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Number processing after stroke: Anatomoclinical correlations in oral and written codes

EUGÈNE MAYER,[1] MICHAEL REICHERTS,[2] GÉRARD DELOCHE,[3] LUCIA WILLADINO-BRAGA,[4] IRÈNE TAUSSIK,[5] MONIQUE DORDAIN,[6] MARTIAL VAN DER LINDEN,[7] AND JEAN-MARIE ANNONI[1]

[1]Neuropsychology Unit, Geneva University Hospital, Switzerland
[2]Psychological Institute, University of Fribourg, Switzerland
[3]Psychological Institute, University of Reims, France
[4]Sarah's Rehabilitation Foundation, Brasilia, Brazil
[5]Psychological Institute, University of Buenos-Aires, Argentina
[6]Service de Neurologie, Clermont-Ferrand, France
[7]Psychological Institute, University of Geneva, Switzerland

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Abstract

Calculation and number-processing abilities were studied in 49 patients with chronic single vascular brain lesions by means of a standardized multitask assessment battery (EC301), as well as through other tasks, testing functions thought to be implicated in calculation such as language, visuo-perceptive abilities, verbal and spatial working memory, planning, and attention. The results show that (1) lesions involving parietal areas—particularly left parietal lesions—are prone to alter calculation processing. A more detailed analysis showed that patients with lesions involving left parietal areas were impaired in both digital (i.e., comprehension and production of numbers written in Arabic code) and oral (i.e., comprehension and production of numbers heard or expressed orally) processing while lesions involving right parietal areas lead to an impairment in digital processing only. However, linguistically related alphanumerical processing (i.e., comprehension and production of numbers written orthographically) was not influenced by parietal lesions. (2) Semantic representations (knowledge of the magnitude related to a given number) as well as rote arithmetical knowledge are also impaired following damage to parietal and particularly left parietal lesions, suggesting that these areas are also implicated in magnitude comparisons and in the retrieval of arithmetical facts. (3) Performance in calculation is highly correlated with language. (4) Moreover, we found a highly significant correlation between performances in oral calculation and verbal working memory, and between written-digit calculation and visuospatial working memory. Performances in regard to visuo-perceptive abilities, planning, and attention were less consistently correlated with calculation. These results stress the close correlation, but relative independence between calculation and language, as well as a dissociated sensitivity of oral and digital processing to brain lesions. (*JINS*, 2003, *9*, 899–912.)

Keywords: Dyscalculia, Cerebrovascular disease, Neuropsychology

INTRODUCTION

Since Henschen (1920) used the term acalculia for the first time, numerous researchers have attempted to isolate calculation deficits from other pathologies such as aphasia—and to dissociate different forms of calculation impairments (Hécaen et al., 1961; Kleist, 1934). The emergence of models based on psychological information processing (Dehaene, 1992; Deloche & Seron, 1982; MacCloskey & Caramazza, 1987) allowed the construction of new tools intended to analyze extensively the aspects of number processing and calculation described by those models. The EC301 battery (Deloche et al., 1994, 1995) is one of these tools. The aim of the present work was to apply this battery to a group of patients with chronic single cerebral lesion of vascular origin, in order to study relations between sub-

Reprint requests to: Dr. Eugène Mayer, Neuropsychological Unit, Neurological Clinic, University Hospital, CH-1211 Genève 14, Switzerland. E-mail: eugene.mayer@hcuge.ch

components of number processing and the site of brain damage, as well as the influence of calculation on other cognitive functions such as language, visuospatial skills, memory, planning, and attention.

Different analyses on a group level have pointed to a role of the left parieto-temporal areas in calculation and number processing, depending on either linguistic—such as transcoding, comprehension of number, arithmetical facts—or nonlinguistic aspects—such as arithmetical signs and magnitude comparison (Dahmen et al., 1982; Grafman et al., 1982; Hécaen et al., 1961; Jackson & Warrington, 1986). Moreover, damage to the same site leads to number-related problem-solving deficits (Vilkki, 1988). Number-processing impairment can be dissociated from language deficits (Basso et al., 2000), despite the fact that some components of calculation, like retrieval of multiplication facts, seem to be mediated by verbal processing (Delazer et al., 1999). Right brain lesions are less prone to impair calculation (Grafman et al., 1982; Jackson & Warrington, 1986). However, right retrorolandic lesions have also been shown to alter number processing and calculation (Ardila & Rosselli, 1994; Rosselli & Ardila, 1989). In functional imaging studies, mental multiplication and number comparisons activate the inferior parietal and the superior temporal regions bilaterally, suggesting that not only left but also right parietal areas are involved in number processing (Dehaene et al., 1996; Pinel et al., 1999; Rickard et al., 2000). Taken together, this data underline the role of right and left parietal areas for calculation, but point to a differential involvement depending on the side of lesion. Verbal *versus* spatial abilities have often been presented as a plausible explanation for these differences (Hécaen et al., 1961). Nevertheless, this explanation is probably insufficient, since right unilateral lesions do not only produce acalculia related to spatial defect, but also other types of impairments such as a loss of calculation automatisms (procedures) and reasoning errors, which are usually considered to be language dependent (Ardila & Rosselli, 1994; Boller & Grafman, 1985). Another way to explain differences in performance of patients with either right or left brain damage could be the dysfunction of modality-specific components of working memory (Baddeley, 1986; Clark & Campbell, 1991; Furst & Hitch, 2000; Lee & Kang, 2002; Logie et al., 1994; Noël et al., 2001). Clark and Campbell, for example, suggest that number concepts are represented by multiple format and modality-specific codes interconnected in a complex network (i.e., articulatory, orthographic, and auditory codes for various spoken and written words, visual and motor codes for digits, etc.). According to this view, a disruption of verbal or visual working memory would affect spoken and digital number processing, respectively. Since these different modalities of working memory rely on different brain hemispheres, alteration is prone to alter differentially calculation and number processing in right *versus* left brain lesion patients. The influence of general short-term memory skills on calculation abilities has indeed been challenged. For example, Butterworth et al. (1996) described a patient suffering a severe verbal working memory deficit without calculation skills impairment. However, more recent behavioral data suggest a consistent influence of subsystems of working memory on certain aspects of calculation. For example, Noel et al. (2001) showed an influence of the phonological loop on temporary storage of addends in additions, while Lee and Kang (2002) reported an effect of the phonological loop on mental multiplication while subtraction was more dependent on the visuospatial sketchpad.

Single case studies, inspired by the cognitive neuropsychological approach, suggest that different components of number processing can be specifically impaired following brain lesions. MacCloskey and Caramazza (1987) and Sokol et al. (1991) proposed a modular model in which digital (written digit), oral (oral number), and alphanumerical (orthographically written) codes can be affected independently. However, they did not make specific predictions concerning brain structures implicated in the different processes. In an anatomo-functional model (Dehaene & Cohen, 1997), three codes have been proposed: (1) a visual–Arabic code—which allows written calculation, parity, and input–output processing dealing with digits. Bilateral occipito-temporal structures are responsible for this code processing. (2) An oral code—where the numbers are represented as a parsed sequence of words—subserved by the left perisylvian areas. (3) An analogical, "semantic" code—implicating the magnitude representations—relying on right and left parietal areas. In the latter model, semantic knowledge of numbers and quantities is supported by bilateral inferior parietal structures, while more linguistic knowledge of arithmetical facts (such as multiplication tables) are supported by anterior left subcortical areas (Dehaene & Cohen, 1997). However, the role of left subcortical (basal ganglia) structures in simple arithmetic functions has been questioned (see, e.g., Rickard et al., 2000).

Most of the predictions made by these recent models on cognitive architecture and on anatomical–functional organization rely on single cases. Our purpose is to evaluate these different hypotheses concerning number processing in a group of patients with focal brain lesions. Recently, Dellatolas et al. (2001) showed that left-brain-damaged patients performed poorly on oral and alphabetical codes and in mental and written calculation, while right-brain-damaged patients were impaired in tasks such as estimating sizes and weights of objects, or placing numbers on a scale. However, they did not take into account the lesion site, particularly the parietal involvement. Given the role of parietal areas in both calculation (Pesenti et al., 2000) and working memory (Paulesu et al., 1993), we found it important to analyze the impact of the side (right or left) and the site (parietal or nonparietal) of the lesion on the different components of calculation abilities. Therefore, our predictions were the following:

1. Lesions involving parietal areas would affect both oral and digital codes more than lesions not involving parietal areas. Alphanumerical codes, which are strongly lan-

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guage related, would depend on the side of the lesion (left hemisphere) but not on parietal involvement.

2. Parietal lesions would impair differentially oral and digital number processing in relation to the affected hemisphere (Dehaene et al., 1996; Hécaen et al., 1961). Particularly, oral codes would be more impaired after left parietal lesions than after right parietal lesions.
3. According to Dehaene and Cohen's predictions (Dehaene & Cohen, 1997), the specific numerical-semantic representations necessary for magnitude comparison should be more impaired after parietal lesions than after nonparietal lesions. Conversely, knowledge of rote arithmetical facts would be affected by left subcortical lesions.
4. Oral and digital numerical abilities would be related, respectively, in verbal and visual components of working memory (Baddeley, 1986; Clark & Campbell, 1991; Furst & Hitch, 2000; Lee & Kang, 2002; Logie et al., 1994; Noël et al., 2001).

METHOD

Population

Eighty-one patients were recruited from six neuropsychological units, four French-speaking (Clermont-Ferrand, Geneva, Liège, Paris), one Portuguese-speaking (Brasilia), and one Spanish-speaking (Buenos Aires). Neuropsychologists or speech therapists administered testing. Inclusion criteria for the patients comprised in a first stage: (1) absence of previous neurological or psychiatric events; (2) single brain lesion of vascular etiology (stroke), verified with magnetic resonance imagery (MRI) or computerized tomography (CT); (3) a postonset delay of more than 3 months; and (4) absence of illiteracy. Preliminary observations gave the impression that non-right-handed patients were slightly less impaired than right-handed patients, but statistics were not applied because of the small number of non-right-handed patients ($N = 7$). Another initial analysis clearly revealed that patients with postonset delay ≥ 18 months ($N = 21$) differed from patients suffering from a more recent lesion < 18 months ($N = 53$) (multivariate analysis of variance, Wilks' Lambda Multivariate Test, $p = .006$). These *post-hoc* analyses prompted us to add two more inclusion criteria: (5) a postonset delay of less than 18 months, and (6) a right-handed laterality, scoring $> .80$ at the Bryden's Handedness Scale (Bryden, 1977). Finally, four patients with missing data were excluded from the group. These supplementary criteria brought the final population to 49 patients. Demographic characteristics of these 49 patients are detailed in Table 1.

The basic neuroanatomical data sets were reported on axial plate (Damasio & Damasio, 1983). The lesions were classified in different groups according to the area involved: frontal, temporal, parietal, occipital, and subcortical. In accordance with the tri-dimensional network models (Mesulam, 1981), we then examined involvement of one specific area, independently of the extension of the lesion to other cortical or subcortical areas. For example, parietal involvement included inferior or superior parietal lesions, temporo-parietal or fronto-temporo-parietal but neither fronto-temporal nor pure subcortical lesions. For the purpose of our research, the population of patients was divided into four groups, depending on the side (left *vs.* right hemisphere) and the site (parietal *vs.* nonparietal) of the lesion. A complementary analysis concerning performances in rote arithmetical facts compared left subcortical *versus* left nonsubcortical lesions. In this design, analyses have always been carried out on 49 cases (corresponding to 49 patients).

Neuropsychological Investigations

Calculation and number processing was assessed using a shortened version of the EC301 battery (Deloche, 1995; Deloche et al., 1995). The battery included the following 13 tests: dots numeration, oral backward counting, digit writing from dictation, mental calculation, performing written numerical operations, reading digit numbers aloud, placing Arabic numbers on an analogical scale, oral number comparison, perceptual quantity estimation, numerical knowledge, Luria's problem, transcoding Arabic numbers in written verbal numbers, and comparison of written alphanumerical numbers (see Appendix I). The tasks do not present any time constraints. Among the 13 different tests of the battery, ten tasks contribute to the evaluation of the components dealing with comprehension and production of numbers in the three main numerical notation systems—Arabic digits, oral, and alphanumeric–orthographic num-

Table 1. Description of the 49 patients included in the final analysis[a]

Origin	Number	Sex	Age	Literacy	P.O.D.
French speaking	40	F = 15, M = 25	53.9 (±15)	I = 10, II = 16, III = 14	7.2 (±3.7)
Portuguese speaking	6	F = 2, M = 4	47.8 (±14.5)	I = 6, II = 0, III = 0	6.8 (±2.3)
Spanish speaking	3	F = 1, M = 2	59 (±21.2)	I = 0, II = 0, III = 3	10 (±7.2)

[a]The first column gives their linguistic background, the second their sex (F for female, M for male). In the age column the following data are given: mean and (standard deviation). The data concerning the literacy include the number of patients with 4–9 years of education (level I), between 9 and 12 years (level II), and >12 years (level III) of education. Postonset delay (P.O.D.) indicates the mean number of months (standard deviation) which separate the stroke from the evaluation for each provenience.

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ber forms (Table 2), according to the model proposed by MacCloskey and Caramazza (1987). Three complementary tests do not directly apply to MacCloskey and Caramazza's model: Luria's problems resolution, which is supposed to test general number processing and planning strategies, quantitative numerical knowledge (or cognitive estimation of quantities, such as knowing if ten people on a bus are too many, too few, or in the normal range), which may depend on numerical-semantic representations (Dehaene & Cohen, 1997); and perceptive estimation of quantities (for example, the estimation of the weight of a drawn person), which relies on visuo-perceptive abilities and magnitude representations. Given the fact that these three tasks are not pertinent for the dissociations between codes, as presented in MacCloskey and Caramazza's model, they are not reported in Table 2. They have been described in the general results but have not been used for further analysis. In visual tests (for example, in dots numeration or in performing written numerical operations), the sheet was presented ipsilaterally to the cerebral lesion.

The complementary neuropsychological assessment focused on language abilities, visuo-perceptive capacities, verbal and spatial working memory, planning, and attention.

Language examination included (1) repetition, reading, and writing of words (10 per modality) and nonwords (5 per modality). Words used in the dictation were mastered very early (score less than 14 at Dubois-Buyse's Scale (Ters et al., 1977)). Nonwords have been constructed with phoneme sequences with the same statistical characteristics of French language, using anagrams (e.g., virtine[virtin] for vitrine[shop window]), morphological assembling (e.g., rapidesse [Rapides] for rapidité [speed] and vitesse [velocity]), and items with *n*-count > 1 (e.g., codre [codre] > cadre [frame] or cidre[cider]). (2) For picture naming, we used ten pictures issued from the DO 80 Battery (Metz-Lutz et al., 1991), all having a high-name agreement and a lexical frequency higher than 4000. (3) Oral and written comprehension was tested with items issued from the Montreal-Toulouse battery (Nespoulous et al., 1992). This small battery was adapted to Spanish and Portuguese by the authors.

Visuo-perceptive capacities were evaluated with the section lines test of Albert (1973) and with an internally developed task of comparison of two sequences of Thai characters (Fig. Thai). Thai characters are not known in our occidental population, and can be compared with nonletters; that is, drawings. Their analysis necessitates perceptive abilities for nonverbal material. In this task, the participants have to decide if two "words" of three or four Thai characters are the same or different. In different pairs, only one character is changed and the difference between two characters is rather small. Twenty pairs of words were presented (10 identical and 10 different). The participants were given one point for each correct answer. Working memory was tested with the forward and backward digit span (Wechsler, 1987) and Corsi blocks tests (Milner, 1971). Planning aspects were assessed through a modified version of the Tower of London Test (Shallice, 1982). Attention was evaluated through a cancellation task, the d2 Test (Brickenkamp, 1981) in which the patients had to cancel as many targets as possible among other signs in a given time.

For correlation analyses with number processing, each cognitive function received a global score. Language capacity was measured in each patient by computing a total score on the battery described above. The number of correct matching of Thai words, as well as the performance in Albert's Test reflected visuospatial abilities. Working memory included both forward and backward digit span and Corsi blocks tests. The number of trials needed to complete the Tower of London Test quantified planning abilities. The number of correct responses at the d2 Test was used to measure attention factors. These different variables were

Table 2. Summary of the participation of the different tests of the battery to comprehension, production, and quantity (semantic) representation of numbers in the three main numerical notational systems: digital, oral, and alphanumerical-orthographic number forms[a]

Codes	Tests for number comprehension	Tests for number production	Tests for semantic representation
Digital	Positioning on scale Digit reading Transcoding: 1 ⇒ one written operations	Dictation of digits Dots counting Written operation	Positioning on a scale in digital code
Oral	Oral comparison Dictation of digit Mental calculation	Digit reading Dots counting Backwards counting Mental calculation	Comparison of 2 numbers in oral code
Alphanumerical	Alphanumerical comparison	Transcoding from 1 ⇒ one	Comparison of 2 numbers in alphanumerical code

[a]Lurias' problems, numerical knowledge, and perceptive estimation of quantities are not represented in this table (see text and Appendix I for more details).

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correlated to performances in oral, digital, and alphanumerical number processing by means of correlation and partial correlation analyses.

Raw Data Transformations, Preliminary Analyses, and Design of Data Analysis

Raw data was used for all patients. The maximum score for each subtest is given in the Appendix I, describing the battery. A first global score was calculated for each patient, by summing the scores of each subtest (maximum is 139). Further description of performances and statistical analysis used a relative score (max = 1) by dividing patient's score by the maximum score available per task. The raw data sets of each task were transformed by arc sine function (a usual transformation following the binomial model of measurement). Transformed arc sine values were summed up over tasks to obtain the different composite scores; for example, performances in digital code (DC), composed of digital comprehension and digital production, or in oral code (OC), composed of oral comprehension and oral production. Additional power transformations were applied to the data in order to ensure homogeneity of variances over groups through stabilizing variances. Raw data was not standardized on the basis of normal participants score because reference norms were not available for all languages. However, an analysis undertaken on the French-speaking subgroup using *Z* score showed comparable results.

To investigate the role of lesions on verbal and digital number processing, the transformed variables were analyzed by a $2 \times 2 \times (2)$ analysis of variance, side (left *vs.* right hemisphere) and site (parietal *vs.* nonparietal areas) of the lesion being 2-level between subjects factors, modality (digital *vs.* oral processing) being a 2-level repeated measures within subjects factor. In function of the hypotheses, the full set of interactions (double and triple) were calculated. To investigate the role of the parietal lesions on numerical-semantic representations and on knowledge of arithmetical facts, a nonparametric comparison (Mann–Whitney) was undertaken between performances of patients with parietal and nonparietal lesions in the relevant tasks. This same analysis was used to compare the left subcortical and left non-subcortical groups.

RESULTS

The final selected subpopulation included 49 fully examined right-handed patients with a postonset delay between 3 and 18 months. There were 33 left hemisphere (LH) lesions and 16 right hemisphere (RH) lesions. The patients were divided in four groups according to the side of the lesion and according to the involvement or not of the parietal areas (Table 3). No patient scored the maximum. However, patients' general performances were relatively high: 12 patients (first quartile) scored between 130 and 137 out of a maximum of 139, 12 (second quartile) patients scored between 118 and 129, 12 (third quartile) scored between 90 and 117, and 13 (fourth quartile) between 65 and 90 points.

Table 3. Lesion localization of the selected subpopulation of the 49 right-handed patients with only one vascular brain lesion and a poststroke delay of < 18 months[a]

Localization	Left hemisphere	Right hemisphere
Frontal	1	1
Frontoparietal*	3	2
Frontotemporal	4	1
Frontoparietotemporal*	2	8
Temporal	1	1
Temporoparietal*	4	0
Temporo-occipital	3	0
Parietal*	6	0
Parieto-occipital*	1	1
Occipital	1	1
Basal ganglia-thalamus	7	1
Total	33	16

[a]Localizations with an * belong to the "parietal" group, the others to the "nonparietal" group.

Influence of Side and Site of Lesions on Number Processing

General performances

All groups of patients were impaired in every task of the battery (Table 4 and 5), except for the nonparietal right lesion patients, who scored well in most calculation tasks. Patients with left parietal lesion were generally the more impaired group, except for perceptive tasks (putting number on a scale and perceptual estimation), in which right parietal lesion patients had the most difficulties. The most discriminating tasks concerning left parietal lesions were the backward counting and the mental calculation, where left parietal lesion patients were significantly more impaired than at least one of the other group (Scheffé procedure $p < .05$). Alphanumerical number processing was specifically tested by transcoding from digit to written words (production) and comparing written words in alphanumerical codes (comprehension). In contrast to digital and oral number processing (see below), there was no effect of the site of lesion neither in comprehension nor in production: parietal involvement of the lesion did not burden the performances of the patients in alphanumerical code. There was an effect of the side of lesion on production [$F(1,45) = 6.41$, $p = .015$], left hemisphere lesion patients having lower scores.

Oral/digital dissociation

To study specific calculation modalities, tasks involving specific and nonoverlapping oral and digital processing performances were further analyzed and compared in function

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Table 4. Performances in each specific task of the calculation battery EC301 according to brain lesions[a]

Localization	Dot numeration	Backward counting	Transcoding digit dictation	Mental calculation	Transcoding digit reading	Number on a scale
L.NP. (17)	0.96 (0.11)	0.79 (0.40)	0.79 (0.25)	0.84 (0.20)	0.83 (0.23)	0.94 (0.09)
L.P. (16)	0.79 (0.34)	0.56 (0.44)	0.55 (0.29)	0.57 (0.33)	0.69 (0.39)	0.89 (0.25)
R.NP. (5)	1.00 (0.00)	1.00 (0.00)	0.93 (0.09)	0.96 (0.29)	1.00 (0.00)	1.00 (0.00)
R.P. (11)	0.71 (0.41)	1.00 (0.00)	0.72 (0.28)	0.83 (0.29)	0.88 (0.15)	0.73 (0.24)
Total (49)	0.86 (0.28)	0.69 (0.42)	0.68 (0.30)	0.72 (0.30)	0.80 (0.28)	0.86 (0.24)
Controls	*.97*	*.97*	*.99*	*.97*	*>.97*	*.96*

Localization	Oral number comparison	Perceptual estimation	Contextual judgement	Operations	Luria's problem	Transcoding 1 ⇒ One	Alphanumeric comparison
L.NP. (17)	0.95 (0.09)	0.84 (0.15)	0.89 (0.18)	0.71 (0.30)	0.59 (0.36)	0.67 (0.32)	0.87 (0.17)
L.P. (16)	0.83 (0.14)	0.91 (0.20)	0.90 (0.13)	0.62 (0.36)	0.27 (0.41)	0.52 (0.39)	0.83 (0.18)
R.NP. (5)	0.99 (0.03)	0.95 (0.11)	1.00 (0.00)	0.85 (0.12)	0.85 (0.27)	0.90 (0.15)	0.98 (0.06)
R.P. (11)	0.95 (0.11)	0.59 (0.41)	0.91 (0.19)	0.55 (0.27)	0.50 (0.33)	0.63 (0.34)	0.76 (0.25)
Total (49)	0.85 (0.19)	0.85 (0.20)	0.91 (0.14)	0.62 (0.36)	0.44 (0.40)	0.66 (0.36)	0.84 (0.20)
Controls	*> .97*	*.93*	*.97*	*.91*	*No data*	*.97*	*.97*

[a]The numbers represent the mean relative performance (standard deviation) of each subgroup of patients out of a maximum of 1. The first column describes the groups and their size (number of patients). P refers to parietal lesions. NP refers to nonparietal lesions. L and R mean, respectively, left and right. A last line, not used for statistical comparison, correspond to the mean result obtained in a population of healthy French controls and is given as an indication of the difficulty of the task (see Dellatolas 2001, for detailed results).

of side and site of lesion (Figure 1). Specific digital processing included positioning on a scale, transcoding from digital to alphanumeric forms (1 ⇒ one) and digital operations. Specific oral processing included oral comparison between two numbers, mental calculation, and backward counting. Analyses revealed a significant main effect of side of lesion [$F(1,45) = 6.25$, $p = .016$] on number processing; right hemisphere lesion patients showed overall better performances than left hemisphere lesion patients. Effect of site of lesion was also significant [$F(1,45) = 10.30$, $p = .002$], patients with lesions involving parietal areas being more impaired than patients without parietal involvement. There also was a better performance in oral than digital modality [$F(1,45) = 13.96$, $p = .001$]. Interaction analysis between side and modality [$F(1,45) = 4.78$, $p = .034$] showed that right hemisphere lesion patients had better performances in oral number processing than left hemisphere lesion patients, while digit number processing did not dissociate both sides. A significant three-way interaction [Site × Side × Modality: $F(1,45) = 4.11$, $p = .049$] was linked to the fact that parietal lesions led to poor performances regardless of the side of the lesion, but oral performance was more impaired by left parietal lesion.

Semantic Representations

Numerical semantic representations were compared in parietal and nonparietal lesions (Dehaene & Cohen, 1997), using oral number comparisons for the oral code, positioning of an Arabic number on a scale for the digital code, and

Table 5. Performances of each group of brain lesion patients with the different codes of number processing[a]

Localization	Oral comprehension	Oral production	Digit comprehension	Digit production	Orthographic comprehension	Orthographic production
L. NP. (17)	.86 (.14)	.86 (.15)	.79 (.18)	.82 (.17)	.87 (.17)	.67 (.32)
L.P. (16)	.65 (.22)	.65 (.27)	.68 (.24)	.66 (.22)	.83 (.18)	.52 (.39)
R. NP. (5)	.96 (.06)	.99 (.01)	.94 (.05)	.93 (.03)	.97 (.06)	.90 (.15)
R. P. (11)	.85 (.19)	.80 (.22)	.75 (.19)	.68 (.17)	.76 (.25)	.63 (.26)
Total(49)	.77 (.22)	.79 (.28)	.75 (.23)	.73 (.24)	.84 (.20)	.66 (.26)

[a]See Table 1 for description of the tasks involved in each column. The numbers represent the mean relative performance (standard deviation) of each subgroup of patients out of a maximum of 1. The first column describes the groups and their size (number of patients). P refers to parietal lesions. NP refers to nonparietal lesions. L and R mean, respectively, left and right.

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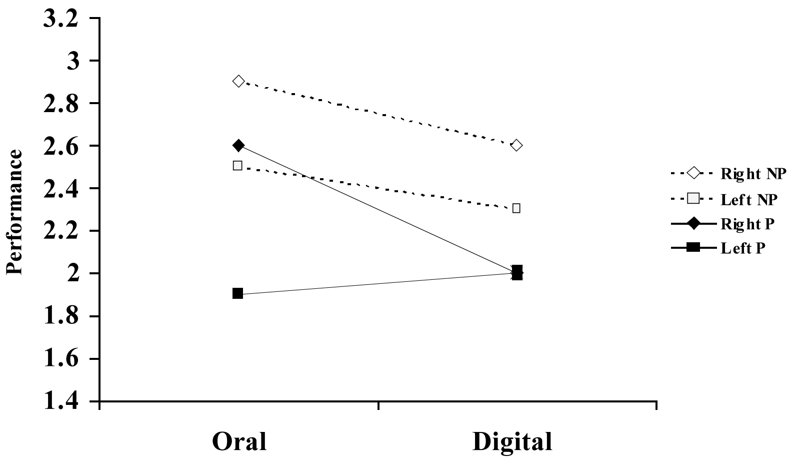

Fig. 1. Performances of brain-damaged patients in verbal and digital code. Number represent compound scores (see text). NP means patients with nonparietal lesion, P means patients with parietal lesions. The significant interaction is due to the fact that left parietal lesions affect both verbal and digital processing while right parietal lesions affect only digital processing.

comparison of orthographically written numbers for the alphanumerical code (see Table 2). Oral comparison was more impaired in parietal than in nonparietal patients (Mann–Whitney $= -1.97$; $p = .049$, see Table 6). Since parietal lesions included also the large fronto-temporo-parietal lesions, we could not exclude that the effect was related to the size of the lesions rather than to its location. We therefore analyzed the effect of frontal involvement as a control. In this complementary analysis, the "frontal group" was composed of all lesions with frontal involvement (fronto-temporal, fronto-parietal, and fronto-parieto-temporal lesions), such that all the larger lesions, previously included in the "parietal group", were now in the "frontal group" . We thought that if size of the lesion alone explained the impairment of the parietal group in the oral comparison task, the same effect would be observed in the frontal patients. In fact, this was not observed either in oral comparison, or in positioning of an Arabic number on a scale, or in comparison of orthographically written numbers (Mann–Whitney; $p > .5$ in all three tasks). Consequently, the impairment of parietal patients on oral comparison cannot be explained solely by the size of lesion and the parietal region must play an essential role in this difference.

To test Dehaene and Cohen (1997)'s hypothesis concerning the brain structures implicated in the processing of rote arithmetical facts, we calculated the mean relative performances of the group with left subcortical lesion and of the group with left parietal lesion on simple mental calculation. Scores were comparable in left lesion patients with subcortical (mean $= .71$; $SD = .32$) and without subcortical involvement (mean $= .72$; $SD = 24$) {Mann–Whitney, $z = -.95$, $p = .922$}. Moreover, mental calculation was more impaired in left parietal patients (mean $= .575$; $SD = .33$) than in left nonparietal patients (mean $= .84$; $SD = .2$), this difference being significant (Mann–Whitney, $z = -2.6$, $p = .01$).

Relation Between Number Processing and Other Cognitive Functions

Language performance was highly correlated to all categories of number processing (all Spearman correlation coefficients being greater than .62, $p < .001$). Therefore we attempted to account for the language effects by partial correlation in order to show specific relationships with the other cognitive functions. The results are presented in Table 7. The strongest patterns of correlation emerged between verbal working memory and oral number processing on one hand, and between spatial working memory and digital processing on the other. This effect was present in both direct and inverse conditions of digit and spatial span. Visuospatial, attentional, and planning deficits did not show a consistent correlation with specific number processing. In particular, spatial neglect as measured by line bisections was not consistently related to performances in digital processing.

Table 6. Mean performances (standard deviations) of patients with parietal and nonparietal lesions in the three tasks measuring magnitude comparisons and numerical-semantic representations[a]

Tasks	Parietal ($N = 27$)	Nonparietal ($N = 22$)	Statistical difference (M–W)
Oral comparison	14.1/16 (2.2)	15.3/16 (1.3)	-1.97; $p = .049$
Positioning on a scale	8.2/10 (2.6)	9.5/10 (.8)	-1.31; $p = .19$
Alphanumerical comparison	12.8 (2.6)	14.3 (3.3)	-1.56; $p = .12$

[a]Statistics between the parietal and the nonparietal have been carried out with the Mann–Whitney non-parametrical test (M–W).

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Table 7. Partial correlations between performances in cognitive tasks and specific number processing[a]

Cognitive tasks	Oral comprehension	Oral production	Digit comprehension	Digit production	Alphabetic comprehension	Alphabetic production
Verbal span	.37; p = .004	.30; p = .016	.02; p = .42	.13; p = .18	.24; p = .04	.07; p = .32
Inverse verbal span	.44; p = .001	.32; p = .012	.25; p = .04	.10; p = .12	.07; p = .31	.26; p = .03
Visual span	.08; p = .30	.08; p = .30	.33; p = .01	.43; p = .001	.42; p = .002	.41; p = .39
Inverse visual span	.04; p = .40	.01; p = .43	.28; p = .03	.32; p = .02	.35; p = .01	.01; p = .47
Fig. Thai	.10; p = .23	.27; p = .42	.16; p = .13	.38; p = .003	.39; p = .002	.20; p = .07
Lines sections	.23; p = .054	.10; p = .23	.10; p = .23	.13; p = .18	.11; p = .22	.13; p = .17
London Tower	.05; p = .36	.08; p = .30	.12; p = .20	.14; p = .17	.05; p = .36	.09; p = .27
D2 cancel task	.13; p = .19	.08; p = .28	.17; p = .12	.15; p = .46	.29; p = .02	.21; p = .08

[a]Because of the high correlation of language with all codes of number processing, this variable has been used to partialize the Spearman correlation's test between calculation and the other cognitive tasks. The underlined values indicate $p < .05$.

DISCUSSION

Inclusion Criteria: Role of Handedness and Postonset Delay on Number Processing

The different steps that were necessary in obtaining a homogeneous group are related to some general considerations in neuropsychology. As language studies have shown some effect of handedness on cerebral organization (Carter et al., 1980), we considered handedness as a crucial variable from the beginning. According to a fMRI study in normal participants, left handedness has been shown to induce more bilateral frontal activation in calculation tasks than right handedness, suggesting some differences in anatomo-functional organization (Burbaud et al., 1995). In our population, *a posteriori* observation gave the impression that non-right-handed patients were slightly less impaired than right-handed patients. Statistics were not applied because of the small number of non-right-handed patients. Influence of postonset delay was taken into account, revealing that the patients with an older cerebral lesion differed significantly from the patients with a more recent cerebral lesion. Similar findings have already been reported in aphasia, where some aspects of language showed better recovery than others (Kertesz, 1977). This result could be consistent with a modular model of number processing where the pattern of recovery could be different for each calculation subcomponent. However, a longitudinal study would be necessary to characterize patterns of recovery.

Effects of Parietal Lesions on Oral, Digital, and Alphanumerical Code

Previous group studies with patients (Grafman et al., 1982; Hécaen et al., 1961; Jackson & Warrington, 1986) have pointed to the role of parietal, especially left, areas in calculation disorders. However, these studies did not separately compare performances in the different codes (oral, digital, alphanumerical). An important result of our study is the lack of sensitivity of the alphanumerical code to parietal lesions: neither transcoding from digits to orthographically written numbers nor comparing orthographically written numbers were impaired by such lesions. On the other hand, parietal lesions selectively affect tasks using verbal and digital codes. This difference is consistent with a degree of independence between number-related (digital and oral) and more language-related (alphanumerical) aspects of numbers. A clear demonstration of this independence is the description of pure Gerstmann's syndrome (GS) (Mayer et al., 1999; Roeltgen et al., 1983), where calculation is affected while language is not. In such pure GS, left inferior parietal area was implicated (Benton, 1977; Mayer et al., 1999). On the contrary, some patients show preserved numerical and digital abilities despite severe aphasia (Dehaene & Cohen, 1991) or agraphia (Anderson et al., 1990). Dahmen et al. (1982) found that Broca's aphasics, whose disorders of calculation were mainly related to linguistic factors, have nonparietal lesions, while Wernicke's patients, whose calculation impairments were more related to spatial "nonlinguistic" components, have parieto-temporal lesions. These results are in accordance with the dissociation found in our patients between parietal and nonparietal lesions. We suggest that digital and oral codes may rely on different cognitive abilities. Furthermore, the specific implication of parietal areas to digital processing without implication of "classical" language areas (Wernicke's, Broca's, angular and supramarginalis gyri) has been shown in normal population with activation studies (Dehaene et al., 1996; Pesenti et al., 2000).

Differential Role of Left and Right Parietal Lesions on Oral *Versus* Digital Code

Another main result of our study concerns the differential role of both parietal areas in number processing. Left parietal lesions affect both oral and digital codes, while right parietal lesions impair only digital processing. What is the reason for such dissociation?

It could be that exact mathematical thinking, as tested for example by oral arithmetical operation, necessitates intact linguistic competences (Dehaene et al., 1999). However, this explanation would then also apply to the digital code, since tasks like digital operations also use exact arithmetic algorithms and therefore should also be more sensitive to left than to right brain lesion. This was not the case in our study. Moreover, oral comparison, which relies on a non-linguistic sense of numerical magnitudes, is more impaired in patients with left brain lesions. One reason that can be postulated for this strong sensitivity of both codes to left parietal lesions is the role of verbal working memory. In fact, the tasks used in our analysis of oral code performances were backward counting, oral number comparison, and mental operations. Although these tasks differ widely in the sense that cognitive processes rely respectively on mental control (backward counting), semantic representations (oral comparison), and arithmetic procedures (mental operations), all necessitate transient storage of oral information (Stone et al., 1998); that is, verbal working memory. This phonological store has been shown to involve the left supramarginal gyrus in the inferior parietal lobe (Paulesu et al., 1993). In an experimental study with healthy participants, where they manipulated the phonological and the visual similarities of two numbers to be added, Noël et al. (2001) showed that the phonological loop played a major role in mental addition, whereas the visual-spatial sketch pad did not seem to be particularly involved. Thus, a verbal recoding of Arabic digits presented visually took place. We suggest that, in our patients, the impairment of the phonological loop in the case of left parietal lesions is a common difficulty that impairs oral as well as digital calculation tasks. The strong correlation between inverse digit span and oral numerical code processing as well as digital comprehension tasks supports this hypothesis.

Two factors can explain the specific sensitivity of digital codes to right parietal lesions. The first is tied to the visuo-perceptive difficulties that are present in right brain lesions. Neglect, for example, is known to impair specifically spatial-sensitive components of digital processing, producing spatial dyscalculia (Ardila & Rosselli, 1994; Hécaen et al., 1961). Even if the presentation of the tests was ipsilateral to the cerebral lesion, we cannot exclude the influence of spatial factors (as in object centered neglect or in spatial disorganization). Indeed, some of our patients with strong neglect showed spatial dyscalculia. However, visuo-perceptive impairment does not seem to be a sufficient condition to impair digital processing: for example, one of our patients with a clear neglect did not have any difficulties in digital code. Furthermore, we did not find in our group any correlation between neglect in line bisections task and digital processing. Finally, a visuo-perceptive origin to digital processing impairment should produce a correlation between digital comprehension and some perceptive task like "fig Thai", which was not the case. Therefore, spatial neglect and visuo-perceptive deficit are not sufficient to explain the specific impairment of digital processing by right parietal lesion. Another explanation could be that the right hemisphere has a dominant role for processing digits. This hypothesis has been suggested by Seron (1993), who commented on performances of alexic patients (Holender & Peereman, 1987), and received some support through recent positron emission tomography (PET) studies suggesting that the right fusiform gyrus is implicated in digit identification processes (Pinel et al., 1999). In an experimental visual half-field study with healthy participants, Ratinckx et al. (2001) also obtained some evidence for a left visual field/right hemisphere advantage in processing digits. In our study, the fact that the digital code was impaired in the right parietal group brings further arguments for a specific role of right parietal structure in the digital code processing.

Since our population comes from different countries, it is not possible completely to rule out linguistic interference on these results. Indeed, Dellatolas et al. (2001), using the same E301 battery, reported difference in calculation performances between German, French, and Italian normal participants. For example, French participants made more errors than Italian participants on subtests of verbal counting, enumeration of dots, and mental calculation. Italian participants were relatively low for subtests involving magnitudes, that is, number comparison and estimation of quantities while performances in transcoding were equal across language. It was supposed that linguistic factors, such as complexities of the French verbal code for numbers (e.g., 70 is "soixante-dix", i.e., sixty-ten; 80 is "quatre-vingts", i.e., four-twenty), could possibly be involved in the counting and calculation problems of French-speaking participants. Thus, linguistic factors could provoke some differences in calculation performances between the French-speaking group on one side, and the Spanish- and Portuguese-speaking groups on the other, the latter sharing a similar linguistic system for numbers with Italians. However, we think that these factors do not play an essential role in our patients' results. An analysis of our population showed that the different linguistic groups were homogeneously represented in the affected side. Among the 33 left brain lesioned patients, 27 (82%) spoke French, four (12%) spoke Portuguese, and two (6%) spoke Spanish. Among the 16 right brain lesioned patients, 13 (81%) spoke French, two (12%) spoke Portuguese, and one (6%) spoke Spanish ($\chi^2 = .02$, $p = .99$). The same homogeneity was present across sites. In the 27 patients with parietal lesion, 22 (81%) spoke French, three (11%) spoke Portuguese, and two (7%) spoke Spanish. In the nonparietal group (total 22 patients), 18 (82%) are French, three (13%) are Portuguese and one (5%) is Spanish ($\chi^2 = .225$, $p = 0.89$). Thus, the present results cannot be attributed to an overrepresentation of one language in the left–right and parietal–nonparietal dimensions. Nevertheless, the predominance of French-speaking patients may influence the results in favor of a specific French pattern of calculation impairment. Further research is needed to resolve this particular point.

Finally, educational factors are also important to consider. Dellatolas (2001) has shown a significant schooling effect in counting backwards, in number transcoding involving a written response, in number comparison especially in alphabetical presentation, in mental calculation, and in written subtractions and multiplications (but not additions). As for linguistic factors, the different schooling levels are homogeneously represented in the affected side groups. Among the 33 left brain lesioned patients, ten (30%) have a low, 12 (37%) an intermediate, and 11 (33%) a high educational level, while among the 16 right brain lesioned patients, six (37.5) have a low, four (25%) a medium, and six (37.5%) a high educational level ($\chi^2 = .65$, $p = .72$). In regard to the site of brain damage, among 27 patients with parietal lesion, six (22%) have a low, nine (33%) an intermediate, and 12 (44%) a high level of education. In the nonparietal group (total 22 patients), ten (45%) have a low, seven (32%) an intermediate, and five (23%) a high level of education ($\chi^2 = 3.6$, $p = .16$). Even if the distribution across parietal–nonparietal dimension is less homogeneous, the difference is nonsignificant. Consequently, the present results cannot be attributed to an overrepresentation of one schooling level in the left–right and parietal–nonparietal dimensions—the level of schooling does not influence our results in a major way.

Role of Parietal Lobes in Semantic Representation of Numbers

Patients with parietal lesions were impaired in number comparison in oral code. This confirms the predominant role of parietal areas in numerical-semantic representations shown by activation studies (Dehaene & Cohen, 1997; Pesenti et al., 2000; Pinel et al., 1999). The difference was not significant in two other tasks aiming to evaluate representation of numbers such as the digital (positioning a given digit on a scale) and alphanumerical (comparison of orthographically written numbers) conditions, where only trends could be seen. Further studies should be done to confirm these trends.

Rote Arithmetical Facts

Parietal lesions, but not left subcortical lesions, impaired specifically mental calculations. These results are in accordance with those of Whalen et al. (1997) who, on a single case study with cortical stimulation, showed that arithmetical processes, and particularly multiplication tables, necessitate integrity of the left parietal areas. In the same direction, fMRI studies show that operations such as simple additions necessitate activation of both precentral and parietal areas (Pesenti et al., 2000). Our data are in contradiction with the assumption that knowledge of rote arithmetical facts is supported by anterior left subcortical pathways (Dehaene & Cohen, 1997, p. 240). In fact, these later authors modified somewhat their point of view (Cohen et al., 2000). They dissociated multiplication and additions/subtractions and concluded that only multiplications are solved by retrieving stored verbal sequences. In the same line, Lee (2000) showed that mental calculations are subserved by different cognitive processes and different anatomical areas. Recently, a patient with left supramarginal and angular lesion was reported to have impaired subtraction but preserved mental multiplication (van Harskamp et al., 2002), supporting such a hypothesis. So the question remains open. In our study, we did not dissociate the different operations, so we are unable to discriminate the differential effect of addition, subtraction and multiplication on number processing. Other group studies focused on this question are needed.

Correlation Between Oral and Digit Calculation with Verbal and Spatial Working Memory

The highly significant correlation between oral calculation production and verbal working-memory performance as well as written-digit calculation and visuospatial working memory confirms the dissociation between both codes. This cannot be attributed exclusively to the "linguistic" (for verbal code) and "spatial" (for digital code) aspects of the tasks. We have seen that working memory correlates better with oral than with alphanumerical processing, the latter being considered more specifically language related, and that digital processing does not correlate with visuospatial tasks. Our results suggest that numerical abilities are code specific (Clark & Campbell, 1991; Noël & Seron, 1993) and rely on different modalities of working memory. As was told just before, the different mental operations were analyzed as a whole in the present study, and thus an eventual role of verbal and visual aspects of working memory on multiplication and addition (Lee & Kang, 2002) cannot be demonstrated. Nevertheless, our results show on a group basis that working memory is not marginal in calculation skills, as was stated by other authors on the basis of single case observations (Butterworth et al., 1996; Cipolotti & van Harskamp, 2001).

In conclusion, the results obtained with the EC301 battery support current data and hypotheses on arithmetic functions and the brain. Particularly, they confirm the role of parietal areas in number and magnitude representations, as well as the importance of the right hemisphere for accessing digital representations. They also add some evidence for the role of working memory in manipulation of numbers. Finally, they suggest an important role of left parietal areas even in simple arithmetical facts. Moreover, the battery for number processing makes it possible to find differences and dissociations in number processing depending on side and site of the lesions, and can be considered as a valuable tool for testing and screening calculation abilities in patients with focal brain lesion.

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APPENDIX I: TASKS USED IN THE SHORTENED VERSION OF THE CALCULATION EC301 BATTERY

Task Evaluating the Components Dealing with Comprehension and Production of Numbers

Enumeration of dots

Counting the number of elements in arrays is one of the most basic and natural numerical activities. The patient has to count 8, 10, and 11 dots drawn pseudorandomly on an A4 sheet. In such task, brain damaged patients may be wrong for different causes: visual hemineglect, memory impairments which would alter the knowledge of already-counted and the to-be-counted dots and aphasic symptoms (verbal paraphasias). For each item, correct response produced in spoken verbal numbers were scored 2 points, but only 1 point was attributed when delivered in another numerical system or on a second trial (maximum: 6 points).

Oral backward counting

The production of the sequence of number words (from 20 to 1 in the EC301) is an example of an automated verbal process. Counting backwards is supposed to be under the control of the working-memory system. Correct responses

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were scored 2 points per item. When subjects had difficulties in responding, they were given a second trial and given 1 point in case of success (maximum: 2 points).

Numerical transcodings

Transcoding refers to the process associating a given representation in some source code (e.g., the Arabic number "205") to the corresponding representation in some other notational system (e.g., the written verbal number "two hundred and five"). For the transcoding from digit to orthographically written numbers, the following items were used: 1430, 2015, 800 000, 113, 96 and 27 319 (maximum 12). For digit dictation, patients were asked to write: 1350, 4012, 700 000, 115, 286 and 35 819 on a sheet of paper.

Reading aloud (i.e., transcoding written forms into spoken forms) is a common example of such cognitive verbal abilities; the items to be read are 1 320, 4016, 500 000, 112, 685 and 32 217.

Scoring: Two points for a correctly transcoded item. The examiner could present a second time the entire number on request of the participant, but correct answer following stimulus repetition received 1 point instead of 2 points (maximum: 12 points for each transcoding task).

Mental calculations

These subtests aimed at evaluating number facts in order to disentangle calculation errors due to handling erroneous procedures from those originating from impaired knowledge of arithmetical facts. Participants are told to mentally calculate $5 + 8$, $9 + 7$, 7×4, 3×8, $17 - 5$, $14 - 6$, 18:3, and 16:2. Patients were given 2 points for each correct operation. A correct answer following stimulus repetition received 1 point instead of 2 points (maximum: 16 points).

Placing numbers on an analogue number line (scale)

The task evaluated number comprehension using a vertical analogue numerical scale representing an interval from 0 to 100. Numbers were presented in Arabic digits: 56, 86, 32, 5, 63 and the participants had to choose between 6 possibilities. Scoring: 2 points for each correct answer (maximum: 10 points).

Magnitude comparisons

The task aimed at evaluating number comprehension processes in two different numerical systems, verbal and orthographically written, since these processes may be disrupted independently. For oral comparison the participant had to decide the bigger item between 200 000 and 100 36; 11 000 and 1040; 967 and 3052; 86 and 101; 1033 and 865; 15015 and 20 040; 130 and 800; 54 000 and 17 000. Similar numbers were given in the orthographically presented items. Patients were given 2 points for each correct response. A correct answer following stimulus repetition received 1 point instead of 2 points (maximum: 16 points).

Written calculation

The operations were selected in order to investigate how the participants mastered the sequence of procedural actions involved in written calculations, namely the conventional spatial processing of the operations on pairs of digits (as intermediary operations and results to be written down). Given the above-mentioned dissociations between calculation procedures and number facts, the items of these subtests were constructed in such a way that the number facts involved in the operations should be sufficiently easy. The operations were $708 + 694$; $457 + 678$; $573 - 246$; $920 - 312$; 542×23; 687×305. Patients were given 2 points for each correct response. A correct answer after correction received 1 point instead of 2 points; in multiplication, 1 point was given for each intermediary result and one for spatial adjustment of each line (maximum for the six operations: 15 points).

Test not Directly Applying to MacCloskey's Model

Contextual magnitude judgements and numerical knowledge

The task evaluates the ability to give a semantic interpretation of numbers in contextual situations where their relative semantic magnitudes do not necessarily follow their numerical values. Subjects had to decide if 20 pages for a letter, 9 children for a class, 35 travelers in a bus, 8 dishes in a restaurant, and 9 children for a present day family were little, normal, or much. Patients were given 2 points for each correct response. A correct answer following stimulus repetition received 1 point instead of 2 points (maximum: 10 points).

Perceptive estimation of quantities

This task explores the ability of participants to perform numerical estimations of visual patterns, such as a number of balls on a page, the height of a plant, and the weight of person presented on a picture. Pictures were presented during a short period of time (5 s). The distribution of responses provided by controls was analyzed, and the central values (< 1.5 *SD*) received 2 points per item. The marginal values were scored 1 point and the values situated at the two extremes of the statistical distribution (> 2 *SD*) were scored 0 points (maximum: 6 points).

Luria's problems

In this task, two problems are given, dealing with the logical analysis and resolution of a mathematical operation. The following questions were given: (1) John earns 6000 francs and Peter earns 2000 francs more than John. How much do both together earn? A second similar problem was given dealing with the age of members of a family. A correct answer following stimulus repetition received 1 point instead of 2 points (maximum: 4 points).

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Percent of subjects with the maximum score in each test by country and education (from Dellatolas, 2001, Annexe 2)

	France			Italy		
Edu*	1	2	3	1	2	3
N	60	60	60	59	58	55
c1 (counting)	78.3	90.0	96.7	93.2	96.5	98.2
c7 (dots counting)	88.3	90.0	96.7	88.1	96.5	94.5
c10 (Trans 1 ⇒ One)	88.3	95.0	100	88.1	94.8	100
c11 (Reading)	95.0	95.0	98.3	94.9	98.3	98.2
c14 (dictation of digit)	98.3	96.7	98.3	71.2	86.2	90.9
c19 (comparison, alphanumerical)	68.3	85.0	91.7	54.2	60.3	70.9
c20 (mental calculation)	71.7	71.7	88.3	89.9	84.5	92.7
c24 (placing number on a scale)	83.3	88.3	91.7	71.2	70.7	67.3
c26 (written addition)	85.0	90.0	90.0	83.0	86.2	89.1
c27 (written subtraction)	76.7	91.7	90.0	81.4	94.8	89.1
c28 (written multiplication)	56.7	70.0	65.0	49.2	63.8	72.7
c29 (perceptual estimation)	66.7	58.3	81.7	61.0	60.3	49.1
c30 (numerical judgement)	88.3	91.7	95.0	79.7	81.0	89.1

*Education: 0 = less than 5 years; 1 = 5 to 8 years; 2 = 9 to 12 years; 3 = more than 12 years. Score in Luria's problem are not reported.

APPENDIX II: SUMMARY OF THE DIFFERENT COGNITIVE TASK CORRELATED WITH THE PERFORMANCES IN NUMBER PROCESSING

Test	Maximum score	Function
Repetition of words	10	Language
Repetition of nonwords	5	
Dictation of words	10	
Dictation of nonwords	5	
Reading of words	10	
Reading of nonwords	5	
Oral comprehension (word-image match)	5	
Oral comprehension (simple orders)	3	
Oral complex orders (complex orders)	3	
Written comprehension (word-image match)	5	
Written comprehension (simple orders)	3	
Written complex orders (complex orders)	3	
Comparison of thai characters.	20	Visuospatial
Line Bisection Test	40	Abilities
Tower of London (four different trials)	18	Planning
Sustained attention (D2 test)	Correct answers minus errors	Attention
Direct verbal span	Raw scores	Working memory
Inverse verbal span	Raw scores	
Direct spatial span	Raw scores	
Inverse spatial span	Raw scores	

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