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SPATIAL ACALCULIA

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Twenty-one patients with right hemisphere damage were studied (11 men, 10 women; average age = 41.33; range 19–65). Patients were divided into two groups: pre-Rolandic (six patients) and retro-Rolandic (15 patients) right hemisphere damage. A special calculation test was given. Different types of calculation errors were analyzed. Spatial alexia and agraphia for numbers, loss of calculation automatisms, reasoning errors, and general spatial defects interfering with normal number writing and reading, were observed. Number processing was impaired, whereas the calculation system was partially preserved. Fact retrieval and procedural difficulties were observed, but arithmetical rules were properly used. It is concluded that calculation abilities in right hemisphere damaged patients are disrupted as a result of: (1) visuospatial defects that interfere with the spatial arrangement of numbers and the mechanical aspects of mathematical operations: (2) inability to recall mathematical facts and appropriately to use them; and (3) inability to normally conceptualize quantities and process numbers.

Keywords: acalculia, right hemisphere.

Henschen (1925) introduced the term "acalculia" to refer to the impairments in mathematical abilities in case of brain damage. Berger (1926) distinguished two different types of acalculia: primary and secondary acalculia. Secondary acalculia refers to a calculation defect resulting from a different cognitive deficit: memory disorders, attention impairments, language defects, spatial deficits, etc. Gerstmann (1940) proposed that acalculia is observed together with agraphia, disorders in right-left orientation, and finger agnosia, conforming the basic brain syndrome usually known as "Gerstmann syndrome."

Boller and Grafman (1983, 1985; Grafman, 1988) consider that calculation abilities can be disrupted as a result of: (1) inability to appreciate the meaning of the number names; (2) visuospatial defects that interfere with the spatial arrangement of numbers and the mechanical aspects of mathematical operations; (3) inability to recall mathematical facts and appropriately use them; and (4) defects in mathematical thinking and in understanding underlying operations. And, it could be added, (5) inability to conceptualize quantities (numerousness) and invert operations (e.g., adding—subtracting).

Hécaen, Angelergues and Houiller (1961) distinguished three types of calculation disorders: (1) alexia and agraphia for numbers, (2) spatial acalculia, and (3) anarithmia (or anarithmetia). Spatial acalculia represents a disorder of spatial organization where the rules for setting written digits in their proper order and position are not followed; spatial neglect and number inversions are frequently found.

Ardila and Rosselli (1990) have proposed a classification of acalculias. A basic distinction between anarithmetia (primary acalculia) and acalculia resulting from other cognitive defects (secondary acalculias) is included. Secondary acalculias may result from linguistic defects (oral or written), spatial deficits and frontal-type disturbances, particularly, perse-

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veration, memory, and attentional impairments. There is, however, certain overlapping among the acalculia subtypes proposed by Ardila and Rosselli. Thus, in anarithmetia some spatial deficits can be observed; spatial acalculia associated with right hemisphere pathology is also partially an alexic acalculia (e.g., some inability to read complex numbers as a result of left hemi-neglect can be observed) (Rosselli & Ardila, 1989).

A general cognitive model of number processing and calculation has been proposed by McCloskey and colleagues [McCloskey, Aliminosa & Sokol, 1991; McCloskey, Caramazza & Basili, 1985; McCloskey & Caramazza, 1987; McCloskey, Sokol & Goodman, 1986). A distinction is drawn between the number processing system, which comprises the mechanisms for comprehending and producing numbers; and the calculation system, which encompasses processing components required specifically for carrying out calculation. In case of brain pathology, eventually these components can be dissociated. Facts (e.g., the multiplication tables), rules (e.g., $N \times 0 = 0$) and procedures (e.g., multiplying goes from left to right) are included as elements of the calculation system, and errors in calculation observed in brain-damaged and normal subjects, can result from inappropriate fact retrieval, misuse of arithmetical rules, and procedural errors.

The association between spatial knowledge and calculation abilities have been strongly emphasized by different authors (e.g., Ardila, Lopez & Solano, 1989; Dahmen et al., 1982; Levin, Goldstein & Spiers, 1993; Luria, 1966, 1973). Luria underlines that the so-called semantic aphasia (inability of use verbally-mediated spatial concepts) is always associated with acalculia. Acalculia (primary acalculia or anarithmetia) can be observed in cases of left posterior parietal damage, and this particular brain area has been strongly associated with some verbally mediated spatial knowledge. LeDoux (1982, 1989) has proposed that the primary functional distinction between human hemispheres involves the differential representation of linguistic and spatial mechanisms: while the right posterior parietal lobe is involved in spatial processing, the left posterior parietal lobe is involved in linguistic processing. Spatial mechanisms are represented in both the right and the left parietal lobe in nonhuman primates, but in man language is represented in a region (posterior parietal lobe) of the left hemisphere which, in the right hemisphere, is involved in spatial functions, and was involved in spatial functions in both hemispheres in human ancestors (Lynch, 1980). In consequence, the evolution of language involved adaptations in the neural substrate of spatial behavior (LeDoux, 1989).

Boles (1991) using different types of tasks (recognition of words, products, locations, dichotic digits, etc.) and applying a factor-analysis procedure was able to identify different lateralized parietal functions: lexical functions (e.g., word numbers) were associated with the left hemisphere, whereas spatial functions (e.g., locations of dots) were correlated with right hemisphere activity. The human origins of calculation abilities has been associated also with some type of body and spatial knowledge (Ardila, 1993).

Dahmen et al. (1982) studied calculation deficits in patients with Broca and Wernicke type of aphasia. Using a factor analysis they were able to identify two different factors: numeric-symbolic and visual-spatial. The milder calculation defects found in Broca aphasia patients are derived from their linguistic alterations, while with Wernicke aphasia defects in visual-spatial processing significantly contributes to calculations difficulties. Luria (1966, 1973) emphasized the presence of defects in spatial conceptualization underlying the primary acalculia observed in left-parietal damaged patients and the strong association between acalculia and semantic aphasia.

Spatial acalculia correlates significantly with spatial alexia and spatial agraphia, but also with visuoconstructive impairments, unilateral spatial agnosia, general spatial agnosia apraxia for dressing, and visual-field defects (Ardila & Rosselli, 1993, 1994; Hécaen & Albert, 1978; Hécaen & Marcie, 1974; Levin, Goldstein & Spiers, 1993). Errors in written arithmetical operations resulting from neglect of the left visual field, difficulties in horizontal positioning, vertical columnar alignment, and transportation of numbers are usually observed in acalculia of spatial type (Cohn, 1961; Lelex, Kaiser & Lebrun, 1979).

In this paper, a further clinical analysis of spatial acalculia observed in a sample of right hemisphere damaged patients is presented. Reading and writing disorders in this same group of patients were reported elsewhere (Ardila & Rosselli, 1993, 1994). Although comparative calculation disturbances in patients with left and right hemisphere damage have been previously reported (Rosselli & Ardila, 1989), this paper will focus on calculation impairments associated with right hemisphere damage, and the analysis of disturbed elements of the normal calculation system.

METHOD

Subjects

Twenty-one patients with right hemisphere damage were studied (11 men, 10 women; average age = 41.33; range = 19–65). These subjects presented various brain damage etiologies (vascular = 15; tumoral = 5; traumatic = 1). The cerebral damage had evolved in a period varying from 1 to 6 months. Patients had no background of previous neurological or psychiatric illness. Average schooling was 7.01 years (range = 5–15). All lesions were confirmed by means of computerized axial tomography. Patients were further divided in two groups: pre-Rolandic (6 patients) and retro-Rolandic (15 patients) right hemisphere damage. Table 1 presents the distribution of the sample.

TESTING PROCEDURE

Besides the general neurological and neuropsychological exams, a special calculation ability test was given to each subject. The following writing subtests were included:

1. Reading of numbers: 2, 7, 5, 27, 49, 731, 3091, 4908, 10003.
2. Writing of numbers: 2, 7, 5, 27, 49, 731, 3091, 4908, 10003.
3. Transcoding from numbers to letters: 8, 15, 29, 47, 382, 1504, 8643, 10003.
4. Transcoding from letters to numbers: seven, eighteen, twenty-three, ninety-two, one hundred and eighty-nine, seven hundred and one, one thousand and eight, twelve thousand three hundred and seventy-nine.
5. Relationships "bigger than" and "smaller than": which in the pair is bigger/smaller: 189–201, 47–74, 3002–1987, 10003–4908.
6. Mental arithmetical operations (given orally): $3 + 5$, $15 - 7$, 9×4, $9/3$, $55 + 38$, $93 - 13$, 13×12, $150/30$.
7. Written arithmetical operations: $3 + 2$, $18 - 6$, 8×4, $18/3$, $55 + 38$, $93 - 61$, 13×12, $150/30$.
8. Complex written arithmetical operations: $689 + 437$, $421 - 277$, 212×324, $818/356$.
9. Reading of arithmetical signs: +, –, ×, /, =.

TABLE 1
General Characteristics of the Sample

Patient	Sex	Age	Years of Education	Etiology	CT Scans	Category
1	F	34	5	tumor	convexital frontal	Prerolandic
2	F	53	5	vascular	infarction anterior branches MCA	Prerolandic
3	M	19	8	trauma	frontal hematome	Prerolandic
4	M	39	5	vascular	anterior cerebral artery	Prerolandic
5	M	63	10	tumor	posterior frontal	Prerolandic
6	M	32	15	tumor	anterior frontal glioma	Prerolandic
7	M	50	11	vascular	posterior cerebral artery	Retrorolandic
8	F	44	4	vascular	parietal-occipital	Retrorolandic
9	F	65	11	vascular	parieto-temporal	Retrorolandic
10	F	33	5	vascular	temporo-parietal	Retrorolandic
11	M	55	5	vascular	temporo-parietal hemorrhagic infarction	Retrorolandic
12	M	26	5	vascular	temporo-parietal-occipital	Retrorolandic
13	F	44	11	tumor	temporo-parieto-occipital glioma	Retrorolandic
14	F	16	7	vascular	temporal	Retrorolandic
15	M	45	5	vascular	parietal	Retrorolandic
16	F	49	5	vascular	insular and temporal hematome	Retrorolandic
17	M	38	5	tumor	temporal glioma	Retrorolandic
18	F	19	11	vascular	temporo-parietal	Retrorolandic
19	M	55	5	vascular	temporo-parietal	Retrorolandic
20	F	29	5	vascular	deep parieto-temporal infarction	Retrorolandic
21	M	60	5	vascular	temporo-parietal infarction	Retrorolandic

10. Successive operations: 1, 4, 7 . . . 40; 100, 87, . . . 61.
11. Forward and backward counting: the patient was required to count in units of one forward from 1 to 20, and from 70 to 80; and backward from 20 to 1 and from 80 to 70.
12. Aligning numbers in columns: numbers orally presented were required to be aligned as if they were going to be summed: 19, 346, 501, 1709, 2, 100030.
13. Numerical problems (orally presented): "How many apples are in one and a half dozen?", "How many centimeters are in two and a half metres?", "If John has 10 oranges and gives 6, how many remain?", "Mary earns eight dollars per hour. How much does she get for four hours of work?", "Peter and Robert together have $150; Peter has twice as much as Robert. How much does each one have?".

Errors in each one of these tasks were individually scored.

RESULTS

All the patients presented various associated neurological and/or neuropsychological disorders, specially left hemiparesis, visual field defects, spatial hemi-neglect, constructional apraxia, spatial alexia, and spatial agraphia. All of them, but left hemiparesis, were more frequently found in right retro-Rolandic patient group. Table 2 shows the percentage of patients presenting these defects.

TABLE 2
Percentage of Patients Presenting Different Associated Neurological and Neuropsychological Defects

	Pre-Rolandic	Retro-Rolandic
Left-hemiparesis	83	60
Visual field defects	0	53
Spatial hemi-neglect	50	67
Constructional apraxia	50	73
Spatial alexia	33	73
Spatial agraphia	50	80

All the types of errors (excepting Writing of Numbers and Relationships "Bigger than" and "Smaller than" errors) were more frequently observed in retro-Rolandic than in pre-Rolandic patients. Excepting Counting Forwards, all types of errors were observed in retro-Rolandic patients. Only in one retro-Rolandic patient errors in Reading of Arithmetical Signs were observed. All the studied patients presented errors in Complex Written Arithmetical Operations. All retro-Rolandic patients presented errors in Mental Arithmetical Operation tasks. Table 3 shows the percentage of patients presenting errors or failures in different calculation subtests.

Table 4 presents the mean number of errors and the standard deviations in the different subtests. Mean number of errors was in general higher in the retro-Rolandic group. Only in Relationships "Bigger than" and "Smaller than", Successive Operations, and Numerical Problems subtests, mean number of errors was higher in the pre-Rolandic group. The highest number of errors was found in Complex Arithmetical Operation subtest with an average of 13.45 errors per patient; all the patients presented errors in this subtest. In both patient groups, Written Arithmetical Operation errors were higher than Mental Arithmetical Operation errors.

Errors in the reading of numbers were observed in 17% of the pre-Rolandic group and 58% of the retro-Rolandic sample. These reading errors were due to: (a) neglect (731 – > 31); (b) spatial inversions (e.g., 49 – > 94); (c) spatial omissions (e.g., 10003 – > 103). Spatial errors in reading single digits (most often, 6 – > 9; 5 – > 2) were observed in one pre-Rolandic and three retro-Rolandic patients.

Errors in the writing of numbers were observed in 50% and 33% of pre-Rolandic and retro-Rolandic patients respectively. When writing numbers it was evident: (a) feature additions (e.g., the digit 3 was written with one or several extra strokes) and digit additions (e.g., the number 731 was written as 7331); (b) inability to use in a correct way the spaces to join and separate numbers (e.g., 49 and 731 were written as 4 97 3 1); (c) difficulty in conserving the written line in a horizontal position; (d) increased left margins and unsteadiness in maintaining left margins ("cascade phenomenon"); and (e) disrespect of spaces and spatial disorganization of the written material.

TABLE 3
Percentage of Patients Presenting Errors or Failures in Different Calculation Subtests

	REA	WRI	N-)L	L-)N	)(	MEN	WOP	COM	SIG	SUC	FOR	BAC	COL	PRO
Pre-Rolandic	17	50	50	34	100	84	84	100	0	50	0	17	50	50
Retro-Rolandic	58	33	83	92	75	100	92	100	8	83	0	25	75	92

Reading of numbers (REA), writing of numbers (WRI), transcoding from numerical to verbal code (N-)L), transcoding from verbal to numerical code (L-)N), relations "bigger" and "smaller" ()(), mental arithmetical operations (MEN), written arithmetical operations (WOP), complex arithmetical operations (COM), reading arithmetical signs (SIG), successive operations (SUC), counting forwards (FOR), counting backw[illegible] numbers in columns (COL), numerical problems (PRO).

TABLE 4
Mean Number of Errors in the Different Subtest. Standard Deviations are Shown in Braquets

	REA	WRI	N-⟩L	L-⟩N	⟩⟨	MEN	WOP	COM	SIG	SUC	FOR	BAC	COL	PRO
Pre-	0.33	0.67	2.83	1.50	1.77	3.67	4.17	11.80	0.00	3.67	0.00	0.67	2.00	2.00
Rolandic	(0.62)	(0.82)	(2.71)	(1.76)	(1.83)	(1.51)	(3.31)	(8.28)	(0.00)	(3.14)	(0.00)	(1.63)	(2.45)	(1.55)
Retro-	0.92	1.08	3.67	2.50	1.67	4.00	4.67	15.10	0.83	2.75	0.00	1.00	2.50	1.75
Rolandic	(0.79)	(1.56)	(2.87)	(2.11)	(1.44)	(1.65)	(2.50)	(8.14)	(1.75)	(3.55)	(0.00)	(1.95)	(1.88)	(1.14)

Reading of numbers (REA), writing of numbers (WRI), transcoding from numerical to verbal code (N-⟩L), transcoding from verbal to numerical code (L-⟩N), relations "bigger" and "smaller" (⟩⟨), mental arithmetical operations (MEN), written arithmetical operations (WOP), complex arithmetical operations (COM), reading arithmetical signs (SIG), successive operations (SUC), counting forwards (FOR), counting backwards (BAC), aligning numbers in columns (COL), numerical problems (PRO).

Errors in arithmetical operations (Mental Arithmetical Operations, Written Arithmetical Operations, Complex Written Arithmetical Operations, and Numerical Problem subtests) were found strongly associated with, and depending on two underlying deficits:

(1) Some loss of calculation automatisms (specially, but not only, the multiplication tables). In all the patients presenting errors in Written Arithmetical Operations and Complex Written Arithmetical Operation subtests, some errors that could be interpreted as a loss of calculation automatisms were observed. However, in Mental Arithmetical Operations, and Numerical Problem subtests (mentally performed and, in consequence, without a written evidence), it was not possible reliably to identify the source of the errors.

(2) Reasoning errors (impossible results from the arithmetical point of view; for example, in substracting, the difference appeared larger than the minuend, no realizing of this absurdity) were observed in 20% of the pre-Rolandic group, and 33% of the retro-Rolandic patients.

DISCUSSION

Calculation disorders observed in right hemisphere-damaged patient presented the following characteristics:

(1) Acalculia appeared particularly in written calculations. There was some dissociation between mental calculation (Mental Arithmetical Operations and Numerical Problems), and written calculation (Written Arithmetical Operations and Complex Written Arithmetical Operations). While the former was better preserved, the latter was seriously impaired. In Complex Written Arithmetical Operation subtest, the maximum number of errors was observed, and not one patient performed errorless.

(2) In reading and writing numbers the same difficulties observed in reading and writing in general were observed. That is, some spatial alexia and spatial agraphia for numbers was evident.

In writing numbers, it was observed: (a) feature and digit additions; (b) inability to use in a correct way the spaces to join and separate numbers; (c) difficulty in conserving the written line in a horizontal position; (d) increased left margins and unsteadiness in maintaining left margins ("cascade phenomenon"); and (e) disrespect of spaces and spatial disorganization of the written material.

In reading numbers, it was observed: (a) some difficulties in the recognition of the spatial orientation of digits and number spatial inversions; (b) left hemi-spatial neglect; and (c) inability to follow lines when performing arithmetical operations, and sequentially explore the spatial distribution of the written material: digits and numbers were sometimes skipped; digits belonging to different lines were read as conforming a single number; spaces were not respected; and reading numbers becomes simply chaotic.

Disturbances in arithmetical operations (observed in Mental Arithmetical Operations, Written Arithmetical Operations, Complex Arithmetical Operations, and Numerical Problem subtests) were found strongly associated with two underlying deficits:

(1) Loss of calculation automatisms, particularly, but not only, the multiplication tables. The performance of arithmetical operations is based in a great extend on some automatisms; "ten minus five equal five", or "seven plus eight equal fifteen" represents calculation automatisms (Grafman, 1988). Without these automatisms, calculation becomes extremely painstaking and slow; and the likelihood of errors notoriously increases. This defect can be associated with the general loss of automatisms that has been pointed out in cases of right hemisphere damage (Luria, 1966); and,

(2) Reasoning errors (impossible results from the arithmetical point of view) were occasionally observed in about one-third of the patient sample.

As a result, of these two underlying deficits not only the performance of written, but also mental arithmetical operations were affected.

In general, calculation defects were more evident in retro than pre-Rolandic patients. That means, spatial acalculia was more noticeable and severe in posterior than anterior right brain lesions. However, in "Bigger than" and "Smaller than" relationships, Successive Operations, and Numerical Problems subtests, the mean number of errors was higher in the pre-Rolandic group. Inability to appreciate bigger and smaller relationships could be associated with defects in the ability to conceptualize quantities (numerousness). Errors in Successive Operations were basically due to perseverative responses (e.g., 1, 4, 7, 17, 27, 37, and so on). The inability to solve (and even, to understand) numerical problems has been frequently considered as the basic defect in frontal acalculia (Luria, 1966, 1973).

According to the model of McCloskey and colleagues (1985, 1986, 1987, 1991) it could be considered that number processing (the mechanisms for comprehending and producing numbers) can be impaired in cases of right hemisphere damage; whereas the calculation system (processing components required specifically for carrying out calculation) may be only partially impaired. Fact retrieval (e.g., the multiplication tables) and procedural errors (e.g., where to add the "carried" unit) can be also impaired. Arithmetical rules (the strategy and sequency required to add, substract, multiply and divide; and the correct interpretation of arithmetical signs) were properly used by this group of patients. And it could supposed, according to Boller and Grafman's (1983, 1985) approach to acalculia, that in acalculia of spatial type, calculation abilities are disrupted as a result of: (1) visuospatial defects that interfere with the spatial arrangement of numbers and the mechanical aspects of mathematical operations; (2) inability to recall mathematical facts and appropriately use them; and, it could be added, (3) inability to conceptualize quantities (numerousness); this defect was particularly evident in right anterior damaged patients.

In summary, it could be concluded that spatial acalculia is related to: (1) spatial alexia and agraphia for numbers, (2) loss of calculation automatisms, (3) reasoning errors, and (4) general spatial defects.

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