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Case History Study

Pure left neglect for Arabic numerals

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ABSTRACT

Arabic numerals are diffused and language-free representations of number magnitude. To be effectively processed, the digits composing Arabic numerals must be spatially arranged along a left-to-right axis. We studied one patient (AK) to show that left neglect, after right hemisphere damage, can selectively impair the computation of the spatial frames underpinning recognition and understanding of Arabic numerals, without impairing the spatial frames for coding alphabetic strings or for coding environmental spatial information. The presence in our brain of these specific and precise spatial frames must be rooted in the paramount importance of Arabic numerals processing in our everyday activities.

1. Introduction

Number magnitude processing is a fundamental neurocognitive activity for successful everyday functioning (for review, see Dehaene, 2011). Specific brain circuits in the intraparietal sulcus of the right and of the left hemisphere are activated during number magnitude processing (for review, see Hubbard, Piazza, Pinel, & Dehaene, 2005). It is thought that the intraparietal sulci sustain our comprehension of number magnitude by means of a continuous and analogical line (i.e., the mental number line: MNL), in which small numbers are represented on the left and relatively larger numbers are represented on the right (Hubbard et al., 2005). In order to access and convey number magnitude, we use specific representations termed numerals (e.g., number words, Arabic digits, etc.). Number words, however, can be effectively processed only by the speakers of a given language, whereas Arabic digits are diffused and language-free representations of number magnitude. The importance of correctly recognizing Arabic numerals in everyday life is paramount. For instance, damage to the brain mechanisms that subserve multi-digit Arabic numerals, renders impossible a vast range of everyday life activities (e.g., finding the correct page of a book, selecting the proper bus, dialing a phone number, or performing a multi-digit multiplication; for review, see Butterworth, 1999). Arabic numerals are recognized by dedicated cortical circuits in the mesial occipital–temporal areas of each cerebral hemisphere (Dehaene & Cohen, 1995). To recognize an Arabic numeral, however, a specific spatial frame of reference must be computed in the brain. Indeed, the meaning of the same Arabic digits is different, depending on their specific spatial frame. For instance, a left-to-right oriented spatial frame is required for the brain to arrange the same digits (e.g., 1,2,3) in distinct spatial sequences, each representing a different magnitude (e.g., 213 vs. 321). In addition, a left-to-right oriented spatial frame is required in order for the brain to code correctly different orders of magnitude, such as hundreds, thousands, millions, billions, and so on.

Spatial frames in the brain are computed by large-scale, frontal–temporal–parietal circuits (for review, see Corbetta & Shulman, 2011) that can be selectively impaired in the case of brain damage causing neglect, a neuropsychological disorder characterized by severe impairment of contralesional awareness, as a result of defective spatial attention orienting (for review, see Umiltà, 2000). More frequently following right hemisphere damage, neglect patients fail to respond, report, or orient to stimuli in the left side of space (i.e., left neglect: LN; for review, see Heilman, Watson, & Valenstein, 2012). For instance, when LN patients are asked to bisect linear segments (>2.5 cm) positioned in front of them, they systematically misbisect to the right of the true midpoint, as if they ignored the leftmost part of the segment (Halligan & Marshall, 1988). LN patients show the same pattern (rightward bisection) even when they bisect mentally long number intervals (i.e., "What number is halfway between 1 and 9?" Patient: "7"). That is, LN patients fail to process relatively smaller numbers along the MNL, revealing its spatial nature (for review, see Umiltà, Priftis, & Zorzi, 2009). Nonetheless, the perceptual and the number spaces are relatively independent because they can be independently affected by LN (for double dissociations, see Doricchi, Guariglia, Gasparini, & Tomaiuolo, 2005; Zorzi, Priftis, Meneghello, Marenzi, & Umiltà, 2004).

While reading aloud, LN patients commit errors that affect the left side of the words (i.e., left neglect dyslexia, LND; for review,

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see Vallar, Burani, & Arduino, 2010). Furthermore, the spatial frames computed for mapping stimuli in the environment are different from those computed for mapping the spatial relations of letters in alphabetic strings (i.e., words and pseudowords; Vallar et al., 2010). LND has been observed following brain damage to different spatial frames, each coding a distinct left-to-right axis (Hillis & Caramazza, 1995).

The relation between the spatial frames underpinning alphabetic strings reading and those subserving Arabic numeral reading is more puzzling. In most reported studies patients were impaired both at reading alphabetic strings and at reading Arabic numerals (for review, see Vallar et al., 2010). The association of impairment between reading alphabetic strings and reading Arabic numerals, however, may be due to the anatomical contiguity of distinct brain mechanisms, which can be both damaged to the same degree by an extended brain lesion. Indeed, Kinsbourne and Warrington (1962) observed that their right-hemisphere damaged patients committed different types of errors in reading words (i.e., substitutions) and in reading numbers (i.e., omissions). The results of Kinsbourne and Warrington suggest that distinct spatial frames might be computed for reading alphabetic string and for reading Arabic numerals. In addition, one case with a developmental disorder of reading has been described, who showed LND in reading aloud words, but not in reading aloud Arabic numerals (Friedmann & Nachman-Katz, 2004). Nevertheless, the aforementioned single case cannot be considered as strong evidence in favor of the presence of distinct spatial frames for coding alphabetic strings and for coding Arabic numerals. For instance, reading aloud alphabetic strings might be simply more difficult than reading aloud Arabic numerals.

More convincing evidence in favor of the independence of the abovementioned spatial frames would be that of reporting a neurological case who shows the opposite pattern (i.e., LND for Arabic numerals, without LND for alphabetic strings, such as words and pseudowords). One patient with left-hemisphere damage has been reported (Cohen & Dehaene, 1991), who had difficulties in reading the leftmost (i.e., ipsilesional) digit of any Arabic numeral, but had no difficulties in reading words. This patient, however, together with all the reported eight left-hemisphere-damaged patients, who commit ipsilesional errors affecting the leftmost letters of words, are now thought to be affected by a linguistic impairment of the encoding of letter/Arabic digit positions in the string, rather than by a deficit of mechanisms of spatial attention (Vallar et al., 2010). The stronger evidence, indeed, would be that of studying a patient with typical LN following right-hemisphere damage, in order to test for dissociations between LND for alphabetic strings and LND for Arabic numerals.

We pursued this aim by studying AK, a patient who initially showed LN as a consequence of right hemisphere damage (Fig. 1). AK showed initially LN for environmental stimuli. While reading, he omitted the letters on the left side of words (e.g. table → able), and on the left side of multidigit Arabic numerals (256 → 56). After the first evaluation (i.e., Preliminary Assessment), we tested AK again in two occasions (Assessment 1: three months after the Preliminary Assessment; Assessment 2: two months after Assessment 1; Table 1).

2. Method

2.1. Case description and neurological history

AK was a 33-year-old, right-handed man. He had 11 years of formal education. Before the accident he worked as an electrician. AK had a road accident, while he was driving his motorbike. As a consequence, AK sustained multiple orthopedic injuries and severe traumatic brain damage. A Computerized Axial Tomography (CAT) scan was executed some hours after his accident. The CAT scan revealed a frontal extradural hematoma with diffuse, small, periventricular lesions. There were also parietal lacerations in his right hemisphere and in the mesial frontal region, bilaterally. Four days after his accident, AK sustained a neurosurgical intervention in the right frontal region, to evacuate the extradural hematoma. Five days following the neurosurgical intervention his neurologic conditions worsened. Therefore, he sustained a second surgical intervention of decompressive craniectomy in the right frontal–temporal-parietal region. After the intervention, his neurologic condition was stable. A CAT scan, performed two months after AK's accident, showed a hyperdense area in his right frontal lobe, with the midline cerebral structures slightly shifted to the left. An electroencephalogram, performed in the same period, revealed the presence of slow waves (i.e., theta) in the frontal regions, which were more evident over the right frontal lobe. At that time, a comprehensive, formal neuropsychological assessment of AK's cognitive functions was impossible because he was very distractible and showed severe, generalized LN.

2.2. Apparatus, stimuli, and procedure

Both on Assessment 1 and on Assessment 2, AK was presented with Arabic numerals (length: 1–6 digits, measuring approximately 1–7.5 cm). The same Arabic numerals were presented in three spatial positions on a PC screen: left side, center, and right side. AK was required to read aloud each numeral. To test whether AK's impairment was specific for the left side of Arabic numerals, he was also asked to read aloud single words, compound words, and pseudowords (length: 6–10 letters, measuring approximately 6–10 cm), presented in the same spatial positions as those of the Arabic numerals. The study was conducted in accordance with the Principles of the Declaration of Helsinki. AK gave his informed consent to participate in the study.

2.2.1. Single words, compound words, and pseudowords

To explore his word and pseudoword reading abilities, we presented AK with 10 compound words (length: 10 letters), 10 simple words (i.e., not compound words; length range: 6–10 letters), and 10 orthographically legal pseudowords (length range: 6–10 letters). AK was presented first with a black fixation cross (Font: Times New Roman; size: 60), placed in the center of a PC screen (15 in.), against a grey background. AK was asked to fix and maintain his gaze on the fixation cross. Then, the fixation cross disappeared, and a single word, a compound word or a pseudoword was displayed. All the single words, the compound words, and the pseudowords (font: Times New Roman; size: 44; color: black; upper case, single spaced) were displayed against a white background and were presented pseudorandomly on the PC screen. Each single word, compound word, and pseudoword was presented for the same number of times on the center, on the left side, and on the right side of the PC screen (see Supplementary file 1). AK was asked to read aloud each single word, compound word, and pseudoword, without time limit. AK was at a distance of about 50 cm from the screen and he was free to move his eyes and his head.

2.2.2. Arabic numerals

To explore AK's reading abilities for Arabic numerals, we presented him with 30 Arabic numerals (length range: 1–6 digits). AK was first presented with a black fixation cross (Font: Times New Roman; size: 60, single-spaced), placed in the center of a PC screen (15 in), against a grey background. AK was asked to fix and maintain his gaze on the fixation cross. Then, the fixation cross disappeared and an Arabic numeral was displayed. All the Arabic

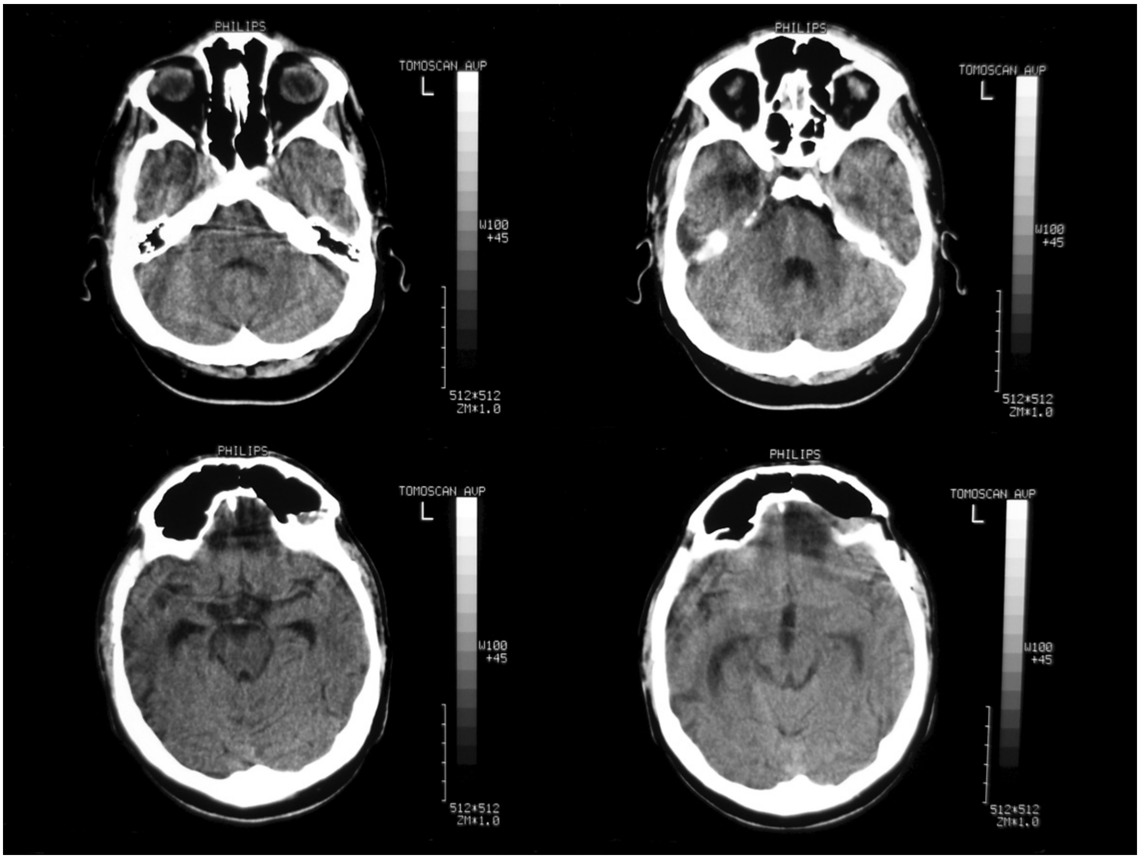

Fig. 1. AK's Computerized Axial Tomography scan showing diffused lesions in the right temporal lobe and a bilateral lesion in the anterior mesial–orbital surface of the frontal lobes.

Table 1
AK's performance on Neuropsychological tests.

Test	Preliminary assessment	Assessment 1	Assessment 2
Overall cognitive status (range = 0–30; cut-off: <24)[a]	22	24	27
Verbal reasoning (range = 0–4; cut-off = 0)[b]	1	2	NA
Phonemic verbal fluency (range = 0–4; cut-off = 0)[c]	1	1	2
Semantic verbal fluency (range = 0–4; cut-off = 0)[c]	0	0	0
Non-verbal reasoning (range = 0–36; cut-off < 18.96)[d]	24.9	27.9	NA
Attentive matrices (range = 0–4; cut-off = 0)[b]	0	0	0
Short term phonological memory (digit span test)[e]			
Forward	5	6	5
Backward	3	3	3
Short term spatial memory (range = 0–4; cut-off = 0)[f]	NA	0	NA
Verbal learning (range = 0–4; cut-off = 0)[g]	NA	2	2
Oral and written language processing[h]	NA	Normal	NA
Peripersonal neglect (Behavioral Inattention Test)[i]			
Conventional part (range = 0–146; cut-off ⩽ 129)	131	143	145
Behavioral part (range = 0–81; cut-off ⩽ 67)	59	68	78

NA = not administered.
[a] Magni et al. (1996).
[b] Spinnler and Tognoni (1987).
[c] Novelli et al. (1986b).
[d] Basso, Capitani, and Laiacona (1987).
[e] Orsini and Laicardi (1997).
[f] Orsini et al. (1987).
[g] Novelli et al. (1986a).
[h] Luzzatti et al. (1994).
[i] Wilson, Cockburn, and Halligan (1987).

numerals (font: Arial; size: 66; color: black) were displayed against a white background, and were presented pseudorandomly on the PC screen. Each Arabic numeral was presented for the same number of times on the center, on the left side, and on the right side of the PC screen (see Supplementary file 2). AK was asked to read aloud each Arabic numeral, without time limit. AK was at a distance of about 50 cm from the screen and he was free to move his eyes and his head.

3. Results

3.1. Preliminary assessment: five months post-lesion onset

AK came to our observation five months post-lesion onset, for a comprehensive neuropsychological assessment, because of his traumatic brain injury. He was alert and collaborative, but logorrheic. His basic sensori-motor functions were intact, but he had a wide-based gait. AK was oriented to space, but he was not oriented to time. His overall cognitive status was mildly compromised (Table 1), his semantic fluency was impaired, and his speed on a task requiring fast visuo-spatial attention orienting was reduced (Attentive matrices; Table 1). The rest of AK's cognitive functions was normal or borderline (Table 1). AK was perfectly accurate in detecting visual stimuli on double simultaneous visual stimulation (i.e., no visual extinction). AK did not show signs of personal LN, given that he was errorless while exploring his body (correct targets in the left hemibody: 10/10; correct targets in the right hemibody: 10/10). In addition, AK was not affected by extrapersonal LN, because he reported correctly all elements in a symmetric, ad hoc created, examination room (correct left-sided targets: 10/10; correct right-sided targets: 10/10). Nevertheless, he showed signs of mild LN for the peripersonal space (Behavioral Inattention Test, Behavioral part, correct: 59/81; Table 1). The vast majority of his errors were due to LND while he was reading a menu and an article. In addition, AK was severely impaired at reading single words, compound words, and pseudowords (correct: 42/90). The majority of his reading errors (34/42) were characterized by omissions of letters on the left side of the letter string (i.e., LND). Finally, he showed LND also for multidigit Arabic numerals (errors: 6/10).

3.2. Assessment 1: eight months post-lesion onset

AK was oriented to space, but he was still not oriented to time. Although his overall cognitive status was normal, his semantic fluency, his short-term spatial memory, and his speed on the Attentive matrices test remained impaired (Table 1). The rest of AK's cognitive functions was normal or borderline (Table 1). He scored above the cut-off on both the conventional and the behavioral parts of the BIT (Table 1). In addition, AK performed normally on a comprehensive test battery for assessing oral and written language functions (Table 1). Because, on the Preliminary Assessment, AK showed moderate to severe LND in the presence of mild LN, we investigated further his reading abilities by presenting him with alphanumeric stimuli (i.e., single words, compound words, pseudowords, and Arabic digits).

AK's performance in reading aloud Arabic numerals was severely impaired (Table 2). He committed 43/90 errors (48%; LND errors: 36/43 [84%]. LND errors were: omissions 35/36 [97%; e.g., target: "11951", AK's response: "51"], omission + repetition 1/36 [3%]; Non-LND errors: 6/43 [14%]. Non-LND errors were syntactic ones, because of misprocessing of the zero; e.g., target "7008", AK's response: "7000 and 08"). Finally, AK committed one mixed error (i.e., a left-sided omission plus a syntactic error). To further analyze AK's performance, we coded the number of errors that he committed on each digit composing the displayed Arabic numerals. For instance, AK read the six-digit-long Arabic numeral "904,318" as "318". We coded his errors as 111,000 (i.e., three omissions on the left side of the Arabic numeral, no omission on the right side; see Table 2). Chi-squared tests of goodness-of-fit were performed to control whether AK's LND errors were equally distributed as a function of the spatial positions (i.e., left side, center, right side on the PC screen), and as a function of Arabic numerals length (i.e., number of digits). The results showed that AK's LND errors were not equally distributed among the spatial positions (χ^2 (2, N = 60) = 17.20, $p < .001$); the number of LND errors was high when the Arabic numerals were presented in the left spatial position (errors = 32), whereas it progressively decreased when the Arabic numerals were presented in the central spatial position (errors = 22) and in the right spatial position (errors = 6). Moreover, LND errors were not equally distributed among the Arabic numerals as a function of their length (χ^2 (4, N = 60) = 30.83, $p < .001$): the longer the Arabic numeral, the larger the LND error on its left side. By contrast, AK's performance was good in reading aloud alphabetic strings. He committed 7/90 errors (8%) in reading single words, compound words, and pseudowords (LND errors: 4/7 [omissions]; Non-LND errors: 3/7 [i.e., AK read three times the word "orchestra" instead of the pseudoword "orchentra"]).

3.3. Assessment 2: ten months post-lesion onset

A CAT scan of AK's brain showed diffuse hypodense right temporal lesions and a hypodense lesion involving the mesial–orbital frontal region, bilaterally (Fig. 1). AK's cognitive functions were normal except for semantic verbal fluency and for his speed on the Attentive matrices test. On both the conventional and the behavioral parts of the BIT, his performance was above the cut-off (Table 1). We investigated AK's reading abilities by presenting him with the same alphanumeric stimuli (i.e., single words, compound words, pseudowords, and Arabic digits) as those presented in Assessment 1.

AK's performance in reading aloud Arabic numerals was severely impaired (Table 3). In reading aloud Arabic numerals, AK committed 43/90 errors (48%; LND errors: 33/43 [77%]. LND errors were omissions 33/33 [100%]; Non-LND errors: 7/43 [16%]. Non-LND errors were syntactic errors because of misprocessing of the zero). Finally, AK committed three mixed errors (i.e., for three Arabic numerals, AK committed three left-sided omissions plus three syntactic errors). Chi-squared tests of goodness-of-fit were performed to control whether AK's LND errors were equally distributed as a function of the spatial positions (i.e., left side, center, right side on the PC screen), and as a function of Arabic numerals length (i.e., number of digits). The results showed that the LND errors were not equally distributed among the spatial positions (χ^2 (2, N = 65) = 28.46, $p < .001$); the number of LND errors was high when the Arabic numerals were presented in the left spatial position (errors = 40), whereas it progressively decreased when the Arabic numerals were presented in the central spatial position (errors = 20), and in the right spatial position (errors = 5). Moreover, LND errors were not equally distributed among the Arabic numerals as a function of their length (χ^2 (4, N = 65) = 25.85, $p < .001$): the longer the Arabic numeral, the larger the LND error on its left side. The majority of his errors were omissions of digits on the left side of Arabic numerals, resulting in syntactically plausible answers that did not respect, however, the magnitude of the displayed Arabic numeral (e.g., Target: 328762 → AK's answer: 62). Thus, AK's performance remained impaired on Assessment 2, which took place two months following Assessment 1. By contrast, AK's performance was very good in reading aloud alphabetic strings. He committed 4/90 errors (4%) in reading single words, compound words, and pseudowords (LND errors: 1/4 [substitution]; Non-LND errors: 3/4 [AK read three times the word "orchestra" instead of the pseudoword "orchentra"]). Note that AK did not show any sign of LN for environmental stimuli (i.e., persons, objects, etc.) both in Assessment 1 and in Assessment 2 (Table 1).

4. Discussion

AK showed pure LND for multidigit Arabic numerals. Indeed, his errors in reading aloud Arabic numerals were highly influenced by

Table 2
Assessment 1: distribution of AK's LND errors in reading aloud Arabic numerals as a function of the spatial position of the displayed Arabic numerals and of the spatial position of the digits within each Arabic numeral. The vertical dashed line indicates the center of the displayed Arabic numeral.

Number length (digits)												Total errors
Left side of the PC screen												
1						0						0
2					2		0					2
3				4		0		0				4
4			4		1		0		0			5
5		5		3		2		0		0		10
6	4		3		3		1		0		0	11
											Grand total	32
Center of the PC screen												
1						0						0
2					0		0					0
3				0		0		0				0
4			2		2		0		0			4
5		6		4		0		0		0		10
6	4		3		1		0		0		0	8
											Grand total	22
Right side of the PC screen												
1						0						0
2					0		0					0
3				0		0		0				0
4			1		0		0		0			1
5		1		0		0		0		0		1
6	2		1		1		0		0		0	4
											Grand total	6

Table 3
Assessment 2: distribution of AK's LND errors in reading aloud Arabic numerals as a function of the spatial position of the displayed Arabic numerals and of the spatial position of the digits within each Arabic numeral. The vertical dashed line indicates the center of the displayed Arabic numeral.

Number length (digits)												Total errors
Left side of the PC screen												
1						0						0
2					2		0					2
3				4		1		0				5
4			5		3		0		0			8
5		3		2		1		1		0		7
6	5		5		5		3		0		0	18
											Grand total	40
Center of the PC screen												
1						0						0
2					0		0					0
3				2		0		0				2
4			4		2		0		0			6
5		4		3		0		0		0		7
6	3		1		1		0		0		0	5
											Grand total	20
Right side of the PC screen												
1						0						0
2					0		0					0
3				0		0		0				0
4			2		0		0		0			2
5		0		0		0		0		0		0
6	2		1		0		0		0		0	3
											Grand total	5

specific spatial manipulations (i.e., position of the Arabic numeral on the PC screen: left side, center, right side) and by the length of the displayed Arabic numeral (i.e., 1–6 digits). His performance cannot be explained by low level visual–perceptual (input) or linguistic (output) disorders, given that AK was able to correctly explore and verbally describe stimuli in the environment, and he was highly accurate at reading aloud single words, compound words, and pseudowords. Furthermore, AK's better performance in reading Arabic than in reading alphabetic strings cannot be attributed to length differences between the two types of stimuli (for review on the length effect in LND, see Vallar et al., 2010). Indeed, if this were the case AK should have been more impaired in reading alphabetic strings than in reading Arabic numerals, given that our alphabetic strings were more lengthy than our Arabic numerals. Finally, AK better performance in reading words could be attributed to top-down lexical and semantic processes, which might have oriented AK spatial attention to the left side of the words. Nonetheless, this cannot account for the fact that AK was also accurate in reading pseudowords (i.e., alphabetic string without lexical or semantic entries).

We show, for the first time, that specific spatial frames of reference for coding Arabic digits are computed in the brain, in order to extract the magnitude of Arabic numerals. These frames are independent from general-purpose spatial frames for coding the coordinates of the environment (or of the body), and from the spatial frames for coding alphabetic strings (for review, see Vallar et al., 2010). Indeed, AK's impaired performance in reading Arabic numerals, but not in reading alphabetic strings, together with the opposite pattern (Friedmann & Nachman-Katz, 2004) constitute the first evidence of a double dissociation between the spatial frames required for reading Arabic numerals and those required for reading alphabetic strings. Further studies on both single cases and groups of patients are required, however, to increase the external validity of the abovementioned double dissociation.

On the basis of our findings, it seems that LN for number processing can dissociate from LN for others domains (e.g., alphabetic strings, environment) at different levels of processing. For instance, LN for the MNL is doubly dissociated from LN for the perceived space (Doricchi et al., 2005; Zorzi et al., 2004). Nonetheless, the MNL is a different cognitive mechanism for number processing (abstract magnitude) from that investigated in the present study (reading aloud Arabic numerals). Indeed, according to Dehaene and Cohen (1995), the MNL is supported by different brain regions from those involved in processing Arabic numerals (i.e., the intraparietal sulcus and the mesial occipital–temporal surface, respectively). Thus, our findings reflect specific effects of LND in processing Arabic numerals, not LN for the MNL.

Our ability to read alphabetic strings and Arabic numerals is one of the most recent achievements of our evolution as species. One might wonder how it became possible for the brain to be prepared for such a complex activity that, however, has been only recently acquired. According to Dehaene's (2005) "neuronal recycling" hypothesis "the architecture of the human brain is limited and shares many traits with other non-human primates. It is laid down under tight genetic constraints, yet with a fringe of variability. Cultural acquisitions are only possible insofar as they fit within this fringe, by reconverting pre-existing cerebral predispositions for another use". Thus, general purpose visuo-spatial mechanisms can be re-shaped by culture and education in order to allow us to read. During the abovementioned neuronal recycling it might be that spatial frames for reading Arabic numerals are different from those for reading Arabic numerals. Computing specific spatial frames for the exact and precise coding of digits, in order to form Arabic numerals, is of elevated adaptive value in modern societies. Indeed, without computing specific spatial frames, it would be impossible for the brain to deal effectively with Arabic numerals, and, thus, to complete many everyday activities.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.bandc.2012.09.008.

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