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Number words and number non-words

A case of deep dyslexia extending to arabic numerals

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Summary

Although the ability to process numerical symbols may be considered a special case of more general linguistic abilities, deficits affecting numbers and words are usually interpreted within entirely independent frameworks. We report a patient presenting typical deep dyslexia, as confirmed in a series of word and non-word reading tasks. Moreover, the main features of his deficit extended to arabic numerals. The patient was equally unable to read aloud non-words and unfamiliar numerals, whereas he performed significantly better with real words and familiar arabic numerals such as famous dates or brands of cars. Additionally, familiar numerals and words yielded qualitatively similar errors, as did unfamiliar numerals and non-words. This contrasting performance with familiar and unfamiliar numerals seems incompatible with any single-route model of number reading. It is rather consistent with the existence of two routes for number reading: a 'surface' route mapping any digit string into a word sequence according to language-specific rules; and a 'deep' semantic route functioning only with familiar items that possess a specific lexical entry. We therefore suggest that number reading is architecturally similar to word reading, although these two processes probably rest on functionally and anatomically distinct pathways.

Key words: reading; numbers; acalculia; dyslexia; aphasia

Introduction

It is a common belief that most subjects from Western cultures master only one written notation system, namely alphabetic notation. However, this overlooks another frequent and overlearned albeit non-alphabetic script, the system of arabic numerals. Arabic notation is akin to an ideographic script, since each elementary symbol, i.e. each digit, roughly corresponds to one word rather than to one phonological unit. Déjerine (1891, 1892) already noticed that in patients with acquired dyslexia, number reading could be relatively spared as compared with word reading. Nevertheless, processing of numerals is but a special case of the more general linguistic endowment specific to human adults. Although their precise relationships presently remain largely unspecified, number and language-processing systems are therefore likely to share the same general operating principles. It seems of considerable neuropsychological interest to understand how the alphabetic and arabic notation systems are represented in the brain, and at which level they interact.

The neuropsychology of number processing has seen an impressive development in the past 10 years (e.g. McCloskey, 1992). Most researchers in this field have taken the a priori stance that numerical deficits were best studied separately from language deficits, even in patients in whom there was evidence of concomitant dysfunction in both systems. As a result, very detailed models of number processing have been developed independently of, and often in contradiction with, models of language processing. This gap is clearest in the case of reading mechanisms. It is now widely acknowledged that word reading may proceed in parallel through two distinct functional pathways (for contrasting views, *see* Humphreys and Evett, 1985). Letter strings may be translated into a sequence of sounds by applying language-specific spelling-to-sound mapping rules. Familiar letter strings such as words, on the other hand, may be identified from a visual input lexicon and pronounced on the basis of their stored phonological representation. Although evidence is still inconclusive on this issue (e.g. Shallice, 1988), we will assume that the latter lexical reading pathway may be further divided into a semantic route and a route directly connecting the visual input lexicon to the phonological output lexicon, thus bypassing the semantic store (*see* Fig. 1).

While the existence of multiple pathways is well accepted in the domain of word reading, most current models of number reading postulate only a single reading route. According to

McCloskey's influential model, any input numeral must be initially converted by dedicated comprehension modules into an abstract amodal semantic representation of numbers, before it can be mapped by dedicated production modules into an adequate sequence of words (McCloskey *et al.*, 1986). Thus, McCloskey's model explicity denies the existence of an asemantic or 'surface' transcoding route for arabic numerals. Conversely, Deloche and Seron (1987) have suggested that number transcoding processes do not involve an intermediate level of semantic coding and they have proposed simple algorithms for the direct mapping, without semantic mediation, of arabic numerals to verbal notation and vice versa.

We report a patient whose word reading performance typically corresponded to the syndrome of deep dyslexia (Marshall and Newcombe, 1973). It is generally admitted that such patients read through a relatively spared lexical semantic pathway. The main defining features of deep dyslexia are the inability to read non-words, an advantage of high-imagery over abstract words and of open-class over closed-class words. In addition, errors with words not only typically include semantic, but also visual and morphological errors.

Detailed explorations of number reading and processing indicated that several characteristics of deep dyslexia extended to arabic numerals. In particular, the patient was much better at reading familiar and meaningful numerals, such as his own birth year or famous dates, than at reading unfamiliar numerals of matched complexity. We argue that his pattern of performance does not fit any single route model of number reading, but can be readily accounted for by a dual-route model. More generally, we suggest that word and number reading share the same general architecture and discuss the extent to which they possess common processing components.

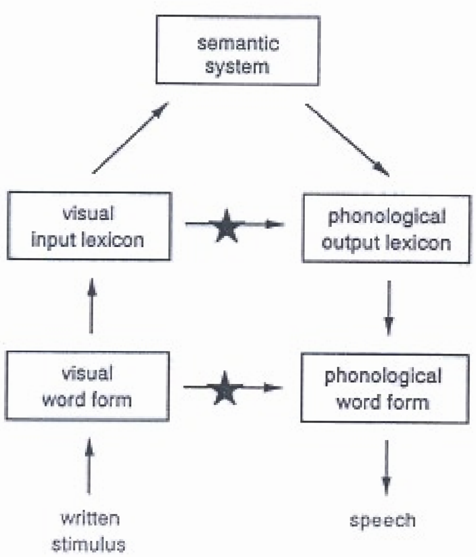

Fig. 1 The standard 'three-route' model of word reading. The surface route directly maps letter strings into phonemic sequences. The lexical route is divided into a direct asemantic pathway, and a 'deep' semantic pathway. Only the latter is considered operational in deep dyslexia (a star indicates lesioned pathways).

Case history

The patient was a 43-year-old right-handed man, with a history of moderate alcohol and tobacco abuse, working as a technician in industry. He was admitted to hospital in a state of acute confusion following a head injury. A CT scan disclosed an extensive left hemispheric subdural haemorrhage with subfalcial cerebral herniation, and the patient underwent emergency surgery. One month later, he showed a mild right motor deficit and severe aphasia. During the course of the following months, his oral language improved very significantly, although he remained severely dyslexic. Our study was carried out one and a half years after onset. At that time, a CT scan showed an extensive hypodense area involving most of the lateral aspect of the posterior half of the left hemisphere (*see* Fig. 2).

The patient was submitted to a French version of the Boston Diagnostic Aphasia Examination (BDAE) (Goodglass and Kaplan, 1972; Mazaux and Orgogozo, 1982). The overall severity rating was 4. Spontaneous speech was rich and informative and showed some phonological paraphasias and word-finding difficulties. Auditory comprehension was excellent except for the most difficult items of the complex ideational material subtest (word discrimination 70 out of 72, body part identification 20 out of 20, commands 15 out of 15, complex ideational material eight out of 12). Automatic speech was correct (automatized sequences eight out of nine, reciting two out of two). Repetition was perfect except for occasional phonemic paraphasias (words 10 out of 10, high-probability sentences eight out of eight, low-probability sentences eight out of eight). Naming subtests were generally correctly achieved (responsive naming 28 out of 30, confrontation naming 78 out of 105, naming of body parts 27 out of 30). It should be noted that the intermediate score on the confrontation naming subtest resulted mainly from difficulties in reading arabic numerals (e.g. 730 was read as 'sept cent trois', i.e. 703; 7000 was read as 'sept cents', i.e. 700) and in naming colours. The patient produced 11 names of animals on the fluency in controlled association subtest. Oral reading was clearly impaired (words 21 out of 30, sentences five out of 10). Two errors from the word reading subtest deserve mention: With the word 'cercle' (circle) the patient produced a typical semantic error, i.e.'rond' (round), and with the number word, 'dix-huit' (18) he readily stated that it was the age of majority, but nonetheless produced the erroneous response, 'dix-neuf' (19). The patient's performance differed widely across the various subtests for reading comprehension. He scored at a fairly good level in some subtests (word-picture matching 10 out of 10; word recognition six out of eight; symbol discrimination seven out of 10) but quite poorly in others (comprehension of oral spelling one out of eight; sentences and paragraphs four out of 10). Writing was slow and laborious but letters were neatly formed (mechanics two out of three). The patient could easily write the numerals 1 – 10, but could only go as far as E when writing the alphabet (serial writing 30 out of 46). He scored 10 out of 15 on the primer-level dictation subtest. The remaining subtests for the evaluation of writing were not performed. Additionally, the patient was asked to read aloud a few informally presented pronunciable non-words. Not a single item could be read correctly.

To summarize, oral language comprehension and production was only mildly impaired, with some word-finding difficulties. By contrast, processing of written language was severely impaired. Informal analysis of the patient's performance was suggestive of deep dyslexia: he was almost totally unable to read non-words and when reading real words he produced mainly semantic and visual errors. When reading arabic numerals, the patient made many errors, apparently sparing simple digits. Anecdotal evidence also suggested that his ability to identify meaningful numerals was better than his performance when reading them aloud (e.g. for 1992 he responded, 'It is now, but I don't know how to say it').

In the following section we shall evaluate the hypothesis that the patient indeed had deep dyslexia. The hypothesis was suggested through systematic investigation of his word reading abilities.

Investigations

Word reading

Experiment 1: lexical status

On clinical examination, the patient was unable to read a single non-word. In order to confirm this observation, we presented him with a visual list comprising 24 words and 24 non-words. Each non-word was matched to a word with respect to length and syllabic structure. The 48 items were presented in random order over two testing sessions.

The patient could only read correctly a single non-word (23 errors out of 24). For seven items, he produced no response. In seven of the remaining 16 errors he produced real words

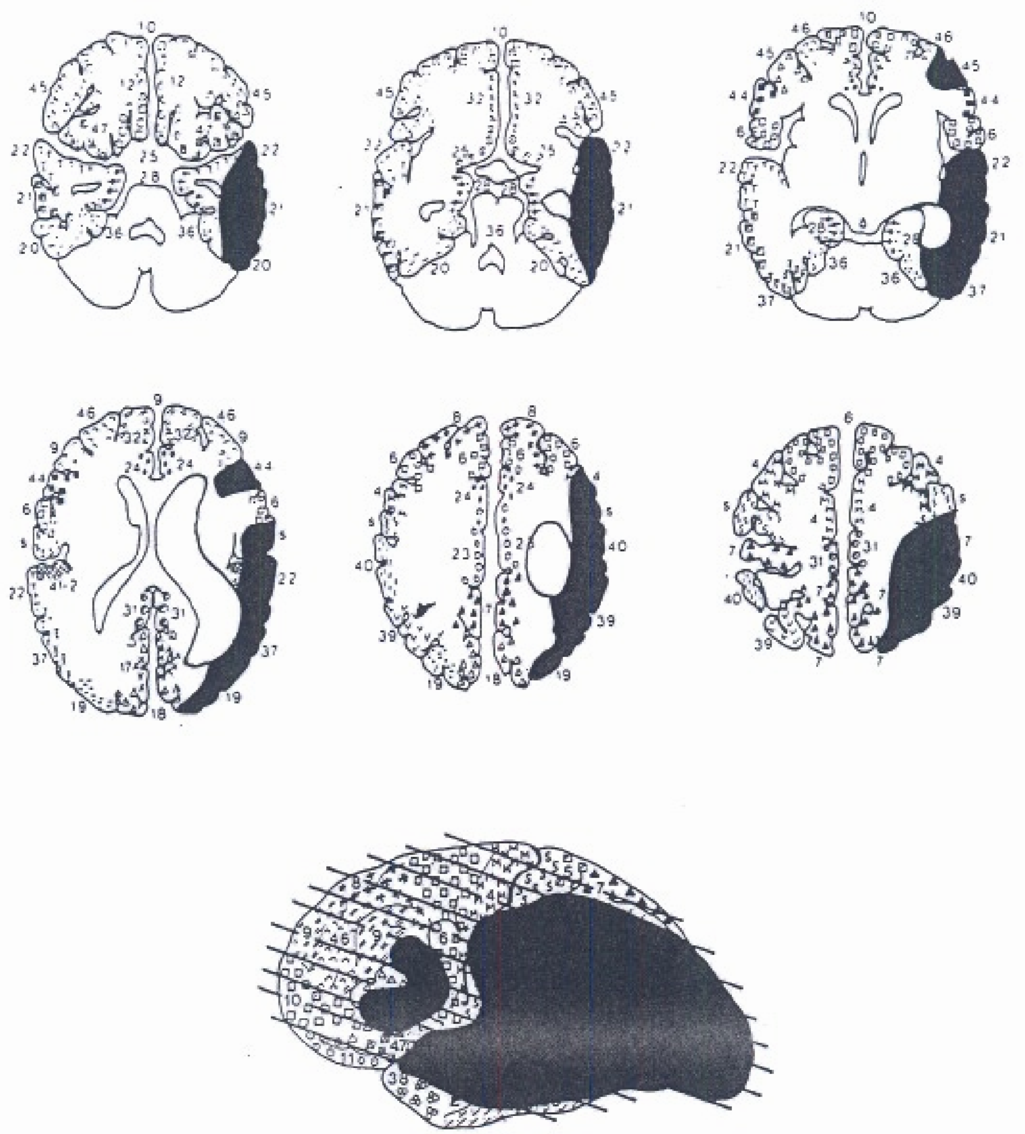

Fig. 2 Reconstruction of the patient's brain on the basis of CT scan using templates from Damasio and Damasio (1989). The left hemisphere is represented on the right side of transversal sections.

visually similar to the target (e.g. for ' mosse' he read 'mousson'; for 'chiloir' he said, 'It looks like Chile, but it is not that!'). In the last nine errors, he produced incorrect non-words. Although clearly impaired, his performance was significantly better with words than with non-words [12 errors out of 24, $\chi^2(1) = 12.76$, $P < 0.0005$]. Four errors were visual (e.g. for 'boucle' he read 'bouche'), five were semantic or morphological [e.g. for 'tissu' (material) he read 'laine' (wool); for 'parole' (speech) he read 'parler' (speak)] and three abstract items (e.g. 'théorie') yielded no response at all.

In brief, non-word reading was almost impossible, reflecting impairment of reading through assembled phonology. However, the patient also produced numerous errors in reading real words, suggesting an additional impairment of reading through addressed phonology. In the following experiments, we examine the factors that govern his performance in reading real words. The critical variables of grammatical class, concreteness, frequency and morphological complexity are studied in turn.

Experiment 2: grammatical category

The patient was presented with a list of 28 open-class and 28 closed-class words, originally devised by Segui *et al.* (1982). Open-class and closed-class words were matched one-to-one with respect to frequency and syllabic length. The 56 items were presented in random order.

The patient performed much better with open-class than with closed-class words [five errors out of 28 and 21 errors out of 28, respectively; $\chi^2(1) = 18.38$, $P < 0.00002$]. Among his errors with closed-class items, the patient produced eight visually similar open-class words (e.g. for 'selon' he read 'salon'), and no answer at all to nine items.

Contrary to the present case, patients with so-called phonological dyslexia, i.e. a selective disruption of their spelling-to-sound pathway, although unable to read non-words, are claimed to show no effect of grammatical class (Beauvois and Derouesné, 1979). In our patient, the deficit in reading closed-class words is suggestive of an additional disruption of the asemantic lexical pathway. Possibly due to their lack of semantic content, grammatical words are considered difficult to read through an isolated semantic route. Although this interpretation remains controversial, it may also account for the advantage of concrete over abstract words displayed by several deep dyslexic patients (Warrington, 1981; Shallice, 1988).

Experiment 3: concreteness

In order to assess the influence of concreteness on the patient's reading performance, we presented him with a list of 15 highly imageable and 15 abstract words. Abstract and concrete words were matched one-to-one for lexical frequency and syllabic length. The 30 items were presented in random order.

The patient was significantly better with concrete than with abstract words [three errors out of 15 and 12 errors out of 15, respectively; $\chi^2(1) = 10.80$, $P < 0.002$]. Most errors with abstract words consisted in the production of visually similar and often more concrete words (e.g. for 'raison' he read 'raisin'; for 'théorie' he read 'théatre').

Experiment 4: word frequency

In order to assess the effect of frequency on reading performance, the patient was presented with a list comprising 20 high frequency nouns (frequency higher than 100 in Gougenheim *et al.*, 1956) and 20 low frequency nouns (frequency lower than three in Gougenheim *et al.*, 1956). In each category, half the items were monosyllabic and the other half were bisyllabic. The proportion of concrete and abstract words did not differ across the two frequency categories. The 40 items were presented in random order.

The performance was significantly better for high frequency than for low frequency words [three errors out of 20 and 12 errors out of 20, respectively; $\chi^2(1) = 8.64$, $P < 0.004$]. It is noteworthy that the three errors with high frequency words occurred with very abstract items ('chose', 'façon', 'moment'). There was no effect of syllabic length.

Experiment 5: morphology

The patient was asked to read a list of morphologically complex words. The list comprised 16 suffixed words, 11 prefixed words and 20 words corresponding to the feminine and masculine of 10 words, the two forms being always orthographically and phonologically different. The 47 words were presented in random order.

The overall error rate was high (36 errors out of 47), probably due partly to the abstract character of many words in the list. As many as half the errors were morphological errors (17 out of 36 errors). Such morphological errors resulted mainly from the suppression of the derivational or inflexional morpheme (e.g. for 'balayeur' he read 'balai'; for 'injustice' he read 'justice'; for 'travaux' he read 'travail').

Experiment 6: lexical decision

The aim of Experiments 6 and 7 was to assess more precisely the function of the presumably intact 'deep' reading route. In order to probe access to the visual input lexicon, the patient was asked to perform a visual lexical decision task. The 56 words were the same as those used in Experiment 2. The 56 non-words were phonologically and orthographically legal letter strings, systematically derived from the real words by changing one letter while maintaining pronunciability. The 112 items were presented visually in random order, and the patient was asked to say whether they were real words or not, while refraining from overt reading.

The overall error rate was 8% (four errors out of 56 with words and five errors out of 56 with non-words). The error rate with words was therefore much lower than in the reading task (four errors out of 56 versus 26 errors out of 56). Classifying a letter string as a word entails an activation of the corresponding record in the visual input lexicon. The patient's excellent performance with stimuli that he could not read, including closed-class words, demonstrates that access to the visual input lexicon was virtually intact (Sartori *et al.*, 1987).

Experiment 7: picture naming

In order to evaluate the function of the phonological output lexicon, as well as its possible involvement in the reading disorder, we compared the patient's performance in matched picture-naming and word-naming tasks. Both of these tasks presumably require access to the same phonological output lexicon (since the patient's non-lexical reading route was not functional). Therefore, any impairment at the level of the phonological output lexicon should affect identically both tasks. The patient was presented with a series of 117 line-drawings for oral naming. The drawings were selected from Snodgrass and Vanderwart's (1981) pictures and displayed on a computer screen. At another session, the patient was asked to read aloud the printed names of the same 117 items.

The patient correctly named 88% of the pictures (14 errors out of 117). Most correct answers (86 out of 103) were produced immediately. With 17 pictures, the patient first verbally commented on the depicted item, demonstrating correct identification and only then reached the correct word. With the 14 items he could not name, the patient always produced correct semantic comments and reportedly had the word 'on the tip of his tongue'. As soon as he was provided with the initial phoneme or syllable, he readily produced the correct answer in all cases.

When reading the corresponding words, the patient was 82% correct (21 errors out of 117). By definition, the list comprised only highly imageable and generally morphologically simple items. This good performance level was indeed quite similar to that observed with simple concrete words in Experiment 3. With 11 words, the patient first commented verbally on the meaning of the item, demonstrating correct identification and only then produced the correct utterance. Among the 21 errors, six were similar to those occurring in picture naming: the patient demonstrated correct identification through semantic comments and produced the correct answer when provided with the initial phoneme or syllable. The remaining 15 errors, just as in all previous reading experiments, were semantic (e.g. for 'girafe' he read 'zebre'), visual (e.g. for 'lapin' he read 'sapin') or morphological (e.g. for 'fourchette' he read 'fourche').

Although quite satisfactory, the patient's performance on the picture-naming task was not perfect. He always correctly identified the pictures, demonstrating normal access to the semantic system from vision and always produced the correct answer, subject to occasional phonological cueing. It is therefore probable that his few errors resulted from a moderate impairment of access to the phonological output lexicon from the semantic system. Since the patient presumably relied only upon his lexical route when reading, it is natural that the very same phonological access difficulties occurred when naming words rather than pictures.

Table 1 *Performance in word and number reading, and in other related tasks (percentage correct)*

READING ALOUD		
Words	12/24 (50%)	$*P < 0.0005$
Non-words	1/24 (4%)	
Open-class words	23/28 (82%)	$*P < 0.00002$
Closed-class words	7/28 (25%)	
Concrete words	13/15 (80%)	$*P < 0.002$
Abstract words	3/15 (20%)	
High frequency words	17/20 (85%)	$*P < 0.004$
Low frequency words	8/20 (40%)	
Elementary numerals	34/42 (81%)	
Complex familiar numerals	24/52 (46%)	$*P < 0.004$
Complex unfamiliar numerals	10/52 (19%)	
Alphabetically written numerals	19/20 (95%)	
OTHER TASKS		
Lexical decision (words)	52/56 (93%)	
Picture naming	103/117 (88%)	
Matched word reading	96/117 (82%)	
Pointing to a number scale	20/20 (100%)	
Two-digit number comparison	96/96 (100%)	
Addition verification	78/84 (93%)	

Discussion of Experiments 1–7

Experiment 1 showed that reading through the non-lexical route was severely impaired, as demonstrated by the complete inability of the patient to read non-words. Experiment 2 further revealed a strong advantage of open-class over closed-class words, suggesting an additional impairment of the lexical asemantic route linking the visual input lexicon directly to the phonological output lexicon. Experiments 6 and 7 showed that these two lexicons were by themselves intact, except for a mild deficit in accessing the phonological output lexicon from semantics. Disruption of both the surface and the lexical asemantic routes are generally considered the functional basis of deep dyslexia. Experiments 3–5 showed that indeed the patient displayed other core features of deep dyslexia, such as concreteness and frequency effects, as well as numerous semantic, visual and morphological errors. The latter features are generally interpreted as reflecting either the function of an intact but isolated semantic pathway, or some additional damage affecting this semantic pathway. In a nutshell, the patient had typical deep dyslexia, with some additional minor word-finding difficulties. Relevant results are summarized in Table 1. We need not be strongly committed to any general position regarding the much debated epistemic status of the deep dyslexia syndrome (for a discussion, *see* Shallice, 1988). The crucial fact is that our patient had a demonstrably completely disrupted surface reading route, together with a relatively spared lexical pathway.

Anecdotal evidence reported above suggested that the patient also had severe difficulties reading numerals. Did this number reading deficit result from the same functional lesion as the word reading deficit? In order to evaluate this hypothesis, a more explicit parallel should first be drawn between arabic numerals and letter strings. Our working hypothesis was that visually familiar numerals are in principle equivalent to real words. They may be identified by sight and thence read through some lexical route. On the contrary, visually unfamiliar numerals are similar to non-words, since they can only be read through non-lexical assembling processes mapping strings of digits to strings of words.

We therefore hypothesized the existence of two categories of arabic numerals: familiar numerals that have a distinctive meaning and unfamiliar numerals that do not have any specific meaning above and beyond the quantity that they represent. Naturally, there are no dictionaries for numerals and it seems likely that there should be considerable inter-individual variability in the size and content of the number lexicon. We therefore used an operational definition and included in the category of familiar and meaningful numerals, highly frequent numerals such as famous dates or brands of cars. Our hypothesis yielded three main predictions. First, a patient with deep dyslexia should perform better when reading familiar than unfamiliar numerals. Secondly, the error pattern with familiar numerals should be similar to that observed with real words. For instance, we should observe numerical equivalents of the semantic, visual and morphological errors. Thirdly, unfamiliar numerals should behave like non-words; for instance, yielding lexicalization errors. These predictions are evaluated in the following section.

Number processing

Experiment 8: reading arabic numerals

The patient was presented with lists of arabic numerals for reading aloud. The lists comprised three types of items: 42 arabic numerals that are realized verbally by a single elementary number word (ones, tens, teens, 100, 1000), 52 familiar arabic numerals and 52 unfamiliar arabic numerals matched to the familiar numerals for number of digits and for syntactic complexity. The familiar numerals were selected for their likely familiarity to the patient: famous historical dates (e.g. 1945), French brands of cars (e.g. 404), familiar zip codes (e.g. 75), etc. The 146 items were presented in random order over two testing sessions.

Reading performance was significantly better with familiar numerals than with matched unfamiliar numerals [28 errors out of 52 and 42 errors out of 52, respectively; $\chi^2(1) = 8.56$, $P < 0.004$]. Elementary numerals were read even more accurately and significantly better than familiar numerals [eight errors out of 42; $\chi^2(1) = 11.91$, $P < 0.0006$]. When asked to read single-digit numbers aloud, the patient often resorted to a counting strategy quite effectively, reciting the overlearned sequence 1, 2, 3 . . . up to the target number. Although less successfully, he used the sequences 11, 12, 13 . . . and 10, 20, 30 . . . with tens and teens, in a similar way. This strategy has been repeatedly reported in patients with left hemispherectomy, extensive left hemispheric lesions or deep dyslexia (Gott, 1973; Coltheart, 1980; Seron and Deloche, 1987; Patterson *et al.*, 1989; Dehaene and Cohen, 1991). The few errors that the patient produced with elementary numerals completely spared single digits and were not homogenous. Three errors affected larger tens, which the patient unsuccessfully attempted to read analytically (for 70 he read 'seven hundred'; for 80 he read 'eight . . .'; for 90 he read 'nine, zero'). There was one semantic approach with no response (for 19 he said 'the age of my daughter'), no response on two trials and two other errors (for 1000 he read 'hundred thousand'; for 16 he read 'eighteen'). The latter error might reflect an inaccurate use of the counting strategy, although this phenomenon was observed only once clearly , during the initial informal evaluation of the patient (for 12 he read 'ten, eleven, twelve, thirteen'). We now turn to a more detailed description of the patient's performance with familiar and unfamiliar numerals.

Familiar numerals. A closer analysis revealed that the patient accurately identified most of the familiar numerals, even when he was unable to read them aloud. For 38 out of 52 stimuli (73%), the patient produced an adequate commentary, demonstrating access to the specific meaning of the item. This semantic approach eventually led him to the correct answer on 16 trials (e.g. for 504 he said, 'the number of the cars that win . . . it was my first car . . . it begins with a P . . . Peugeot, Renault . . . it's Peugeot . . . 403 . . . no, 500 . . . 504!'). In the remaining 22 cases, this adequate semantic approach yielded (i) on seven trials, an adequate commentary with no number name produced (e.g. for 1789 he said, 'It makes me think of the takeover of the Bastille . . . but what?'); (ii) on four trials, a semantically related numeral (e.g. for 1918 he said, 'the end of World War I . . . 1940'); (iii) on 11 trials, various lexical or syntactic errors (e.g. for 205 he read '204'; for 20 000 he read '2000') with an occasional spelling strategy (e.g. for 78 he read 'seven, eight'). Five other familiar numerals were correctly read immediately on presentation, and semantic access was therefore highly probable. Nine of the familiar numerals failed to evoke any meaning to the patient and were apparently treated like the meaningless control numerals (eight errors and no response on one trial).

Unfamiliar numerals. When unsuccessfully attempting to read the unfamiliar numerals, the patient resorted to various strategies. On 14 trials, he produced no response at all. This is similar to the high percentage of 'no response' when he read non-words. On the remaining 28 errors, he often tried to identify, within the target, familiar substrings that he could read more easily. These substrings could be either elementary digits, yielding digit-by-digit reading (e.g. for 726 he read 'seven, two, six'), or more complex meaningful numerals. In the latter case, the patient's semantic approach was similar to that reported earlier with isolated familiar numerals: some substrings could be named accurately [e.g. for 120 he read 'douze' (12); for 330 he said, 'The number of the doctors . . . 'say 33' . . . but with a zero'—when testing the transmission of vocal vibrations through the lungs, French physicians used to ask their patients to utter the numeral 'trente trois' (33)], and others could only be commented upon (e.g. for 1387 he said, 'Marseille is in it') (the zip code for Marseille is 13). Finally, a few stimuli that were not expected to be meaningful were actually familiar to the patient, who identified them readily (e.g. for 65 he said, 'The age of retirement').

Unsuccessful attempts to combine such familiar substrings into complex number names may account for the observed syntactic or substitution errors [e.g. for 602 he read 'six mille deux' (6002)]. For instance, when presented with a numeral in the seventies (e.g. 74), the patient recognized it as 'similar to 75'. He knew that 75, which is the zip code for Paris, is to be pronounced 'soixante quinze'. He also recognized the far right digit 4, which is generally to be pronounced 'quatre' when in the units position. He therefore combined 'soixante quinze' and 'quatre' into 'soixante quatre' (64). On an additional informal experimental list comprising only two-digit numerals, this pattern of error systematically affected all numerals from 70 to 79, except for 75 itself, which was always read correctly.

Discussion. We had derived three predictions from the hypothesis that the patient's impairment with numerals and with letter strings might result from similar functional mechanisms. These predictions were clearly fulfilled in Experiment 8. The patient was significantly better with meaningful than with ordinary numerals, and his errors with these two types of stimuli were qualitatively similar to his errors with words and non-words, respectively.

Even when he could not read a familiar numeral aloud, the patient could often correctly access its specific semantic content. In this context, however, numerals may simply be considered as undecomposable and arbitrary labels pointing to general encyclopaedic knowledge. The specific semantic function of numerals is to refer to quantities. Correct access to the quantity represented by a given arabic number requires the adequate interpretation of each digit in relation to the other digits in the string. The next section evaluates the patient's quantitative comprehension of numerals. If the semantic route of number processing is preserved, and if the deficit affects only a surface reading route, then one might expect number comprehension to be intact.

Experiment 9: number comprehension

Pointing to a numerical scale. The patient was presented with numerals distributed over the interval 0–100. Ten numerals were displayed visually in arabic notation, and 10 others were read aloud by the experimenter. The patient was asked to mark their appropriate location on a vertical axis, 16 cm long, labelled '0' at the bottom and '100' at the top. A different blank axis was used on each trial, so that the patient could not refer to his previous responses.

The patient responded rapidly and accurately. For both oral and written presentations, the location to which he pointed was highly correlated with the correct location ($r = 0.99$ and $P < 0.0001$, in both modalities). The average absolute error was 3.5 units (5.6 mm, range 0–19 mm).

Number comparison. The patient was presented with a list of 10 pairs of arabic numerals of equal length (one to six digits) and asked to point to the larger numeral in each pair. He responded rapidly and with no error.

Two-digit arabic numerals were presented visually for comparison with a standard of 55. On each trial, the patient pressed a response key with his right hand if the target numeral was >55, and another response key with his left hand if the target numeral was <55. In each of two testing sessions, all numerals 31–79 were presented once in random order, preceded by10 training trials. The patient was both fast and very accurate. He did not produce a single error in 96 trials and his mean response time was 1023 ms. Additionally, he displayed a normal distance effect (Hinrichs *et al.*, 1981; Dehaene, 1989; Dehaene *et al.*, 1990): mean reaction times decreased linearly with the logarithm of the absolute difference between the standard and the target [$r = -0.69$, $F(1,22) = 19.80$, $P = 0.0002$].

Verification of written additions. The patient was submitted to a timed addition verification task. Arabic stimuli were presented horizontally on a computer screen (e.g. $2+2 = 5$). The material included 28 additions with one-digit operands and 56 additions with two-digit operands, requesting no carry operation. The proposed result was correct in one-third of the problems, and false in the other two-thirds. The patient was asked to push on a response key with his right hand if the proposed sum was correct and on another response key with his left hand if it was false.

Here again the patient was accurate, although somewhat slow. He only made 7% errors and his mean response time, when responding correctly, was 2391 ms with one-digit problems and 4736 ms with two-digit problems.

In summary, it can be concluded from Experiments 8 and 9 that the patient was excellent at accessing the meaning of numerals, whether they referred just to quantities or to facts stored in semantic memory.

Experiment 10: reading written verbal numerals

The status of alphabetically written number words should be of particular interest, since they stand at the boundary between the two domains whose relationships we are studying: general language and numbers. Documentation of our patient's abilities in reading aloud this type of numeral was unfortunately quantitatively limited, but nonetheless very suggestive. The patient was asked to read aloud 20 written verbal numerals ranging from one to five words, comprising a total of 36 number words. Contrary to arabic numerals, correctly reading aloud complex alphabetically written numerals does not require any syntactic processing of the stimulus. It is sufficient to read each word in turn, without considering its position within the general structure of the number. Indeed, the patient read accurately

Table 2 *Parallels between errors in word and number reading*

FAMILIAR ITEMS			
Semantic approach with correct response*			
504	The number of the cars that win . . . it was my first car . . . it begins with a P . . . Peugeot, Renault . . . it's Peugeot . . . 403 . . . no, 500 . . . 504!	**Candle**	One lights it to illuminate a room . . . Candle!
Semantic approach without response*			
1789	It makes me think of the takeover of the Bastille . . . but what?	**Tomato**	It's red . . . one eats it at the beginning of a meal . . .
Semantic errors*			
1918	The end of World War I . . . 1940	**Giraffe**	Zebra
Visual or morphological errors			
205	204	**Lapin**	Sapin
20000	2000	**Balayeur**	Balai
UNFAMILIAR ITEMS			
Lexicalization errors or analogies*			
120	12	**Mosse**	Monssoon
330	The number of the doctors . . . 'say 33' . . . but with a zero	**Chiloir**	It looks like Chile, but it is not that!
Visually similar non-lexical items			
602	6002	**Pouble**	Pourblé

*Translated from French.

almost all of the individual number words (the one error out of 36 was, for 'thousand' he read 'hundred', self-corrected). He was therefore able to read complex numbers that he surely could not read in their arabic form (e.g. one thousand three hundred and nineteen) correctly. With each individual number word, just as with elementary arabic numerals, he frequently resorted to a counting strategy. For instance, when presented with the word 'five', he immediately raised five fingers, and then counted orally from one to five. He proceeded similarly with tens (e.g. for thirty he said 'ten, twenty, thirty') and teens (e.g. for sixteen he said, 'ten, eleven, . . . sixteen'). Although this question was not explored systematically, the patient did not appear to access the meaning of long written verbal numerals. For instance, he did not recognize the meaning of the number 'nineteen hundred and thirty-nine' upon seeing it. This is hardly surprising since, although '1939' is visually familiar, the corresponding written verbal numeral is clearly not.

In short, as expected, alphabetically written number words were similar both to other spelled out stimuli and to arabic numerals. Just like other written words, individual number words were read through the semantic route, as revealed for instance by the occurrence of semantic errors (e.g. for nineteen he read 'eighteen', from the BDAE). Just like arabic numerals, however, they were read more accurately than other written material, thanks to the availability of a compensatory counting strategy. The main difference between alphabetically written and arabic numerals was that most likely complex alphabetically written numerals comprising several words did not possess their own entry in the visual input lexicon and were therefore always processed word by word.

General discussion

We have explored a single case of deep dyslexia whose word reading deficit generalized to arabic numerals. The patient was able to read elementary or even quite complex arabic numerals when these stimuli were familiar to him. However, he was largely unable to read unfamiliar numerals of matched complexity. An analysis of his reading errors disclosed several qualitative similarities between letter strings and arabic numerals (*see* Table 2). For instance, the patient produced semantic errors with familiar numerals as well as with real words (e.g. for 1918 he read '1940'). With unfamiliar numerals, which the patient treated like non-words, he often tried to infer a pronunciation from the identification of familiar substrings of digits. Additionally, it should be noted that number comprehension was intact, as shown by the patient's excellent performance in several quantitative tasks, and by his ability to explain the meaning of familiar numerals (e.g. for 1918 he said, 'it is the end of World War I').

Although there is no comparable detailed examination of word and number reading in the litterature, cases similar to the present one have been reported. We have previously encountered at least one case with selective preservation of reading of meaningful numerals, patient A.N.D., who could not, however, be submitted to acomplete analysis (Dehaene and Cohen, cited in Dehaene, 1992, p. 32). Another patient, N.A.U., also suffered from a severe deficit in word and number reading, with preserved number comprehension (Dehaene and Cohen, 1991). Other deep dyslexic or left-hemispherectomized patients have occasionally been reported to read single digits or simple numbers, and errors such as 'one-half' given as 'fifty' or 'threequarters' given as 'seventy-five' have already hinted at a parallel with semantic errors in word reading (*see* Deloche and Seron, 1984, and references therein).

Our observations may provide significant empirical constraints to several current neuropsychological debates concerning (i) models of number processing; (ii) the relations between numerical and general linguistic abilities; (iii) the neural basis of deep dyslexia. These three questions will be discussed in turn.

Models of number processing

Even though the system of arabic numerals constitutes a distinct linguistic notation with its own lexicon and syntax, our study shows, not surprisingly perhaps, that it shares several properties with the rest of the language system. Our results suggest the existence of at least two routes for number reading: via the 'lexical route', a semantic representation of the input numeral is accessed and permits the retrieval of the adequate lexical entry in a phonological output lexicon; via the 'surface route', the output phonemic string is constructed directly from the information provided by the input string of digits. The lexical route functions only with familiar or meaningful numerals that have developed a specific lexical entry. The surface route, on the other hand, which is analogous to 'assembled phonology', may be used to read any well-formed arabic numeral. [In most models of word reading, the surface route is based on simple letter-to-sound correspondences and therefore cannot handle irregular words such as 'come' or 'have'. This explains that surface dyslexics typically regularize such irregular words. However, most, if not all, arabic numerals are regular, with the possible exception of teens and words like 'soixante-dix' (70) or 'quatre-vingt' (80) in French. We would therefore expect a putative 'surface dyslexia for numbers' to be essentially undetectable.]

Straightforward as it may be, this account conflicts directly with McCloskey's model (McCloskey and Caramazza, 1987; McCloskey, 1992), currently the most influential model of the architecture of number processing. McCloskey and his colleagues postulate distinct modules for the comprehension and production of numerals in verbal or in arabic notation. However, according to a central hypothesis of McCloskey's model, the only communication between input and output modules passes through an abstract, amodal, semantic representation of numbers (*see* Fig. 3). This representation specifies only the quantity associated with the input numeral, and it is therefore not obvious how the model would account for other aspects of number semantics (e.g. the fact that 1918 is the end of World War I). Even if its semantic representation was somehow extended, McCloskey's model is fundamentally committed to the postulate of a unique, semantic route for number processing (*see* the discussion of asemantic transcoding in McCloskey, 1992, pp. 119–22). Within this framework, our patient's functional lesion could only be located in the production module, since comprehension of written numerals was clearly intact. However, this approach provides no way to explain the dissociation between familiar and unfamiliar numerals.

Conversely, Deloche and Seron (1982*a*, 1982*b*, 1987) have argued for the existence of a direct, asemantic route of number transcoding. They have described simple algorithms for writing arabic numbers in verbal notation, and they have shown how the writing errors of several brain-damaged patients reflected the disruption of these putative algorithms (*see* Cohen and Dehaene, 1991, for a similar approach to number reading). However, their focusing on tasks of formal number transcoding has obscured the fact that the main function of the number processing system is to convey semantic information about quantities, dates, etc. (McCloskey, 1992, p. 120). Deloche and Seron's model cannot explain the relative preservation of reading of familiar meaningful numerals in our patient. Similar difficulties confront more general models that deny the very existence of abstract semantic representations of number and attribute all aspects of number processing to format-specific codes (e.g. Campbell and Clark, 1988).

The triple-code model of number processing (Dehaene, 1992) allows for multiple routes in number reading and is therefore more apt at accounting for the present data. It postulates three cardinal representations of number: a visual arabic number form encoding numerals in arabic notation, an auditory verbal word frame encoding numerals in verbal notation and an analogue magnitude representation of quantities. As shown in Fig. 3, two routes may be used to transcode from the arabic representation to the verbal representation. The arabic-to-verbal translation route, which sidesteps the semantic representation of quantities,

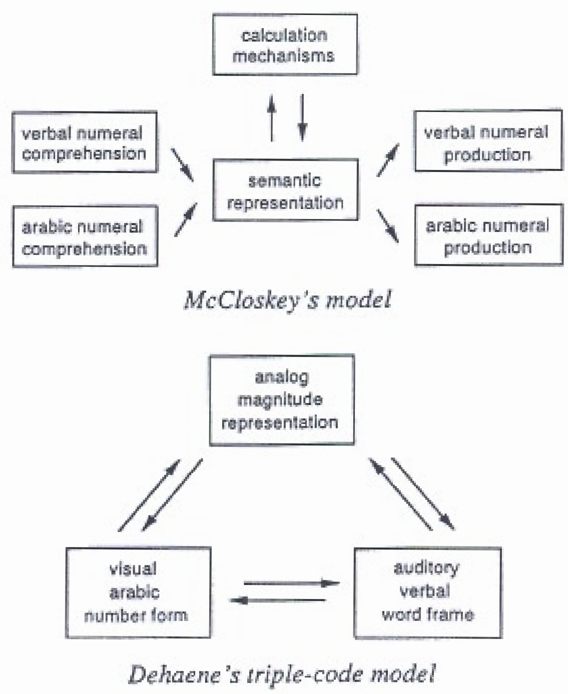

Fig. 3 Schematic representation of McCloskey's and Dehaene's number processing models. The former features a single semantic reading route, whereas the latter incorporates an additional direct asemantic reading pathway.

directly constructs the word sequence corresponding to a given arabic numeral, using rules of syntactic composition and lexical retrieval as described in Cohen and Dehaene (1991). The alternative semantic route goes through an intermediate step of activation of the quantity associated with the target numeral.

Dehaene (1992) hypothesized that the representation of quantity is only approximate, especially for large numbers, and therefore permits only approximate number reading. This hypothesis fitted well with the performance of patient N.A.U., who was unable to achieve exact symbolic computations and could only process approximate quantities (Dehaene and Cohen, 1991). However, the semantic representation of the triple-code model must be extended to account for the more complex semantic responses observed in the present case (e.g. 19 was given as 'the age of my daughter'). It may be assumed that frequently encountered arabic numerals promote access to a store of semantic number knowledge. Semantic records would specify not only approximate number magnitude, but also the referent of the number in various domains such as dates, ages, weights, brands of cars, etc. Other numerals would only possess a generic semantic representation in terms of approximate quantity which, beyond the range of small numbers, would be useless for exact reading.

The multiple route model of number reading is depicted in Fig. 4. This schema may be viewed as a partial elaboration of the triple-code model of number processing and was designed

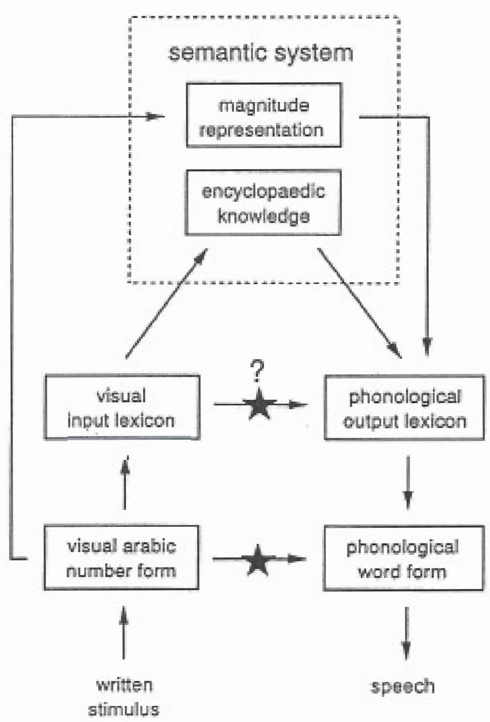

Fig. 4 Modified model of arabic number reading. This model combines a surface route, a putative asemantic lexical route and a 'deep' semantic route. It also postulates a non-lexical semantic pathway allowing access to the magnitude associated with any well-formed numeral.

to make clear the parallel with the standard model of word reading. Like word reading, arabic number reading is postulated to involve three main processing pathways: (i) a non-lexical surface route; (ii) a 'deep' semantic route; (iii) possibly a lexical asemantic route. The latter pathway is only proposed by analogy with the lexical asemantic route which is sometimes postulated in word reading. Its very existence is not entailed by our data and remains to be empirically established.

One major difference with word reading is the postulate of a non-lexical route to semantics. Contrary to non-words, which do not have any meaning, non-lexical numerals, even those that the reader encounters for the first time, are meaningful in that they represent a specified quantity or magnitude. The non-lexical route of number comprehension accounts for the fact that we understand the quantity represented by any arabic numeral, whether familiar or not. Preservation of this route may explain the patient's satisfactory performance in larger−smaller comparison or in pointing to a numerical scale, even with numbers that he could not read well. However, he did not seem able to use this intact semantic route for reading. Remember that the patient suffered from a mild impairment of access to the phonological output lexicon from the semantic system, which may also be partly responsible for his numerical word-finding difficulties. Additionally, his intact quantity representation was perhaps too imprecise for exact naming. Indeed, previous studies of normal and brain-lesioned subjects have suggested that the mental representation of number magnitude is only approximate and is more accurate for smaller numbers than for large ones (Fechner's law; *see* e.g. Dehaene and Cohen, 1991; Dehaene, 1992). (The patient managed to increase his number naming and calculation abilities beyond those afforded by the approximate representation by using a counting or recitation strategy. Upon seeing a numeral, he recognized the series to which it belonged, i.e. ones, tens or teens, and started to recite it. We speculate that his preserved auditory comprehension enabled him, upon hearing a numeral, to mentally access the corresponding quantity and possibly also its arabic representation. He could thus stop reciting as soon as he heard himself pronounce a spoken numeral whose interpretation matched the visual symbol he was trying to read. Mental counting may also account for his good performance in verifying additions, although it also seems possible that some simple addition facts figured among his intact semantic−encyclopaedic knowledge of numbers.)

A second major departure from the word reading model concerns the functioning of the surface number reading route. In word reading, this route supposedly relies exclusively on grapho-phonemic regularities and does not make any use of lexical information. In number reading, however, each digit is translated not into one or several phonemes, but into one or several number words. At some point in the course of this process, the phonological features of number words must be retrieved from a lexicon. Thus, although the surface route is represented in Fig. 4 as a single arrow, it actually corresponds to a complex process of lexical access and composition according to rules of number syntax. For further discussion, the reader is referred to Cohen and Dehaene (1991), where a detailed model of the interplay of visual, lexical and syntactic information in the surface reading route is proposed.

Language and numbers

The structural analogy between the modified number reading model (Fig. 4) and standard models of word reading (Fig. 1) is obvious. While our results suggest that the general architecture of arabic numeral reading is similar to that of word reading, do both actually share common processes or do they behave like two independent languages, with parallel non-overlapping processing systems? This question may be raised separately for both the surface and the 'deep' routes of word and number reading.

First, is there a common 'surface' non-lexical reading route for both letter strings and arabic numerals? At an abstract level, the rules for transcoding from digit and letter strings to sounds are somewhat similar. Both involve a basic mapping of individual symbols (letters or digits) to sounds (phonemes or number words), together with rules of transformation depending on context or on the position within the string. However, the specific implementations of these mappings differ to such an extent that they do not seem to share a single common rule. Furthermore, in the course of development, the alphabetical and arabic writing systems need not be mastered at the same age. It is therefore not surprising that number reading may dissociate from letter or word reading. Déjerine (1891, 1892) himself had noted that some of his alexic patients could read arabic digits and simple numerals. More recently, Anderson *et al.* (1990) have described a patient who, following a small lesion confined to the left premotor cortex, developed alexia and agraphia for letters and words, but not for numbers. Although she could not read any non-word and read only 21% of all words presented to her, she had no difficulty reading arabic numerals up to seven digits in length. Some instances of the opposite dissociation have been reported, although in much less detail (e.g. Henschen, 1919).

Such cases seem to indicate that the surface route for 'assembled phonology' in word reading is dissociable from the surface route for 'assembling digits' in arabic number reading. We would therefore suggest that number reading rests on processing pathways parallel to, but functionally and anatomically distinct from those for word reading. According to this account, the patient we have reported would have suffered from a simultaneous loss of these two pathways, possibly because they are implemented by contiguous neural areas or projections.

Anatomical data also seem to support this conclusion. Deep dyslexia is generally observed following extensive parieto-temporal lesions of the left hemisphere. The inferior parietal lobule, in particular the supra-marginal gyrus, seems to play a critical role in reading disorders (e.g. Marin, 1980). Although less is known about the critical region for number reading, a similar parietal locus may be suspected (Henschen, 1919; Hécaen, *et al.*, 1961). In their series of > 100 cases, Hécaen *et al.* (1961) found a different incidence of alexia for numbers and alexia for letters after lesions limited to the left parietal, temporal or occipital lobe. They concluded that 'reading of letters and words and reading of digits and numbers do not seem to be totally confounded, even from an anatomo-clinical point of view' (p. 99; our translation).

At the semantic level, does the representation of digits and numbers also dissociate from other types of word knowledge? When tested on the BDAE, patients may show selective impairments or preservations of the category of numbers relative to other categories such as objects, geometric forms, letters, actions and colours (Goodglass *et al.*, 1966). However, there are few suggestive cases of calculation deficits with a documented preservation of language comprehension (e.g. Benson and Weir, 1972; Corbett *et al.*, 1986; Mazzoni *et al.*, 1990). A remarkable exception is the study by Cipolotti *et al.* (1991), who described a patient with a complete loss of any knowledge of numbers above 4, but whose knowledge of other categories such as animals, fruits and vegetables, body parts, musical instruments, vehicles or household objects was close to perfect. These authors framed their observations in terms of category-specific impairments of semantic memory. Such a selective deficit may be taken as evidence for separate semantic representations for numbers and words. In brief, it appears that, although number and word reading are based on similar dual-route architectures, numbers are dissociable from other categories at both the surface and semantic levels.

The neural basis of deep dyslexia for words and numbers

The large extension of our patient's posterior left-hemispheric lesion is compatible with the hypothesis that his intact semantic route for word and number reading rests on a preserved right-hemispheric system (Coltheart, 1980). Although the hypothesis that deep dyslexia reflects the functioning of an intact right hemisphere remains highly controversial, it is worth re-examining in the context of arabic numeral reading. Déjerine (1891) stated that 'arabic or roman numerals, algebraic equations, etc., or for that matter one's signature, are equivalent to drawings of objects rather than to letters' (p. 200; our translation). Arabic notation is indeed similar to an ideographic system and might enjoy a right-hemispheric advantage relative to other categories of linguistic stimuli (Coltheart, 1980). Indeed, although the literature on lateralized tachistoscopic presentation of numerals is fairly inconclusive (*see* Boles, 1986), data from commissurotomized or left-hemispherectomized patients indicate good comprehension of single digits by the right hemisphere (Gazzaniga and Hillyard, 1971; Gott, 1973; Teng and Sperry, 1973). For instance, the commissurotomized patient L.B. could report 80% of digits presented to his left hemifield, but only 22% of letters (Teng and Sperry, 1973). Holender and Peereman (1987) have reviewed evidence from patients with alexia without agraphia, and confirmed that simple arabic numerals show a consistent advantage over letters and words, although more complex multidigit numbers are rarely preserved. They suggest that this might result from the ability of the right hemisphere to process digits 'semantically', and to transfer this 'semantic' code to the left hemisphere for verbal output.

Reading of arabic numerals may also be compared with reading of Kanji (Coltheart, 1980), the ideographic component of the Japanese writing system. Just like reading of simple arabic numerals is often preserved in Western deep dyslexics, there is a relative preservation of Kanji as compared with Kana in Japanese deep dyslexics (e.g. Sasanuma, 1980; Hayashi *et al.*, 1985). Furthermore, these patients also frequently exhibit good reading of simple numerals (e.g. 1–20) in both arabic and Kanji notation. Unfortunately, their performance with more complex familiar and unfamiliar numerals has not been reported. However, there is some evidence that in normal Japanese subjects, single Kanji characters show a right-hemisphere advantage, whereas Kana and multiple-Kanji words show a left-hemisphere advantage (Coltheart, 1980, p. 339). It may thus be suggested that the right hemisphere processes meaningful ideographic material (single digits, meaningful arabic numerals and Kanji words) more successfully than stimuli requiring some form of syntactic or combinatorial analysis. The assembly of complex sequences of phonemes or words from visual strings of letters or digits would rely crucially on the parieto-temporal areas of the left-hemisphere.

Conclusion

We have reported the case study of a deep dyslexic patient whose reading deficit extended to arabic numerals. Our results are consistent with the existence of two routes for number reading: a 'surface' asemantic transcoding route and a 'deep' semantic route. Number reading is therefore architecturally similar to word reading, although these two processes may rest on anatomically distinct pathways, perhaps occupying contiguous sectors of cortex. As a final point, we note that the controversial question of the existence of an asemantic transcoding procedure for numbers was addressed here, paradoxically, by demonstrating the dramatic reading deficit that arises when this procedure is lost.

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