaene & al., 1998); however, the examination of other number meanings crucially lacks in these studies. Numbers, in fact, don't only refer to quantities. When used in ordinal contexts, numbers will describe the relative position of one entity within an ordered set (Wiese, 2003), and not the numerosity of that set (cardinal meaning). In a sequence situation, the conventional sequence of number words will be recited in much the same way as other familiar ordered series, and will not refer to quantities (Fuson, 1988). Furthermore, the use of number words in different contexts and their associated meaning were also shown to be acquired at different stages during development. For instance, a developmental distinction was described between children's early acquisition and elaboration of the number word sequence, and their later construction of cardinal meaning (Fuson, 1988). Whether sequence knowledge and cardinal meaning rely on (at least partially) distinct processing mechanisms that can be impaired selectively after cerebral lesion is still unresolved and was addressed in the present study. Besides, because sequence (and more generally order) knowledge has been poorly investigated in acalculic patients, it is still largely unknown whether it can be damaged after parietal lesions; yet, this what neuroimaging studies would suggest since parietal activations were reported during order processing tasks (Acuna & al., 2002; Marshuetz & al., 2000; Turconi & al., 2004). The present investigation also aimed at clarifying this second issue. Overall, our single case-study showed an atypical pattern of number processing deficit after bilateral parietal damage: quantity meaning, that was expected to be impaired, was largely preserved in this patient, while sequence knowledge was extensively damaged, and this affected non-numerical series as well. Hence, this severe impairment for sequence processing suggests that parietal areas are crucial for the processing of sequence order relations, and that

sequence and quantity processing might rely on at least partially distinct mechanisms.

Investigation of CO's number processing abilities has shown largely preserved capacities for quantity processing, with both symbolic and non-symbolic stimuli. The patient was able to compare and arrange dot patterns according to their numerosity; he could subitize small patterns of dots and use counting to find the numerosity of larger sets; he could answer 'How many' questions, thus showing preserved understanding of the cardinality principle of counting (i.e., knowing that the last number word said in counting items in a set gives the numerosity of that set; Gelman & Gallistel, 1978). Yet, beside preserved understanding of the core principles of counting, his counting performance was increasingly error-prone for larger sets because of a procedural impairment in coordinating oral counting and finger pointing (Fuson & Hall, 1983). Understanding the inclusion property of cardinality (Piaget, 1941) was also spared, and so was CO's understanding of the quantity conveyed by Arabic numerals, as attested in AN-to-dots matching. Performance with symbolic stimuli (Arabic and verbal numerals) was equally preserved. The patient could choose the larger of two Arabic or verbal numerals and, what is more, he showed a standard distance effect on RTs when comparing small Arabic numerals. Such faster processing for large (5 9) than small distance pairs (5 4) has been repeatedly reported in studies of number comparison with normal subjects and interpreted as evidence that numerals activate a magnitude representation analogous to an oriented mental 'number line' (e.g. Moyer & Landauer, 1967; Dehaene, 1992; Dehaene, Dupoux, & Melher, 1990). Besides, the patient's better performance for physically congruent compared to incongruent pairs (in a 'Stroop comparison task') further suggests that magnitude information was automatically accessed when processing small Arabic numerals (Henik & Tzelgov, 1982). Comparing large spoken numerals was slightly impaired which might be explained by CO's limited working memory capacities. Yet, positioning Arabic and verbal numerals on an analogue scale and producing a number smaller or larger than a given target were (almost) flawless. Preserved processing of non-numerical quantities (e.g. object or animal size) was also observed. Overall, the

collected data suggest that CO's cardinal number meaning (Fuson, 1988) was preserved, and that his understanding of quantity extended beyond the category of numbers. Yet, the patient's ability to compare, order, and produce numbers according to their corresponding quantity suggests that the analogue-magnitude representation (i.e. the so-called 'number line'; Dehaene, 1992) was spared and could be accessed during quantity processing.

The patient was nonetheless impaired in simple calculation tasks. Better preservation for addition and, to a smaller extent, subtraction, coupled with the small distance between the expected answer and the patient's response in addition problems suggest that CO could provide a good approximation of the result. This was not the case in multiplication and division, which were impaired even for very simple problems, due to impaired retrieval of rote arithmetic tables. With respect to subtraction, impairment for the simplest (e.g. -1) problems could be explained by CO's inability to recite the number sequence backwards.

The present investigation was specifically devised to assess the patient's knowledge, and processing abilities, of the number sequence, including sequence order relations. We started with a detailed examination of the patient's sequence recitation skills following the five stages described by Fuson (Fuson & al., 1982) for the elaboration of the number word sequence. This examination revealed that forwards recitation skills were preserved up to the 'Breakable chain level' for numbers, but they did not reach the level of 'Numerable chain'. CO was unable, in fact, to precisely count ' n ' from any given number, a capacity that requires some kind of keeping-track procedure, like finger counting (see Fuson & al., 1982). With respect to backwards recitation skills, CO was largely impaired. Reciting the number sequence backwards from 10 was possible only when primed with the first three numbers, and this recitation was far from being automatic. With respect to non-numerical sequences, recitation skills for the series of days and months also appeared to attain the level of the 'Breakable chain', like numbers; but this was not the case for the alphabet whose recitation was far from being automatized (CO couldn't start recitation from any given letter).

We then examined sequence order relations and confirmed the hypothesis that CO was only able to process those relations that relied on preserved levels of his sequence elaboration/knowledge (i.e., that required basic forwards sequence recitation skills). These included producing the next item in the series of numbers, days and months, with a slight impairment for letters. Conversely, producing the previous element ('just before' relation) was found impaired for all series, which was expected because of CO's impaired backwards recitation skills. CO generally produced the next, instead of the previous, element when answering 'just before' questions, which suggests an automatic activation of forwards sequence recitation in this task. Interestingly, comparing performance in 'just before/just after' questions with 'any before/any after' instructions suggests that the automatic activation of forwards sequence recitation was restricted to the former instructions. In fact, 'just before' questions elicited the erroneous production of the 'just following' item in the sequence on many more occasions than did 'any before' instructions, and this was equally observed for numerical and non-numerical series.

Finding the n^{th} element in a series was correct for tokens (spatially determined order), but impaired for linguistic series (order held in Long-Term Memory, LTM). Correct performance with tokens means that CO could understand the meaning of ordinal numbers, count up to the requested position while pointing to the tokens, and make a count-to-ordinal shift (Fuson, 1988). This was not possible with linguistic series held LTM. Yet, finding the n^{th} element in an ordered series (e.g. finding the ninth letter in the alphabet) requires the ability to count n from a (i.e. count 9 positions from letter A) while reciting the series (alphabet) and simultaneously keep track of already counted entities, in order to stop recitation at the requested position and give the item reached as answer (Fuson & al., 1982). Hence, possibly because of finger agnosia, CO was no longer able to use his fingers for keeping track of counted entities during sequence recitation (see Alibali & DiRusso, 1999, for the importance of gesture in counting and keeping track of already counted items). This procedural inability does not explain, however, why the patient was mostly unable to use the written ordered series to perform this task (Part 2). He almost never used sequence recitation in

this task and resorted, instead, to a direct memory retrieval strategy (as suggested by the better performance for items at the beginning and at the end of the series, compared to items in the middle). Overall, the patient was found unable, in several tasks, to intentionally resort to sequence recitation to process order relations in sequence contexts. Order verification is another example. CO performed at chance when asked to tell whether or not a pair of numbers, letters, days or months was presented in the conventional sequence order. Using forwards sequence recitation from one of the items in the pair (or from the beginning of the sequence) would have led to the correct response, but this behaviour was never observed. With respect to number pairs, deciding if they are presented in the counting order (e.g. 2 5) might well be performed without using a recitation strategy, by simply processing their cardinal values (i.e. verifying that the larger number is on the right side of the pair is sufficient to infer that the pair is in the conventional order). This requires, however, preserved knowledge of the association between positions in the sequence and cardinal number meaning (i.e., knowing that the larger a number is, the farther it is located in the counting sequence; Wynn, 1992). Yet, although CO was able to identify the smaller or larger number in a pair, he did not use this kind of quantity-based strategy to verify the order of numbers in a sequence context. This brings us to the hypothesis that the patient became unable, after parietal damage, to match the quantity meaning of numbers with their corresponding position in the sequence. Further evidence for his inability to use quantity information in sequence contexts was provided by the direct comparison of quantity and sequence order tasks using the same material.

When presented with the same target numeral and asked to produce a larger number (or to 'add 1') or a number coming 'after' (or 'just after') it, CO showed a similar pattern of performance for both quantity and order instructions. However, when asked to produce a number smaller or a number coming 'before' that target, the patient's performance was completely different: it was almost flawless with quantity instructions and drastically impaired with order instructions. Hence, this suggests that quantity and sequence instructions did not activate the same mechanism and/or semantic representation. Quantity processing possibly triggered the activation of intact

magnitude representations, that entailed correct finding of both smaller and larger numerals; whereas sequence instructions triggered a sequence recitation mechanism (correct 'after' responses are consistent with the use of preserved forwards recitation skills, and impaired responses to 'before' questions are due to impaired backwards recitation). When the same sequence task was proposed with non-numerical series, performance was also impaired, though again better for 'after' compared to 'before' instructions.

A similar dissociation between sequence and quantity instructions was found when CO had to choose the smaller/larger or before/after item in a pair. His performance was flawless with quantity instructions, but truly impaired with sequence instructions, whether they referred to numerical or non-numerical ordered series. The pattern of performance in the bisection task also showed a better processing with quantity relative to sequence instructions. Yet, quantity processing was nonetheless more error-prone for the smallest intervals (e.g. give a number larger than 7 and smaller than 9). This might be explained by the activation, in quantity tasks, of a magnitude representation (number line) that is only approximate in nature (see Dehaene, 2001; Gallistel, & Gelman, 1992). Using a preserved sequence recitation strategy might have elicited, instead, a more precise representation and processing of small intervals. But CO did not intentionally use sequence recitation to perform this task and he rarely produced the next element in the sequence for numerical material, whereas he did it sometimes for non-numerical series.

In all sequence tasks discussed above, CO was never found to use the quantity meaning of numbers to process their relative order in the sequence. However, because numerical quantity and order are intimately linked, processing either quantity or sequence may automatically activate the other dimension as well (see Turconi & al., 2005 for evidence in this direction in normal subjects). This appeared to be rarely the case for CO, with one exception, however. In the computerized comparison/relative order judgment task, CO was again almost flawless in quantity processing (deciding whether a numeral between 1 and 9 was smaller or larger than 5), while he was extremely slow and made more errors when he had to process their

sequence order (deciding if the number came before or after 5 in the number sequence). A standard distance effect was found on RTs in the quantity task, confirming CO's preserved access to a spared representation of analogue magnitudes. Yet, a standard distance effect was also observed, on both RTs and error rates, in the number sequence task. Hence, this might suggest that CO resorted to a quantity-comparison strategy when processing numbers according to their sequence order in this task. In fact, using a sequence recitation strategy (i.e. serial search; Jou, 2003) would have led, instead, to the production of a reverse distance effect (Turconi & al., 2005), which was not found here. Besides, impaired performance for non-numerical (non-quantitative) series (CO performed almost at chance level) with the same sequence instruction lends further support to the hypothesis that the patient used a quantity-based strategy when processing the sequence order of numbers. Hence, the present pattern of performance suggests that CO was able, sometimes, and under certain conditions, to activate his preserved quantity representation when processing the sequence order of Arabic numerals. Nonetheless, converting sequence order into a magnitude representation appeared to be a non-automatic, time-consuming, error-prone process, as suggested by the patient's extremely longer RTs (over 4 seconds) and accrued error rate with sequence relative to quantity instructions. Moreover, because the quantity task was performed just before the corresponding sequence task, a potential carry-over effect of the order in which tasks were performed may not be excluded to explain the use of a quantity representation in the subsequent sequence processing task (see Turconi & al., 2005 for a similar carry-over effect in normal adults).

In sum, CO could process quantity in various cardinal contexts and had a preserved quantity representation. Processing sequence order was, instead, profoundly impaired with the only sparing of forwards sequence recitation skills and of the corresponding order relations. With respect to non-numerical series, letters were consistently more impaired than days and months. Direct comparison of equivalent tasks using quantity and sequence instructions on the same material revealed that processing of order relations in cardinal contexts (i.e. applied to magnitudes; e.g. smaller/larger relation) was spared, whereas processing order relations in sequence contexts (e.g.

before/after relation) was constantly impaired. Thus, CO's preserved quantity representation did not appear to be automatically activated when processing numbers' order relations in sequence contexts, with one exception however (comparison to 5 with sequence instructions). Hence, CO was generally unable to map the position of numbers in the sequence (i.e. their order during recitation) with their corresponding cardinal meaning. With respect to forwards sequence recitation, it was sometimes automatically activated to perform basic sequence tasks, such as finding the item just before/just after a given target in the series. Nonetheless, CO did not appear to intentionally resort to a sequence recitation strategy, especially when performing sequence tasks that required more elaborate processing (e.g. 'order verification' or 'choosing the item coming before/after in a pair'). Correct performance in these tasks requires, in fact, not only to correctly recite the sequence but also to infer the response (e.g. pair in the conventional order) from more elaborate sequence knowledge (i.e., a pair is in the conventional order when the first element pronounced during sequence recitation is on the left side of the pair; or, a number comes 'before' when it is pronounced sooner, and not later, than the other number); yet CO did not appear to possess such elaborate sequence knowledge and was unable to infer the expected response from recitation. In certain complex tasks, such as finding the n^{th} element in a sequence, the patient used a direct LTM retrieval strategy to find the answer. Performing this task using sequence recitation would have required, in fact, some kind of keeping track procedure to which CO was unable to resort. With respect to lexical or semantic knowledge of ordered series, it was largely spared and cannot account for the patient's impaired performance in processing order relations.

Overall, these data suggest that numbers can be processed through different mechanisms according to whether instructions (or context) emphasize on quantity meaning or sequence knowledge. Quantity might be processed through a magnitude comparison mechanism that would in turn activate an analogue magnitude representation (Dehaene, 1992). Sequence order is expected to rely on a serial search (i.e. sequence recitation) mechanism that might function either forwards or backwards (see Jou, 2003; Turconi & al., 2005). Yet, backwards serial search was impaired in CO and

forwards sequence recitation was not intentionally used in many complex order tasks. Moreover, when processing numbers in sequence contexts CO did not appear to access their analogue-magnitude (quantity) representation (a process that might be automatic in normal adults) possibly because he had lost the knowledge that the farther a number is located in the sequence of number words, the larger the quantity it refers to (Wynn, 1992). Overall, the data argue for separate processing mechanisms for sequence and quantity meanings that can thus be damaged selectively after cerebral lesion.

Such separate coding may be surprising in adults who, when normally behaving, shift easily and unconsciously from one number use to another; nonetheless, children studies have reported a developmental distinction between the early acquisition of sequence knowledge and the later understanding of cardinal number meaning (Fuson, 1988). Yet, whether processing cardinal relations derives from the earlier acquisition of sequence relations, or whether cardinal and sequence relations develop independently, is still an open question (Fuson & Hall, 1983). Some developmental evidence has suggested that once the sequence order relations 'Just After/Just Before' (e.g. '4 comes just after 3') are acquired they are later used to answer similar questions in cardinal contexts ('One Greater Than/Smaller Than', as in '4 is one greater than 3', cardinal order relation; Fuson & al., 1982). The opposite was described, however, for the sequence relations 'After/Before' (i.e. that do not refer to successive numbers: '5 comes after 3') that appeared to develop only after the equivalent capacity in cardinal contexts was achieved (i.e. 'More Than/Fewer Than', e.g. '5 is more than 3'), at least for the number words below 10 (Fuson, 1988). It is not clear then whether order relations in sequence contexts are derived from the corresponding order relations in cardinal contexts or whether they involve different (although possibly similar) representations and independent processing.

Further evidence that sequence knowledge and quantity meaning can potentially dissociate after cerebral lesion comes from the case description of patient SE (Delazer & Butterworth, 1997). SE showed, after a left frontal

infarct, preserved (forward) sequence processing (e.g. telling the ‘next’ number in the sequence)¹⁴ in the face of impaired automatic access to the quantity meaning of numbers (e.g. he initially showed a reverse distance effect in number comparison). Yet, cardinal number meaning did not appear to be impaired in this patient (e.g. he could answer ‘How many’ questions), but was unable to easily activate his magnitude representation from Arabic numerals, thus forcing him to rely on sequence recitation to perform cardinal tasks. On the contrary, CO could perform cardinal tasks through magnitude representations, while he was unable to infer quantity meaning from relative positions in the sequence and had impaired sequence knowledge.

Overall, the present case study, together with developmental evidence and with neuropsychological dissociation between (preserved) sequence knowledge and (impaired automatic access to) quantity meaning, support the hypothesis that numbers might be processed through distinct and potentially dissociable mechanisms when referring to quantity meaning or sequence knowledge. None of the existing models of number processing can account, however, for the observed pattern of dissociation. All models focused, in fact, on quantity meaning and did not take into account knowledge of the number sequence. With respect to the Triple-code model (Dehaene, 1992; Dehaene & Cohen, 1995), the auditory-verbal frame may provide some kind of sequence coding through forwards recitation. However, sequence knowledge is more than forwards recitation, and we doubt that, for instance, backwards sequence recitation would be coded at the level of the verbal frame. Whatever its position in a model, yet, the reported dissociation could be explained by impaired access from sequence knowledge to analogue-magnitude representations, with the latter being largely preserved and the former only partially elaborated.

With respect to the cerebral localisation of sequence knowledge, certain areas of parietal cortex appear crucial (Szűcs & Csépe, 2004; Turconi & al., 2004). Yet these areas might be distinct from the HIPS that is thought to underlie quantity processing and representation, but closely related to it (see

¹⁴ Sequence knowledge is preserved in SE as far as forward sequence recitation is involved, since we know nothing about his backwards recitation skills; hence, (preserved) sequence knowledge must be considered cautiously.

the recent study by Caessens, Fias, & Orban, 2005, suggesting that the processing of magnitude and order information might both recruit intra-parietal areas). The angular gyrus might also play a crucial role in sequence order processing (see Hubbard, & al., 2005). Yet, bilateral posterior parietal areas could be involved as well in processing order relations. These areas were found, in fact, to be recruited in the selection of locations in space (Dehaene & al., 2003), and might be involved when processing proximity relations between numbers (e.g. deciding whether a number comes before or after another in the sequence).

Processing order relations on numbers might be linked, in fact, to more general spatial processing (see Hubbard & al., 2005, for a recent review). A relationship between numbers and space was initially established by the SNARC effect (Dehaene, & al., 1993), which was originally thought to reflect the association between number *magnitude* and spatial response preference. However, recent evidence showing that the SNARC effect extends to non-numerical ordered series (e.g. letters, months, and days; Gevers, & al., 2003, 2004) suggests, instead, that it might be relative order, rather than numerical quantity, that underlies the association between numbers (or other ordered series) and space (see also Fias & Fischer, 2004; Tzelgov & Ganor-Stern, 2004). Visual neglect after right parietal damage is another evidence for the relation between number processing and spatial abilities. Neglect patients were shown to misplace to the right, both the midpoint of physical lines and the midpoint of numerical intervals, in bisection tasks (Zorzi & al., 2002). Though not showing visual neglect, CO was also profoundly impaired in bisection tasks with numbers (especially when they involved sequence instructions) and other ordered series. Besides, he had impaired performance in processing spatial locations as well (e.g. when these were expressed by locative prepositions)¹⁵. Hence, conjoint impairment in processing sequence order relations (before/after) and their spatial counterpart (left/right), as well as spatial locations expressed by

¹⁵ This is consistent with studies that reported parietal areas to be sensitive to spatial relations expressed in sentences (see Goel & Dolan, 2001; Reichle, Carpenter, & Just, 2000). Besides, Tranel and Kemmerer (2004) also described patients with parietal lesions who were impaired in processing locative prepositions.

locative prepositions (in front of/behind and above/below) might tentatively suggest that sequence and space processing would rely on some common underlying representation or processing mechanism. Yet, whether a more general impairment in right-left discrimination might explain the observed association of impairments is at present tentative and needs further investigation.

Finally, we haven't considered, yet, the hypothesis that CO's limited working memory (WM) skills might also contribute to his inability to process sequence relations among numbers. WM was shown to play an important role in counting situations (e.g. in remembering already counted items and distinguishing them from to-be-counted objects; Fuson, 1988) and could also be involved in the less automatized aspects of sequence processing (e.g. backwards recitation in young children; Fuson, 1988; Fuson & Hall, 1983). CO was found unable, after parietal damage, to automatically recite the number sequence backwards; yet, because he had poor WM skills, he was unable to compensate for this inability and was impaired in processing sequence relations that relied on backwards recitation (e.g. 'what comes before' questions). Hence, conjointly impaired backwards recitation skills and poor WM abilities might give an explanation for CO's pattern of performance in *some* of the tasks. However, low WM skills don't explain the whole picture and, in particular, they don't explain why CO didn't rely on his preserved quantity meaning of numbers to perform sequence (order) tasks (e.g. 'give a number before 5'). Moreover, even when tasks were carefully matched in terms of cognitive demands (including WM load), CO was still found to be impaired in processing numerical and non-numerical sequence order (e.g. in judging 3 as coming *before* 5) but preserved in the equivalent quantity tasks (e.g. judging 3 as *smaller* than 5).

In the present study, we have described the case of a patient who was unable to process elaborate sequence order relations, in the face of preserved quantity processing, after bilateral parietal lesions. Thus, while cardinal number meaning and sequence knowledge appear to be closely connected in adults, the present study suggests that they can be selectively spared or impaired after cerebral, parietal, lesions. The fact that these concepts were

acquired at different times during development and refer to distinct numerical contexts might explain why they recruit distinct cognitive mechanisms, and/or different mental representations. This study further strengthens the importance of studying sequence order, and not only quantity processing in acalculic patients. Besides, certain regions of parietal cortex appear to play a crucial role in processing order relations on both numerical and non-numerical sequences; yet these regions might be distinct from the neural substrate underlying quantity processing, and could be involved, instead, in processing spatial relations.

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