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Calculating without reading:

Unsuspected residual abilities in pure alexia

Laurent Cohen

Service de Neurologie 1, Hôpital de la Salpêtrière, Paris

and

Stanislas Dehaene

INSERM U. 334, Service Hospitalier Frédéric Joliot, CEA/DRM/DSV, Orsay

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Correspondence:

Laurent COHEN
Service de Neurologie 1
Clinique Paul Castaigne
Hôpital de la Salpêtrière
47/83 Bd de l'Hôpital
75651 Paris CEDEX 13
Tel: 01 42 16 18 49 / 01 42 16 18 02
Fax: 01 44 24 52 47
E-mail: laurent.cohen@psl.ap-hop-paris.fr

Abstract

In pure alexic patients, clear-cut dissociations between impaired naming and preserved comprehension abilities can be found in the domain of number processing (Cohen and Dehaene, 1995). In the present study, we report a novel case of pure alexia with striking preservation of some calculation abilities. The patient was fully able to decide which of two numbers was the larger, or whether a number was odd or even, even with two-digit numerals for which she made close to 90% reading errors. In arithmetic, the patient, though unable to read aloud correctly the operands of visually presented problems, could still produce verbally the *exact* result of the very same problems. For instance, when presented visually with the subtraction problem 8 – 6, the patient read the problem aloud as “ five minus four ”, but nevertheless produced the correct result “ two ”. Such capacities for “ calculating without reading ” were observed in subtraction, addition, and division tasks, but not in multiplication tasks. We discuss how both the existence of residual abilities and the pattern of dissociations between operation types can be explained by current theories of the cerebral substrates of number processing (Dehaene and Cohen, 1995).

Introduction

In 1892, Dejerine first reported the case of a patient who, following a left occipito-temporal infarct, suffered from a complete and isolated inability to read words, while his writing abilities were fully preserved, as were his production and comprehension of oral language (Dejerine, 1892). Over time, many similar cases were studied under the names of pure alexia, alexia without agraphia, or agnosic alexia, among others.

While many studies were devoted to delineating the critical cerebral lesions (e.g. Binder and Mohr, 1992; Damasio and Damasio, 1983), and to clarifying the underlying pathophysiological mechanisms (e.g. Warrington and Shallice, 1980), others revealed an unexpected range of preserved reading abilities in patients with pure alexia. Given that many patients are unable to read aloud a single word, one might have expected them to be totally devoid of visual word processing abilities, apart from the slow and indirect letter-by-letter reading strategy. However, some patients were shown to exhibit above-chance performance in lexical decision or semantic classification tasks with quickly presented stimuli (Bub and Arguin, 1995; Coslett and Saffran, 1989; Coslett *et al.*, 1993; Shallice and Saffran, 1986; Warrington and Langdon, 1994), or lexicality effects in letter identification tasks (Bub *et al.*, 1989; for review, see Coslett and Saffran, 1998; Miozzo and Caramazza, 1998).

Residual abilities in pure alexia are of considerable theoretical importance because they may bear on the existence of multiple routes for word reading, as well as on the abilities of the right hemisphere for language (Beeman and Chiarello, 1998). Yet in spite of years of research, their replicability remains a debated issue, and various sources of artifact have been proposed to explain them (e.g. Behrmann *et al.*, 1990; Bub and Arguin, 1995; Miozzo and Caramazza, 1998; Patterson and Kay, 1982; Warrington and Shallice, 1980). It is therefore important to identify tasks in which pure alexic patients would perform way above chance, or even within the normal range, while remaining unable to name the stimuli. Our purpose here is to demonstrate that such heretofore unsuspected residual abilities can be observed in the domain of number processing.

In a previous publication (Cohen and Dehaene, 1995), we showed that two patients with pure alexia, who were severely impaired at reading aloud arabic numerals, were still able to decide with perfect ease and accuracy which of two numerals was the larger. This observation, which was recently replicated in another patient (Miozzo and Caramazza, 1998), indicated that symbolic stimuli that could not be read aloud could nevertheless gain access to a semantic level of representation. In the present study, beyond replicating this finding in a further pure alexic patient, we introduce novel arithmetical tasks in which the discrepancy between impaired naming and preserved number processing is also clearcut. In those tasks, the patient, though unable to read aloud correctly the operands of visually presented problems, is still found capable of verbally producing the *exact* result of the very same problems. For instance, when presented visually with the subtraction problem 8 – 6, the patient read the problem aloud erroneously as “ five minus four ”, but nevertheless produced the correct result “ two ”. This pattern of behaviour shows that the identification of the operands, computation of their difference, and eventual production of the result, ca often proceed without error in spite of the grossly impaired naming of the operands. Capacities for “ calculating without reading ” were observed in addition, subtraction, and division tasks, but not in multiplication tasks. In the discussion, we explain how both the existence of residual arithmetic abilities and the pattern of dissociations between operation types can be explained by current theories of the cerebral substrates of number processing (Dehaene and Cohen, 1995).

Case report

Clinical history

V.O.L. was a 66-year-old right-handed woman, working as an art critic and exhibition manager, specialized in contemporary painting and sculpture. She had a long-standing history of Crohn’s disease. On awakening following surgery for peritonitis, a severe visual impairment was discovered. CT-scan and MRI revealed an infarct in the superficial territory of the left posterior cerebral artery, affecting the infero-mesial aspect of the occipito-temporal region (Figure 1).

Goldmann perimetry evidenced right hemianopia with macular sparing. There was a severe and typical alexia without agraphia, which will be described in more detail in the next section. The patient also suffered from visual agnosia for objects. She was tested with the Birmingham Object Recognition Battery (Riddoch and Humphreys, 1993). Her score was normal in all subtests of pre-categorical visual processing, while she was more than 2 SD below the mean of controls in all subtests assessing access to stored knowledge. This pattern corresponds to the classical syndrome of associative agnosia. There was no prosopagnosia. The patient was also markedly impaired at understanding the precise meaning of concrete nouns and at retrieving such nouns on definition. Other aspects of language were fully preserved. Agnosia did not interfere in any way with reading and number processing abilities, and will not be mentioned any further in this study.

Assessment of pure alexia

Reading aloud words and letters

V.O.L. was almost completely unable to read any word aloud. She was presented with a randomized list comprizing 15 concrete and 15 abstract nouns 4-6 letter long, in lower-case print. She tried to resort to an effortful and distressing letter-by-letter reading strategy. She made many letter naming errors, and testing had to be discontinued after the first few items of the list. In contrast, she did not make a single error in naming the same 30 words when they were spelled-out orally her.

The patient was asked to name the 26 letters of the alphabet, displayed in upper case, in random order. She made 30.8% (8/26) errors. Even when correct, her responses were often effortful, with self-corrections. On some trials, she reached the correct response through first tracing the outline of the target letter with her right index finger.

Reading aloud arabic numerals

V.O.L. was asked to read aloud a set of 80 single digits 1-9. Digits were presented one pair at a time, horizontally aligned on a computer screen, for an unlimited amount of time. Overall, she made 41.3% (33/80) errors. Interestingly, on trial 28, V.O.L. for the first time resorted to an overt counting strategy (7 → " ...5, 6, 7 "). This and all following trials were almost flawless (1/26 errors, 3.8%), as compared to the 27 first trials (32/54 errors, 59.3%). The patient explicitly observed that while guessing was unsuccessful, counting apparently did better.

The patient was asked to read aloud a set of 64 2-digit numbers. Numerals were presented one pair at a time, horizontally aligned on a computer screen, for an unlimited amount of time. V.O.L. made as much as 89.1% errors (57/64).

In a subsequent session, she was asked to read aloud a list of 20 Arabic numerals 2-4 digit long. She made 55% (11/20) errors. In this session, she proceeded very slowly, often counting on her digits in order to name individual digits subvocally before responding aloud. This strategy may explain why her performance was somewhat better than in previous naming tasks. In contrast, when the same 20 arabic numerals were spelled-out orally to the patient, she identified them flawlessly (e.g. " one, five, one, one " → " one thousand five hundred and eleven ").

In all number reading tasks, the patient made almost exclusively digit substitution errors, with frequent perseverations of previous responses (Cohen and Dehaene, 1998).

Writing to dictation

The patient could write letters, words and sentences normally, either spontaneously or to dictation, with the exception of sporadic phonologically plausible errors (e.g. femme → famme). She was asked to write down to dictation 30 arabic numerals ranging from 1 to 5 digits. She made only 2 errors, which she readily self-corrected.

Residual word processing abilities

The patient's residual word processing abilities were assessed using lexical decision, language decision, and semantic classification tasks, using randomized lists of lower-case alphabetic stimuli. These experiments were performed only as a background to our main study of number processing. Any conclusion should therefore be considered as tentative, given the limited amount of testing that was performed. The available data are reported in the Appendix. In summary, the results suggested above chance performance in several lexical decision and language decision tasks, but no evidence for access to word meaning was found.

Residual number processing

In order to evaluate the patient's residual number processing abilities, we presented randomized lists of briefly presented arabic stimuli (300 ms), with a forced-choice manual response.

Letter-digit decision

The patient was presented visually with a list comprizing 36 pairs of symbols. Each pair consisted of an upper-case letter and a digit. On half the trials, the digit was on the left, and on he other half it was on the right. V.O.L. was asked to indicate on each trial on which side was the digit by pressing the corresponding key. She made only 1/36 error, which she spontaneously corrected (mean reaction time = 1634 ms).

Magnitude comparison

We have shown previously that two patients with pure alexia could access and manipulate the quantities represented by numerals that they were unable to read aloud, allowing them to decide which of two numerals is larger (Cohen and Dehaene, 1995). In an attempt to replicate this observation, we presented patient V.O.L. with the same pairs of 2-digit numerals that were used in the above reading task (mean absolute difference = 8.8; range: 2-36), and asked her to simply press the key on the side of the larger numeral.[1]

The task was very easy for the patient. She made 1/88 error, which she readily corrected. Correct reaction times decreased, the larger the difference between the numbers in the pair, as found in normal subjects (mean RT = 1579 ms; r(85 df) = –0.42; $P = 0.0001$).[2] When reading pairs of 2-digit numerals, the patient made 5/32 errors that reversed the relative size of the two numbers (e.g. the stimulus pair 65 62 was read as “ 92 94 ”). Her comparison performance was thus significantly better than what could be expected on the basis of her reading (Fisher Exact Two-Tailed $P = 0.005$). It should be noted that the pattern of reaction times, i.e. short latencies and normal distance effect, clearly confirm that the patient did not resort to a counting strategy in this task (Dehaene *et al*., 1990).

Parity judgement

The patient was presented twice with a list comprizing all Arabic numerals 1-10, each presented three times. A second list comprizing 30 2-digit arabic numerals (15 odd and 15 even) was also presented to the patient. She was asked to press the left-hand key for odd numbers, and the right-hand key for even numbers.

She made 8/30 errors on the first presentation of the list of single digits, 1/30 errors on the second presentation of this list (mean RT = 793 ms)[3], and 2/30 errors with the list of 2-digit numerals (mean RT = 846 ms). Again, the pattern of reaction times confirmed that the patient did not resort to counting: latencies were short, and did not depend on the rank of the unit digit in the counting sequence (r(85) = 0.09, $P = 0.41$).

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[1] The task was run with and without the experimenter being blind to the stimuli. The patient's performance did not differ across these two conditions and data were pooled.

[2] One response longer than 6 seconds was excluded from the RT analysis.

[3] Three reaction times longer than 6 sec were excluded from the analysis.

Summary and discussion

To summarize, patient V.O.L. showed a pattern of deficit typical of pure alexia for words and Arabic numerals: following a left infero-mesial occipito-temporal lesion, she was severely impaired at reading aloud alphabetic and Arabic stimuli, while writing was preserved. Furthermore, she showed residual processing abilities for symbols that she was unable to read aloud. In particular, she showed a better access to quantity information than could be expected on the basis of her number reading performance, as demonstrated by her largely correct performance in magnitude comparison and parity judgement. The availability of a counting strategy to compensate for the digit reading impairment is a further indication of preserved digit comprehension. The patient reported that she immediately knew the rank of the target digit in the series of numerals. However, in order to retrieve the appropriate word, she had to recite the whole word series up to the appropriate rank.

Since the very existence of residual implicit recognition abilities has been disputed on methodological grounds, it is worth stressing that the patient's good performance in dichotomic decision tasks could not be due to any form of unconscious experimenter influence (" Clever Hans effect "). All crucial tasks were performed while the experimenter was blind to the stimuli.

Considering the efficiency of access to number meaning from visual Arabic input, one may ask whether such residual number processing abilities extend beyond the range of simple non-verbal forced-choice tasks. If indeed our alexic patient can manipulate the magnitudes associated with Arabic numerals, we wondered, might she be able to solve simple arithmetic problems that she could not read aloud?

Mental arithmetic

Material

We used simple addition, subtraction, multiplication, and division problems. The set of subtraction problems comprised all 36 possible pairs of operands 1 through 9 with a strictly positive result. The same 36 pairs of operands were used for the multiplication and the addition problems. In multiplication problems, the order of the two operands was reversed in order to present the problems in the more familiar order (smaller operand first). The set of division problems comprised 28 problems with the first operand ranging from 3 to 20 and the second operand larger than 1 and smaller than the first operand.

Whenever the patient produced several successive responses on a given trial, which occured rarely, only the last response was scored. As a consequence, spontaneous self-corrections were scored as correct responses. Error rates are summarized in Table 1.

Orally presented problems

To provide baseline information about the patient's calculation abilities, she was orally presented with the four sets of arithmetic problems, in randomized order within each set, and was asked to produce the result orally. Overall she made 11.0% errors, with errors rates varying from 8.3% to 13.9% depending on the type of operation (Figure 2). There was no significant difference in error rates across the four operation types ($\chi^2(3) = 0.50$, $P < 1$). One may note that errors were qualitatively similar to those made by normal subjects: All 3 multiplication errors as well as 2 out of 3 division errors were close within-table errors; all 4 addition errors as well as 4 out of 5 subtraction errors were false by only one unit.

In brief, the patient behaved relatively satisfactorily on oral presentation of arithmetic problems although her performance seemed slightly below her expected level of expertise. Importantly, there was no difference in error rates across operation types, and particularly no difference between multiplication and subtraction. This pattern of results may be considered as a baseline for the study of mental arithmetic on visual presentation.

Problems presented in Arabic form

The same sets of problems were presented twice in Arabic notation. In a first version of the task, the patient was asked to produce the result without reading aloud the operands. In a second version, she was asked to read aloud the problem, and then to produce the result.

Operand reading errors

As expected considering her severe alexia, the patient made numerous errors when reading aloud the operands before solving the problems. Such reading errors affected 84.6% of problems and 64.3% of operands[4], and equally concerned all types of operations (Figure 2). Like in simple reading tasks, many perseverations occurred over trials.

Calculation performance

The rates of calculation errors were virtually identical whether the patient was asked to read aloud the operands or not, and error data were therefore pooled in the analyses (Table 1 and Figure 2).

Overall, the patient made 47.8% calculation errors. This error rate seemed to be remarkably low, considering that as many as 84.6% of problems were read erroneously. In order to evaluate this observation, we compared the rate of calculation errors with the rate of " critical " operand reading errors, i.e. reading errors that would entail an erroneous operation result. As an example of such critical trials, the patient, when presented with the problem 5 × 9, read aloud the operands as " 4 × 6 ". This is a critical trial because the result of 4 × 6 is different from the result of 5 × 9. Considering only critical reading errors did not alter the strength of the dissociation: The 47.8% rate of calculation errors was still far below the 80.1% rate of critical reading errors ($P < 10^{-6}$). However, we will now see that the discrepancy between extremely poor reading and relatively preserved problem solving varied among operations.

Inspection of Table 1 and Figure 2 shows that errors rates differed widely across operation types ($\chi^2(3) = 63.7$, $P < 10^{-5}$). In particular V.O.L. made 87.5% errors with multiplication problems, but only 27.8% errors with subtraction problems. Addition problems yielded a 38.9% error rate, and division problems a 33.9% error rate. Multiple comparisons confirmed that multiplication problems were solved significantly worse than each of the 3 other types of problems (all Ps $< 10^{-5}$), which did not differ from one another (all Ps > 0.16).

In assessing dissociations between arithmetic operations, one should consider a potential source of bias, namely the fact that multiplication results included larger numbers (maximum result = 72) than the results of either addition, subtraction, or division problems (maximum result = 17, 8, and 10, respectively). We therefore analyzed separately 3 subsets of

[4] The rate of reading errors did not differ from the 59.3% error rate observed in the simple digit reading task, when the patient did not resort to a counting strategy ($\chi^2(1)=0.501$, $P = 0.48$).

multiplication trials, with results not exceeding the maximum result of each of the 3 other problem types. As appears in Table 2, error rates for these relatively small multiplication problems was as high as with the entire set of multiplication problems (above 85% errors), and very significantly higher than the corresponding subtraction, addition, and division problems (all *P*s $< 10^{-4}$). We may therefore conclude that the disproportionate impairment of multiplication truly reflects its specific functional status among other operations.

Thus, multiplication was the only operation that did not benefit from a relative sparing of calculation relative to reading. There was no difference between the error rate in calculation and the rate of critical reading errors for multiplication problems ($\chi^2(1) = 0.34$, $P < 1$). In contrast, the error rates for subtraction, addition and division were very significantly lower that those expected on the basis of reading errors (all $\chi^2(1) > 16$, all *P*s < 0.00005).

Two striking observations should be summarized at this point. First, calculation performance with subtraction, and to a somewhat lesser degree with addition and division, was much better than expected from the very high rate of operand reading errors. This partially preserved ability with a visual input, contrasting with the poor reading performance, may be considered as a paradoxical “ residual ” ability in this patient with pure alexia. Second, while the 4 problem types – and particularly multiplication and subtraction – did not differ on oral presentation, there was, on visual presentation, a major differential increase in error rate for multiplication problems only. Since these phenomena are probably related to the patient’s alexia, we tried to trace their origin through a closer study of the relations between operand reading errors and calculation errors.

Relations between reading and calculation errors

Multiplication problems

With multiplication problems, the patient very often misread the operands, then correctly performed the multiplication on the basis of the numbers that she had uttered. For instance, when presented with the problem 5 × 9, she said “ 4 × 6 ”, then answered “ 24 ”. To quantify this effect, the analysis was restricted to the set of 30 critical trials in which the result of the problem spoken by the patient differed from the result of the original problem. On these trials, it should generally be possible to decide whether the patient performed the operation on the basis of the original problem or on the basis of the spoken problem. In this set, as many as 23 trials (76.7%) conformed to the above example: the result proposed by the patient was the correct solution to the spoken problem, not to the original problem (Figure 3). On only one trial did the patient produce the result of the original problem. On the remaining 6 trials, the response was false relative to both the original and the spoken problems. Yet even then, it seems that the patient's responses on these trials were best described as failed attempts to multiply the numbers that she had said. In all 6 cases (except for a single failure to respond), the results fell close to and within the correct row or column of the spoken problem within the multiplication table. For example, when presented with 7 × 8, the patient said " 4 × 6 " and then answered " 12 ", which is a plausible within-table error to the spoken problem 4 × 6, but is completely unrelated to the original problem 7 × 8.[5] In summary, the patient appeared to solve multiplication problems by attempting to read them aloud and then to multiply the numbers that she had uttered.

Subtraction problems

With subtraction problems, in contrast, the patient generally produced the correct response to the original target problem, irrespective of her reading errors. For instance, when presented with the problem 8 – 7, she said " 6 – 4 ", but then answered " 1 ", which is the correct result of the original problem. Again, the analysis was restricted to the set of 29 critical trials on which the result of the problem spoken by the patient differed from the result of the original problem. In this set, 20 trials (69.0%) conformed to the above example: the result proposed by the patient was the correct solution to the original problem, not to the spoken problem (Figure 3). On only 3 trials did the patient produce the result of the spoken problem. On the remaining 6 trials, the response was false relative to both the original and the spoken problems. Yet even then, it seems that the patient's responses on these trials were best described as failed attempts to subtract the original operands. Although the number of relevant trials is very small, one may note that 5 out of 6 produced results were false by 1 unit relative to the original problem, while only 2 out of 6 were false by one unit relative to the spoken problem. For example, when presented with 7 – 2, V.O.L. said " 5 – 4 " and then answered " 6 ", which is a

[5] This pattern would lose part of its interest if the patient was always producing the same correct but stereotyped multiplication fact on all trials. Actually, in spite of her tendency to perseverate, she retrieved as many as 14 different correct multiplication facts, showing that she could access a wide range of arithmetical facts.

plausible close error to the original problem 7 – 2, but is an unlikely error for the spoken problem “ 5 – 4 ”.

Two further observations illustrate the independence of the subtraction computation from the process of reading aloud the operands. First, V.O.L. occasionally made reading errors reversing the relative size of the operands. For instance, when presented with the problem 6 – 3, she read aloud “ 4 – 6 ”, and then correctly answered “ 3 ”. Second, as mentioned before, V.O.L. made frequent perseverations when reading aloud the operands. For instance, on 6 out of 36 subtraction trials, she read aloud the operands with the same stereotyped response “ 4 – 3 ”, yet she always produced the correct result, which was a variable number ranging from 1 to 7 (Table 3).

In summary, the patient appeared to solve subtraction problems on the basis of the actual original operands, even when reading them aloud erroneously.

Addition problems

Addition problems behaved largely like subtraction problems, with responses often appropriate to the original problem and not to the spoken problem (e.g. 7 + 5 → “ 7 + 3 = 12 ”). Out of the 27 critical trials on which the result of the problem spoken by the patient differed from the result of the original problem, the result proposed by the patient was the correct solution to the original problem in 15 cases (55.6%). On 6 trials the patient produced the correct result of the spoken problem (Figure 3). On the remaining 6 trials, on which the response was false relative to both the original and the spoken problems, the response was on the average closer to the result of the original problem (error range 1-3) than to the result of the spoken problem (error range 2-5).

Division problems

Division problems behaved largely like subtraction and addition problems, with responses often appropriate to the original problem and not to the spoken problem. Actually, on 17/28 trials, the patient did not even read out the problem as a possible integer division. For instance, when presented with the problem 16 ÷ 2, she said “ 14 ÷ 4 ”, but then correctly answered “ 8 ”. Out of the 23 critical trials on which the result of the problem spoken by the patient differed from the result of the original problem, the result proposed by the patient was the correct solution to the original problem in 17 cases (73.9%). On only one trial did the patient produce the correct result of the spoken problem (Figure 3).

General discussion

We have reported the case of a patient with typical pure alexia following infarction in the territory of the left posterior cerebral artery. A dissociation between impaired reading and preserved comprehension of Arabic numerals was demonstrated. The patient remained largely capable of deciding which of two numbers was the larger, or whether a number was odd or even, even with two-digit numerals for which she made close to 90% reading errors. Furthemore, she was often able to verbally produce the correct result of simple addition, subtraction, and division problems, far better than she could read them aloud. Such " calculating without reading " was not, however, observed for multiplication problems.

Residual number processing in pure alexia

In the domain of numbers, clear evidence for partially preserved access to the meaning of Arabic numerals was found, since our patient could often compare and even calculate with numbers that she could not read aloud. The present results are in good agreement with previous publications on numerical abilities in pure alexia. Cohen and Dehaene (1995) described two pure alexic patients (G.O.D. and S.M.A.) in whom the ability to compare two numbers was perfect, contrasting with their impaired reading of the same stimuli. This finding was recently replicated by Miozzo and Caramazza (1998) in another patient with pure alexia. Patients G.O.D. and S.M.A. were also tested with addition problems and, for patient G.O.D. only, with multiplication problems. They showed no preservation of arithmetic abilities with Arabic numerals. Unfortunately, neither subtraction nor division were tested in this study.

McNeil and Warrington (1994) also studied a patient (H.A.R.) whose case description clearly indicates as suffering from pure alexia in the context of additional anomic aphasia. This patient erred in reading single and multidigit Arabic numerals, yet could compare them perfectly. Furthermore, while H.A.R. was impaired at solving simple multiplication and addition problems presented in Arabic notation (from 31% to 68 % errors), subtraction problems were almost entirely spared (4% errors). Calculation on spoken operands was fully intact. In summary, all other published patients showed spared comparison abilities, while sparing of arithmetic problem solving seems at first sight to be more variable across patients and operation types.

A theoretical account based on the triple-code model

The ability of patients with pure alexia to compare Arabic numerals accurately can be naturally accounted for in the context of the anatomical and functional model of number processing depicted in Figure 4 (Cohen and Dehaene, 1995; Dehaene and Cohen, 1995). In essence, we propose that both the left and the right hemispheric visual systems are able to build a structural representation of Arabic numerals (a representation called the " visual number form ") and to access their meaning, i.e. the quantity to which they refer. Only the left-hemispheric visual number form, however, provides direct input to the Arabic-to-verbal translation system that maps strings of arabic digits into strings of words. Pure alexia is thought to result from the destruction or deafferentation of the left-hemispheric visual number form, depriving the Arabic-to-verbal translation system from its normal input. However, Arabic numerals may still be recognized through the intact right-hemispheric visual system. Pure alexic patients can then manipulate the appropriate quantities and compare them accurately. This hypothesis is supported by independent evidence from split-brain patients, whose right hemisphere can compare numbers that it cannot read aloud (Cohen and Dehaene, 1996; Gazzaniga and Smylie, 1984; Seymour *et al*., 1994), and from patients with large left hemispheric lesions (Cohen *et al*., 1994; Dehaene and Cohen, 1991; Grafman *et al*., 1989), in which the comparison task is invariably spared.

We suggest that the residual arithmetic abilities of patient V.O.L. reflected the operation of essentially the same processing pathways as comparison. Indeed, if patients with pure alexia are able to manipulate quantities well enough to compare numerals with normal accuracy, they may be expected to solve at least some arithmetic problems.

Dissociation between operation types

According to the triple-code model, all types of arithmetic operations are not handled by the same cerebral circuits (see Figure 5). Familiar multiplication problems are often learned by rote and solved through the retrieval of automatic verbal associations (e.g. Campbell, 1994). In contrast, other problems, particularly subtraction problems, are not systematically memorized and require the manipulation of the quantities represented by the operands (Dehaene and Cohen, 1995). In a previous publication, we showed that these two types of arithmetic routines (verbal vs semantic) can be doubly dissociated in brain damaged patients with anarithmetic acalculia (Dehaene and Cohen, 1997). Thus, in patient BOO, multiplication was impaired in the context of more widespread deficit of rote verbal memory, while subtraction was relatively preserved. Patient MAR showed the opposite pattern, with a disproportionate impairment of subtraction and other quantity manipulation tasks, as compared to multiplication.

Precise expectancies can be derived from this approach as to which types of operations should be impaired or preserved in pure alexic patients. Assuming that multiplication facts are retrieved as rote verbal memories, a prerequisite to the retrieval is that arabic operands be first encoded in a verbal format. Since this translation process is not operative in pure alexia, the arithmetic fact retrieval routine receives wrong inputs and therefore the wrong result is retrieved. This is precisely what occurred with patient V.O.L. For instance, she wrongly transcoded the problem 5 × 9 into “ 4 × 6 ”, and therefore retrieved the erroneous result “ 24 ”. This account explains quite naturally why the patient’s errors were generally the correct responses to the problem she had actually uttered. Note that patient G.O.D., the only other pure alexic patient tested on a multiplication task with operand reading, showed exactly the same pattern of behaviour as did patient V.O.L. (Cohen and Dehaene, 1995).[6]

In contrast, there is no verbally memorized table of subtraction facts. Therefore solving subtraction problems does not necessarily follow Arabic-to-verbal transcoding. The uncoupling of the reading and calculation processes was clearly observable in patient V.O.L.’s behaviour. For instance, the problem 9 – 2 was read erroneously as “ 4 – 3 ” but, in contrast to multiplication, the patient did not compute the result on the basis of what she had verbally produced. Rather she often appeared to correctly identify the operands for the purpose of subtracting them, and to apply a procedure semantically appropriate for subtracting two quantities. These processes operated in parallel with, and independently from, the impaired Arabic-to-verbal transcoding, eventually resulting in the correct response on a majority of trials. As mentioned before, patient H.A.R. showed just the same dissociation as V.O.L. between impaired multiplication (68% errors) and preserved subtraction (4% errors) (McNeil and Warrington, 1994). As visible on Figure 4, the triple code model asserts that

[6] It would be logically possible that the patient misread the multiplication operands, and then retrieved the result appropriate to the numbers she had uttered using any *nonverbal* type of representation. However this hypothesis would require additional processing stages and representations, relative to our more economical proposal. Also this hypothesis would not explain by itself why multiplication behaved differently from other operations.

quantity manipulation abilities are distributed over the two hemispheres. If we adhere to the anatomical account of pure alexia presented before, it follows that patients V.O.L. and H.A.R. relied (1) on their intact right hemisphere for digit identification; (2) possibly on both their right and left hemispheres for semantic subtraction abilities; and (3) on their left hemisphere for the verbal output from both the (impaired) naming and the (relatively preserved) subtraction processes. These localizations should presently be considered as working hypotheses predicted from the triple-code model, which should help guide further research.

The status of addition and division is in principle more ambiguous, and no clearcut prediction can be derived from the triple-code model (Dehaene and Cohen, 1995). While many simple addition problems are memorized in a verbal form like multiplication problems, they can also be solved rapidly using counting and other backup strategies such as referring to 10 (6 + 5 = 6 + 4 + 1 = 10 + 1 = 11). The contribution of such strategies has been mostly studied in children (e. g. Ashcraft, 1992), but is also attested in normal adults (LeFevre *et al*., 1996).[7] Two parallel circuits, then, seem to be available for addition: rote verbal retrieval, or strategical quantity manipulations.

Because of this redundancy, it should therefore not be surprizing that addition sometimes benefits from the same sparing as subtraction in patients in whom rote verbal retrieval is impaired but quantity processing is preserved. Such was the case in patient V.O.L. One additional difficulty, however, is that in other patients, rote verbal retrieval may be the preferred strategy for single-digit addition. It is rather frequent, indeed, for patients with even very severe impairments of arithmetic fact retrieval to refuse to use backup strategies such as counting, stating that they should know the answer by rote. In such patients, addition should then behave like multiplication: both should be spared or impaired together. Such was the case, indeed, in patients H.A.R. (McNeil and Warrington, 1994) and G.O.D. (Cohen and Dehaene, 1995). The trouble, of course, is that it is not easy to predict whether a given patient will behave one way or the other. Table 4 summarizes the patterns of dissociations between multiplication, addition, and subtraction that are possible according to the triple-code model. The only clear prediction concerning addition is that it should always fall in-between

[7] Use of strategies has also been reported for multiplication (Lefevre, 1996). However such strategies then typically consist in resorting to other stored facts (e.g. computing 7 × 8 as 8 × 8 − 8). Hence, contrary to addition, strategy use in multiplication cannot be considered as a distinct alternative to rote fact retrieval.

multiplication and subtraction. It should never be possible to find a patient with impaired multiplication *and* subtraction, yet with relatively preserved addition; nor should it be possible to have a selective impairment of addition relative to multiplication *and* subtraction. To the best of our knowledge, no published case to date contradicts this prediction. Leaving aside the case of patient H.A.R. that we just discussed, several patients have been reported with arithmetic impairments affecting multiplication more severely than subtraction (Dagenbach and McCloskey, 1992; Dehaene and Cohen, 1997; Lampl *et al*., 1994; Pesenti *et al*., 1994), or subtraction more severely than multiplication (Dehaene and Cohen, 1997; Delazer and Benke, 1997). The performance of all these patients with addition problems was intermediate between their performance with multiplication and subtraction problems.

Division is the less routinized of all four arithmetic operations, and has received even less attention than subtraction in cognitive studies. It can probably be solved using a variety of methods. One such strategy consists in searching in memory for the corresponding multiplication fact. For instance, 45 ÷ 9 may be solved by searching the 9 times table, retrieving " 5 × 9 = 45 " in verbal format, and producing the result " 5 ". While this is probably the dominant strategy for relatively large problems, the simplest division problems, such as those presented to patient V.O.L., can also be solved using semantic procedures. For instance, halving a number can be performed by referring to the corresponding tie addition fact (6 ÷ 2 = 3 because 3 + 3 = 6). Indeed, patient V.O.L.'s error rate with such extremely simple division problems was lower than her error rate for multiplication, and similar to her error rate for addition facts, suggesting that she did not resort to her multiplication table to compute these division facts.[8] Conversely, Cipolotti and de Lacy Costello (1995) studied a patient with a selective impairment of division, suggesting that when rote arithmetic facts are preserved, an impairment of semantic elaboration may deprive the patient of the ability to search his store of multiplication facts under semantic guidance (Dehaene and Cohen, 1995).

To close this discussion, it should be acknowledged that the sparing of subtraction, addition, and division in patient V.O.L. was only relative. While V.O.L.'s arithmetic abilities with arabic operands were significantly superior to what could be expected from her reading

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[8] We computed V.O.L.'s error rate with a subset of multiplication problems matched to the division problems in terms of the underlying numerical fact, i.e. multiplication problems with a product less than or equal to 20. She made 84.0% multiplication errors, while division problems yielded only 33.9% errors ($P < 10^{-5}$).

performance, she still made more errors with Arabic than with orally presented problems (28-39% vs 11-14%). This difference would be predicted by essentially any model of number processing (including the triple-code model). It is not surprising that an impairment of the direct visual input to left-hemispheric calculation routines should affect to some extent *all* types of operation with visually presented operands. This point, however, is independent from our crucial prediction that all operations should not be affected to the same degree. The patient was unable to activate normally her left hemispheric arithmetic routines on visual input, for all types of operations. However, the availability of a residual (presumably right-hemispheric) numeral identification system allowed her to compensate significantly, albeit not completely, for this deficit, at least for operations that normally involve quantity manipulations.

Is it possible to speculate more precisely as to why the residual mechanism subtending the spared operations was not perfectly accurate? Several compatible sources of inaccuracy may be considered here. First, there may be a small left-hemispheric advantage for visual identification of digits, as suggested by the slight asymmetry observed in split-brain patients in number comparison and same-different judgement tasks (Cohen and Dehaene, 1996; Corballis, 1995; Seymour *et al*., 1994). Second, there may be some loss of information due to callosal transfer. We proposed that this mechanism explained why when reading aloud arabic numerals presented in her left visual field, a patient with a posterior split-brain produced errors numerically close to the target (Cohen and Dehaene, 1996).

Third, the quantity representation which is presumably involved in the residual arithmetical abilities is thought to encode quantities as distributions of activation on a internal number line (Dehaene and Changeux, 1993). Because the distributions that encode two nearby quantities are assumed to overlap, any variance in the quantity representation may generate confusions between nearby numbers. Such variance could have been increased as a result of patient V.O.L.'s lesion, which disrupted the left-hemispheric route for accessing the quantity system from Arabic numerals. According to our model, contrary to a normal subject, V.O.L. could not access her normal quantity system bilaterally, but only through a right-hemispheric visual-to-quantity route. This would have placed a greater emphasis on V.OL.'s right-hemispheric quantity system, which may be inherently less precise that the right. Two empirical finding provide some support for this argument. First, the analysis of V.O.L.'s subtraction and addition errors confirmed that these errors reflected the intervention of quantity processing: as mentioned before, most erroneous responses to subtraction problems were false by only 1 unit. Second, another patient, N.A.U. (Dehaene and Cohen, 1991), following a large left-hemispheric lesion which presumably affected the left-hemispheric visual, quantity, and language components of the number processing system, could only calculate in an approximate manner. Patient N.A.U. made numerous proximity errors with addition problems, but could not provide any sensible approximation to multiplication problems. This pattern of errors may be considered as an exacerbation of the one observed in patient V.O.L.

Role of counting in the preserved abilities

During the digit naming task, we observed that, although she used it only occasionally, a counting strategy was available to the patient, allowing her to circumvent to some extent her reading impairment. One should note that the availability of this strategy, that is common to many patients with a number reading deficit, does not speak against the idea that the Arabic-to-verbal translation system was deprived of its normal input. According to the triple-code model, the normal reading pathway involves the left temporal visual identification system, the verbal system, and their connexions, with no necessary involvement of quantity representations. In pure alexia, the normal reading pathway is deprived of its input, and residual visual recognition is presumably achieved by the right-hemispheric visual system, allowing for an access to number meaning (e.g. quantity N). Concurrently patients start reciting the verbal series of number names, and stop when they reach the N^{th} element in the series.

One may still ask whether patient V.O.L. used a counting strategy for covertly naming the operands during calculation, which might explain her relatively good performance. While no direct evidence is available, several converging arguments suggest that the patient did *not* recode the operands as words through counting. First, there was no positive evidence of counting during arithmetic tasks, contrary to what was observed during part of the simple reading task, in which the patient overtly counted in order to name Arabic targets. Second, as shown in footnote 4, the rate of operand reading errors did not differ from the error rate observed in the simple digit reading task, when the patient *did not* resort to a counting strategy. Third, the counting strategy is fundamentally used by patients to compensate for their naming deficit, and it is therefore very unlikely that the patient should first read aloud the operands erroneously, and subsequently name them correctly through covert counting; there was no observable indications that the patient ever proceeded in this way. Furthermore, if we assume that the patient counted during subtraction and not multiplication, even if covertly, one could expect a lower rate of operand reading errors in the former than in the latter case, which was not the case. Fourth, why would the patient resort to counting for subtraction and not multiplication, since it would be equally beneficial in all cases? One may speculate that, as subtraction can be solved through counting more naturally than multiplication, the patient may have used counting for naming subtraction operands more than multiplication operands. However, while we acknowledge that some internal counting process may have contributed to subtraction solving, still there is no indication that V.O.L. named operands covertly through counting. Finally, one may note that in comparison and parity judgement tasks, RT data are clearly incompatible with the idea that the patient named covertly the operands through counting.

Other accounts of pure alexia and number processing deficits

The triple-code model, with its distinction between rote verbal arithmetic and quantity manipulations, provides a coherent account of the present observations. For other models, the pattern of dissociations presented by patient VOL poses special challenges.

Most models of number processing, or indeed of word processing, have postulated a single module devoted to visual identification, serving as input to all subsequent processing (McCloskey, 1992; Warrington and Shallice, 1980). Yet it seems difficult for number processing theories that feature a single visual number identification system to explain how pure alexic patients can both read Arabic numerals aloud erroneously and correctly identify them for the purpose of calculation. It has been suggested that “ partial identification ”, or “ weak activation ” could be sufficient to perform above chance level in some gross classification tasks, but not to read aloud a word or a numeral accurately (e.g. Bub and Arguin, 1995; Bub *et al.*, 1989; Farah and Wallace, 1991). Could our data be explained entirely by residual processing within a partially deteriorated left-hemisphere, rather than by an intact right-hemispheric route? We previously argued that a partial deterioration of the identification of numerals could not explain the sharp contrast between pure alexics’ flawless performance in number comparison and their major impairment in reading the same stimuli aloud (Cohen and Dehaene, 1995). The argument may be even more compelling in the present case with preserved arithmetic operations. Within the very same trials, patient V.O.L. was correct in solving arithmetic problems which demanded an exact identification of the operands, and largely mistaken in reading them aloud. Such behaviour is incompatible with the hypothesis of a single, partially damaged identification system. Furthermore, even assuming that a single partially damaged route could explain some paradoxical residual processing, one would not expect that such sparing would differentially affect the various types of operations. Rather one would expect that a visual input of equivalent quality would be delivered, say, to addition and multiplication routines. Since these routines were themselves essentially intact, or at least equally preserved, as demonstrated by the good performance on orally presented problems, performance with Arabic problems should not show such a dissociation between operations.

A contrario, this argument implies that the dissociation between operations necessarily results from a differentially impaired input from vision to multiplication and to the other arithmetic operations. Therefore our observation poses a problem not only for single-route models of arabic number recognition, but also for models of mental arithmetic that assert that all problems are solved using a unique abstract and amodal representation of numbers (McCloskey, 1992). In this view, an impairment of a peripheral module devoted to the identification of visual Arabic inputs should affect all types of operations equally.

Conclusion

In summary, our observations support both a firm functional conclusion and a clearly more tentative anatomical hypothesis. The functional conclusion is that there must be two distinct visual identification processes for numbers, one that is the mandatory input pathway to naming and multiplication processes, and the other that is able to supply comparison, addition, subtraction and simple division routines. Only the first of these seems to be impaired in patient V.O.L. The tentative anatomical hypothesis is that the second of these processes may well depend on the patient’s intact visual processing in the right hemisphere. Indeed, this assumption is central to the anatomical implementation of the triple-code model of number processing. Its eventual validation, however, will have to await further experiments.

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Appendix: Residual word processing abilities

The patient's residual word processing abilities were assessed using several tasks, all based on the same experimental method. The patient was presented with randomized lists of lower-case alphabetic stimuli, and instructed to perform a dichotomic decision and to respond by pressing either a left-hand or a right-hand key. In order to discourage explicit reading and letter-by-letter strategies, stimuli were displayed on a computer screen for 300 ms using the EXPE software (Pallier *et al*., 1997). It was stressed that the patient should not attempt to read stimuli, but just try to guess and to respond at a glance. Considering her own insuperable reading difficulties, the patient willingly accepted such instructions. Error rates and mean reaction times are summarized in Table 5.

Lexical decision

The patient was presented with several lists, each comprizing an equal number of real words and of matched non-words. The patient was asked to decide whether each stimulus was a real word or not, and to respond by pressing the right-hand key or the left-hand key, respectively. Unless stated otherwise, the experimenter was blind to the stimuli displayed to the patient.

Lists 1 and 2 each comprized 15 concrete and high-frequency nouns (mean $\log_{10}$ frequency = 2.47 per million; range = 2.05-3.30), 4-6 letters and 1-2 syllables in length, and 15 random consonant strings of matched length. List 2 was run twice. Lists 3 and 4 differed from lists 1 and 2 in that the non-words were orthographically and phonologically legal pseudo-words derived from the real words by changing a single letter at varied positions. List 3 was presented twice, and list 4 was presented 3 times.[9] Lists 5 and 6 obeyed exactly the same constraints as lists 3 and 4, including a high frequency range (mean $\log_{10}$ frequency = 2.42 per million; range = 2.01-3.47), except that the words were abstract low-imageability nouns. List 5 was presented once and list 6 was presented twice. List 7 comprized 28 open-class and 28 closed-class words matched with respect to frequency and syllabic length (Segui *et al*., 1982), and 56 legal pseudo-words derived from the real words by changing one letter at varied positions.

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[9] Lists 1, 3, and 4 were run both with the experimenter blind to the stimuli, and with the experimenter seeing the stimuli. The patient's performance did not differ across these two conditions and data were pooled.

As shown in Table 5, the patient performed very significantly above chance level in all 4 variants of the task. She was also quite fast, with mean reaction times ranging from 1096 ms to 1736 ms. Such fast reaction times confirm that the patient did not resort to a slow and error prone letter-by-letter reading strategy. This conclusion was reinforced by the fact that reaction times were never correlated with stimulus length, as measured by the number of letters.

The patient was almost perfect when she had to discriminate real words from consonant strings (4.4% errors). She then had the feeling that she was not responding randomly, but rather spotting out letter combinations that looked unusual or impossible in French. However, she said she had not been able to identify a single word. When real words were mixed with legal pseudo-words, V.O.L.'s performance decreased to a 20-30% error rate. She had the feeling that she responded in an essentially random fashion, and reported that all items looked about as good to her. She denied having identified a single word. Finally, one should note that error rates did not differ between concrete and abstract words (28.0% and 30.3% errors, respectively), nor between closed-class and open-class words (25.0% and 21.4% errors, respectively).

Language decision

V.O.L., who spoke and read English fluently, was presented with a list comprizing 38 frequent French words (19 body parts and 19 number words), and the English translation of these words.[10] The patient was asked to decide whether each stimulus was a French or an English word, and to respond by pressing the right-hand key or the left-hand key, respectively.

The patient made 25.7% errors, a performance far better than chance. Her mean reaction time was 1365 ms, and reaction times were not correlated with word length. V.O.L. had the feeling that she did not respond quite randomly, but rather that she could identify letter combinations that looked unusual in French or were suggestive of English words. She said she had not been able to identify a single word, and indeed had no idea that the list comprised names of body parts or number words.

In order to determine whether the patient performed the language decision on the basis of orthographic regularities or on the basis of real word identification, she was asked to perform

[10] For technical reasons, the responses to 2 English words were not recorded.

the same task with another list comprizing 42 English and 42 French frequent words. English words were selected to be potential orthographically legal French words (e.g. voice, give, etc). The patient expressed the feeling of responding at random, which was indeed the case (48.8% errors). Her mean reaction time was 1302 ms. Hence, her previous performance in French-English discrimination was likely due to a partially preserved ability to recognize the structure of French and English orthography.

Semantic decision

In order to determine whether she could gain access to the meaning of words that she was unable to read aloud, the patient was asked to perform a semantic decision task. We used four different lists of stimuli. List 1 comprized 25 names of familiar foods and 25 other concrete names matched one-to-one in terms of frequency, number of letters, and number of syllables. List 2 comprized 25 names of familiar animals and 25 other concrete names matched on the same criteria. List 3 comprized 19 names of body parts and 19 spelled-out number names, matched in overall frequency and length. List 4, which was presented twice, comprized 24 emotionally pleasant familiar words and 24 unpleasant familiar words (e.g. friend, love, nice, laugh, vs ugly, bitter, cry, death).

With the first 3 lists, the patient was asked to decide on each trial whether the stimulus belonged to the target category (food, animal, body part) or not, and to respond by pressing the right-hand key or the left-hand key, respectively. With the fourth list, she was asked to press the right-hand key to pleasant words, and the left-hand key to unpleasant words. With the first two lists, the experimenter was blind to the stimuli.

As shown in Table 5, V.O.L. did not respond significantly above chance level with any of the 4 experimental lists. Mean reaction times ranged from 1115 ms to 2374 ms. She had the feeling that she responded completely at random, and reported having absolutely no intuition as to the meaning of stimulus words.

Legends for figures

Figure 1:

Axial MRI section of patient V.O.L.'s brain showing an infarct in the territory of the left posterior cerebral artery.

Figure 2:

Error rate in solving orally presented arithmetic problems (*left*), and in reading aloud (*middle*) and solving (*right*) visually presented arithmetic problems. On oral input, error rates are low and do not differ across operations. With visually presented problems, reading performance is severely impaired for all operations types. However, calculation performance is better than could be expected from the performance in reading, for all operations except multiplication.

Figure 3:

Percentage of trials in which the patient's proposed solution to an arithmetic problem was correct relative to the original problem (*left*), or relative to the problem as it was read aloud by the patient (*right*). Only critical trials in which the patient's operand reading errors changed the problem result were included in this analysis. In subtraction, addition, and division, the response was generally correct relative to the original problem. In multiplication problems, the patient's response was generally correct relative to the spoken problem.

Figure 4:

Anatomical and functional model of the normal number processing system (*upper panel*), and of the system as lesioned in pure alexia (*lower panel*). Arabic numerals and abstract quantities can be processed by both hemispheres, while only the left hemisphere is able to represent numbers in a verbal format. Pure alexia for numbers results from an impairment of the left-hemispheric visual number form, precluding the translation of arabic numerals into words, and hence the retrieval of stored multiplication facts. Subtraction problems can still be solved, like number comparison, on the basis of the quantity representation.

Figure 5:

Default pathways thought to be used for solving familiar multiplication problems (*upper panel*), and subtraction problems (*lower panel*).Multiplication facts are learned by rote and retrieved as automatic verbal associations. Subtraction requires the manipulation of the quantities represented by the operands.

Table 1: Summary of arithmetic tasks (error rates).

	multiplication problems	subtraction problems	addition problems	division problems	total
Calculation on oral input	3/36 (8.3%)	5/36 (13.9%)	4/36 (11.1%)	3/28 (10.7%)	15/136 (11.0%)
Reading aloud Arabic operands					
all errors	31/36 (86.1%)	31/36 (86.1%)	29/36 (80.6%)	24/28 (85.7%)	115/136 (84.6%)
critical errors only	30/36 (83.3%)	29/36 (80.6%)	27/36 (75.0%)	23/28 (82.1%)	109/136 (80.1%)
Calculation on Arabic input					
with operand reading	30/36 (83.3%)	10/36 (27.8%)	14/36 (38.9%)	8/28 (28.6%)	62/136 (45.6%)
without operand reading	33/36 (91.7%)	10/36 (27.8%)	14/36 (38.9%)	11/28 (39.3%)	68/136 (50.0%)
pooled	63/72 (87.5%)	20/72 (27.8%)	28/72 (38.9%)	19/56 (33.9%)	130/272 (47.8%)

Table 2: Comparison of error rates with subtraction, addition, and addition problems *vs* multiplication problems matched in result magnitude.

	subtraction problems	addition problems	division problems	total
Calculation errors	20/72 (27.8%)	28/72 (38.9%)	19/56 (33.9%)	67/200 (33.5%)
Errors with multiplication problems matched in size	16/18 (88.9%)	28/32 (87.5%)	20/22 (90.9%)	64/72 (88.89%)
	$P < 10^{-4}$	$P < 10^{-4}$	$P < 10^{-4}$	$P < 10^{-4}$

Table 3: Illustration of the dissociation between perserverative operand naming and preserved calculation. On 6 out of 36 subtraction trials, the patient read aloud the operands as " 4 – 3 ". Nevertheless, she always produced the correct result, a variable number ranging from 1 to 7.

Stimulus	patient's response	
	operand reading	result
2 – 1	4 – 3	1
4 – 2	4 – 3	2
9 – 2	4 – 3	7
4 – 3	4 – 3	1
5 – 3	4 – 3	2
7 – 1	4 – 3	6

Table 4: Patterns of dissociation between operations predicted by the triple-code model of number processing. For each operation, crosses indicate relatively impaired, and dashes relatively preserved performance. The first five patterns have been observed in the literature. The last two patterns are predicted not to occur. Patient VOL's deficit falls in the first category (impaired access to rote verbal memory from written problems).

Multiplication	Addition	Subtraction	Commentary
×	-	-	Impaired rote verbal memory
-	-	×	Impaired quantity manipulations
×	×	-	Impaired rote verbal memory + reliance on rote memory for addition
-	×	×	Impaired quantity manipulations + reliance on quantity manipulations for addition
×	×	×	Global acalculia
×	-	×	Impossible pattern

-	×	-	Impossible pattern

Table 5: Summary of residual word processing abilities. Error rates are compared to chance level using χ^2 tests for goodness-of-fit.

	error rate		mean RT [a]
Lexical decision			
concrete words vs consonant strings	4/90 (4.4%)	$P < 10^{-5}$	1178 ms
concrete words vs pseudo-words	42/150 (28.0%)	$P < 10^{-5}$	1736 ms
abstract words vs pseudo-words	27/89 (30.3%)	$P < 10^{-3}$	1384 ms
open-class words vs pseudo-words	14/56 (25.0%)	$P < 10^{-3}$	1096 ms
closed-class words vs pseudo-words	12/56 (21.4%)	$P < 10^{-4}$	1109 ms
Language decision (French vs English)			
without orthographic matching	19/74 (25.7%)	$P < 10^{-4}$	1365 ms
with orthographic matching	41/84 (48.8%)	$P = 0.83$	1302 ms
Semantic decision			
food vs non-food	29/50 (58.0%)	$P = 0.26$	1840 ms
animals vs non-animals	22/50 (44.0%)	$P = 0.40$	1666 ms
body parts vs numerals	19/38 (50.0%)	$P = 1$	2374 ms
pleasant vs unpleasant	42/96 (43.7%)	$P = 0.22$	1115 ms

[a] A total of 6 trials with a RT longer than 6 seconds were excluded from the computation of mean reaction times.

Figure 1

Figure 2

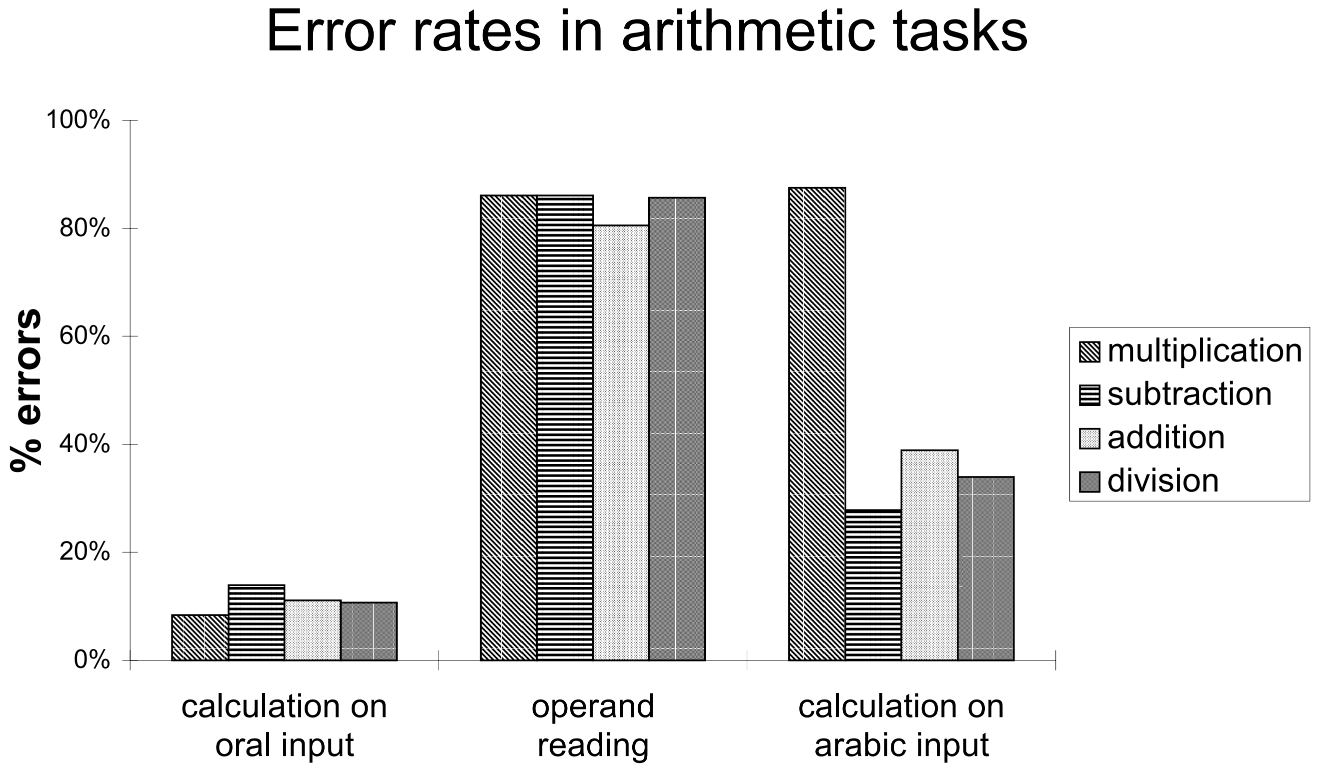

Error rates in arithmetic tasks
100%
80%
60%
40%
20%
0%
% errors
calculation on oral input
operand reading
calculation on arabic input
multiplication
subtraction
addition
division

Figure 3

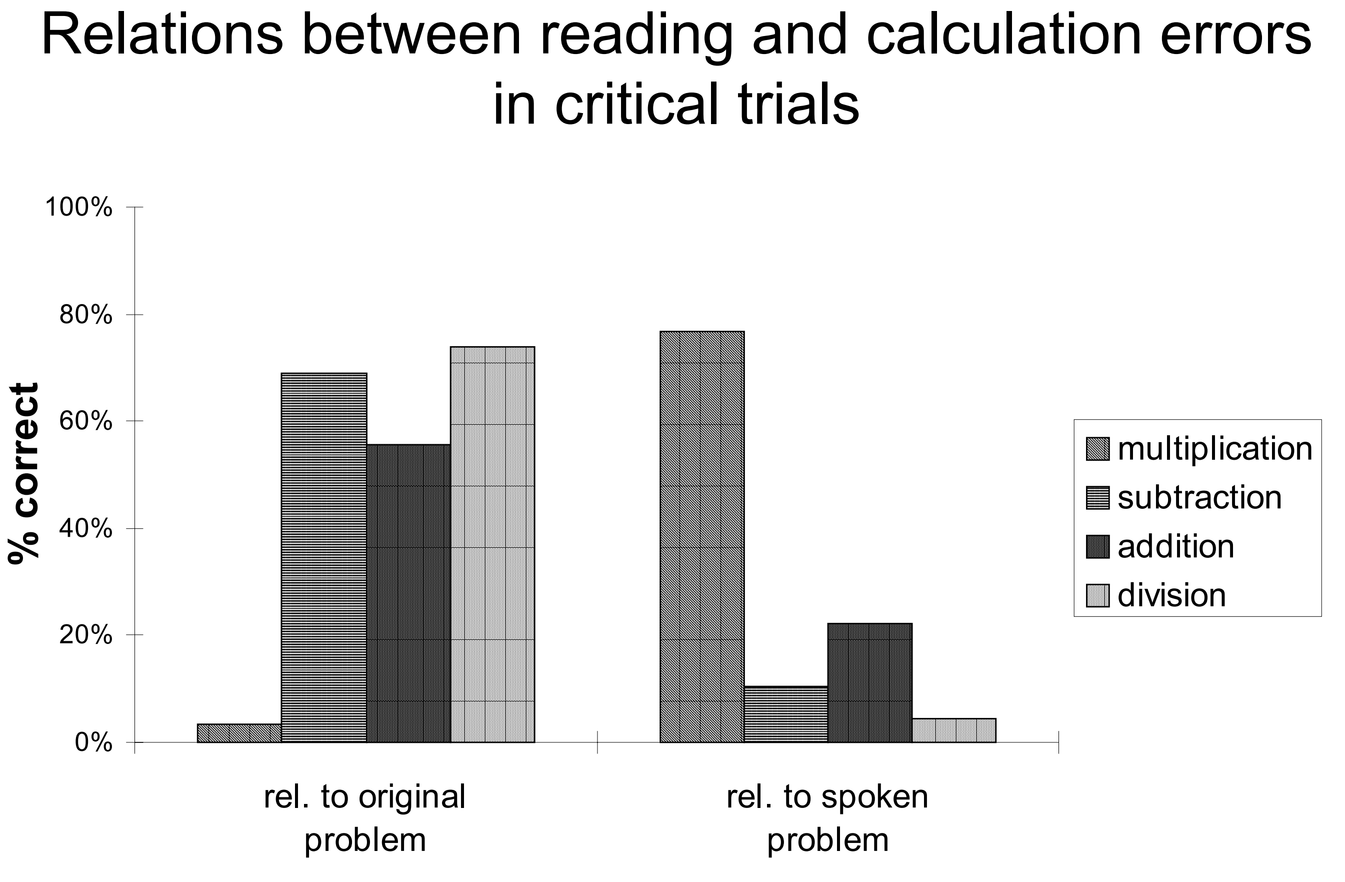

Relations between reading and calculation errors in critical trials
100%
80%
60%
40%
20%
0%
% correct
rel. to original problem
rel. to spoken problem
multiplication
subtraction
addition
division

Figure 4

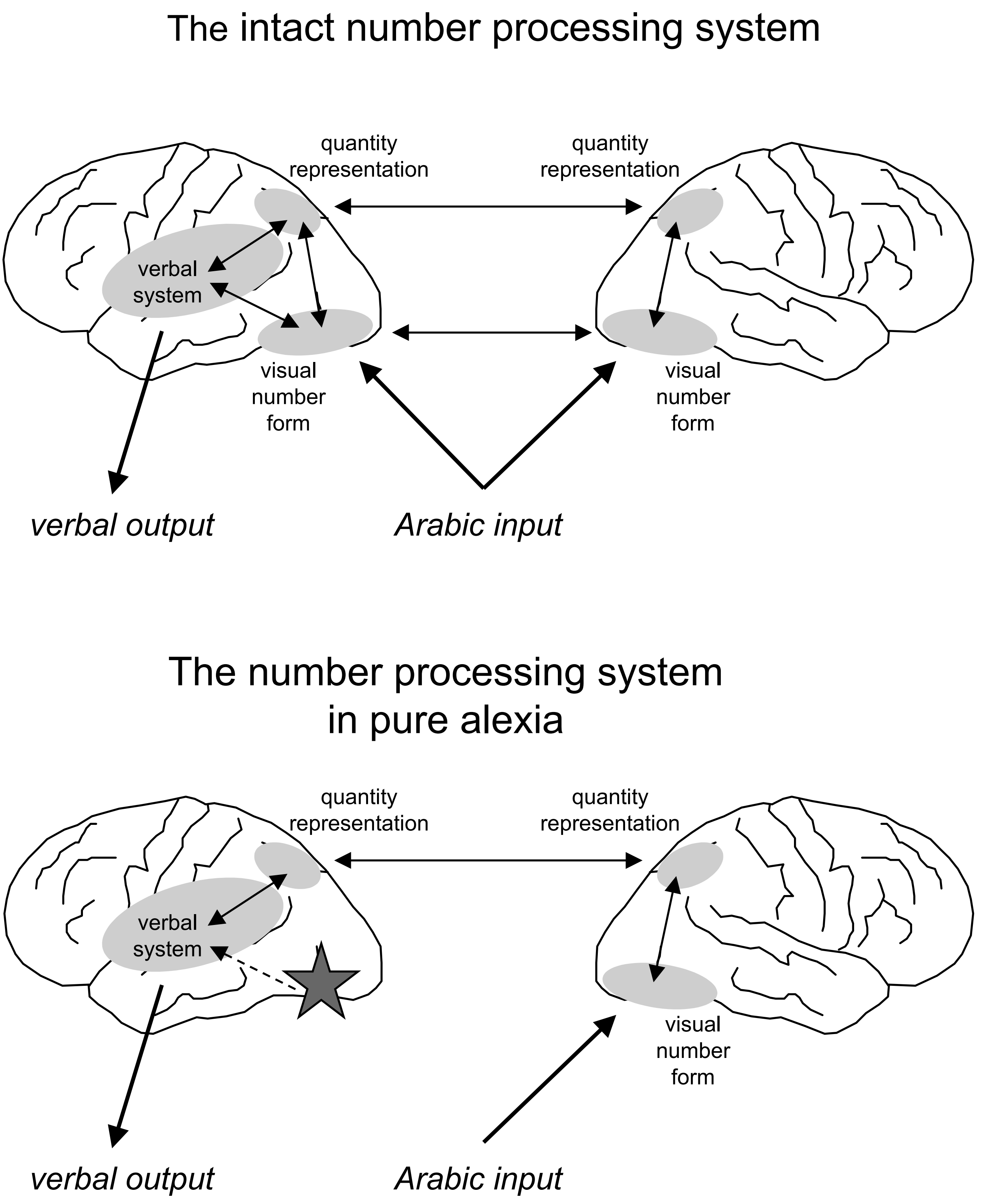
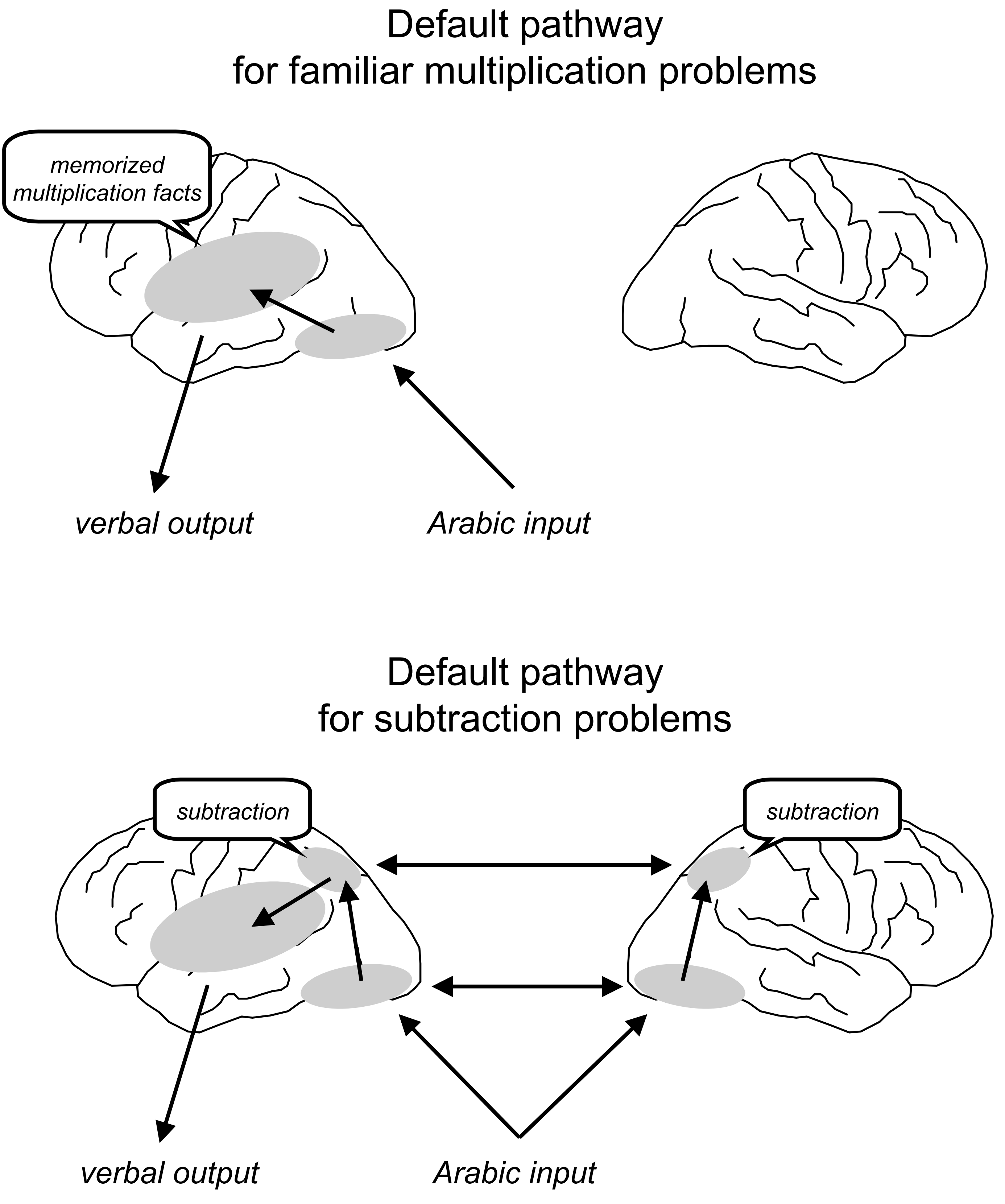

The intact number processing system
quantity representation
quantity representation
verbal system
visual number form
visual number form
verbal output
Arabic input
The number processing system in pure alexia
quantity representation
quantity representation
verbal system
visual number form
verbal output
Arabic input

Figure 5


Default pathway
for familiar multiplication problems
memorized multiplication facts
verbal output
Arabic input
Default pathway
for subtraction problems
subtraction
subtraction
verbal output
Arabic input