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Neglect Dyslexia for Numbers? A Case Report

Laurent Cohen
Clinique des Maladies du Système Nerveux, Hôpital de la Salpétrière, Paris, France

Stanislas Dehaene
I.N.S.E.R.M. & C.N.R.S., Laboratoire de Sciences Cognitives et Psycholinguistique, Paris, France

We report the case study of a patient (YM) with a specific number reading deficit, but with fairly preserved number comprehension and calculation. YM exhibits a spatial error pattern akin to neglect dyslexia, making most of his reading errors and perseverations on the leftmost digit of any number. This and a strong effect of visual similarity on errors suggest a visual deficit. Yet number syntax is preserved: most productions are legal number names, and less errors are observed on digits 0 and 1 when they bear a silent or syntactic role. On the basis of a detailed account of the deficit, we propose a revision of McCloskey, Sokol, and Goodman's (1986) model of number reading. We further discuss the apparent contradiction between the symbolic and the spatial aspects of YM's reading deficit, and the adequacy of the concept of neglect dyslexia.

INTRODUCTION

The study of brain-damaged patients has helped crucially in designing cognitive models of number processing. For instance, the analysis of specific impairments of number reading resulted in the breakdown of this task into input and output components (McCloskey & Caramazza, 1987). The output component could be further subdivided into syntactic and lexical processes (Deloche & Seron, 1987). We present the case study of a patient (YM) whose deficit may help us to understand the interplay of syntactic and lexical information in number reading. YM's number comprehension and calculation abilities are fairly preserved, but he makes

Requests for reprints should be addressed to L. Cohen, Clinique des Maladies du Système Nerveux, Hôpital de la Salpétrière, 47 Bd. de l'Hôpital, 75651 Paris CEDEX 13, France.

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numerous errors reading Arabic numbers. Errors consist essentially in digit substitutions and perseverations, and are most likely to occur on the leftmost digits of the target numbers. This pattern of errors resembles that observed in neglect dyslexia (Kinsbourne & Warrington, 1962). We attempt to identify, within the functional architecture of number reading, the locus of impairment which accounts for both the nature and the spatial distribution of errors.

CASE HISTORY

YM, a 58-year-old, right-handed male, just retired from being an executive salesman, was first admitted to hospital in July 1986 for an acute confusional state. Neurological examination was normal. The confusion receded spontaneously in less than 48 hours, and its aetiology could not be ascertained satisfactorily. Neuropsychological evaluation identified a clear-cut memory impairment. YM's global score on the Wechsler Memory Scale was 91. Language comprehension and production were normal, except for a reduced fluency in controlled association. C.T.-scan and C.B.F. were normal. E.E.G. showed occasional slow waves, mostly in the left temporal region.

From July 1986 to March 1987, YM experienced progressively increasing memory loss and language difficulties. On admission in March 1987, he was severely aphasic. There was no evidence of sensory or motor impairment. Visual field was clinically normal. C.T.-scan showed a left temporal tumour extending into the left parietal lobe and the lower part of the splenium of the corpus callosum. YM underwent temporal lobectomy, and a malignant glioma was diagnosed on pathological examination. YM died one year later due to further extension of his tumour.

The patient was tested two months post-surgery. He had an upper right quadrantanopia but still exhibited no sensorimotor impairment. He had no clinical indication of apraxia or spatial neglect. At that time, his spontaneous speech was fluent and grammatical, but of little informative value, due to pervasive word-finding difficulties. There were occasional semantic or phonemic paraphasias. Conversation was further hampered by reduced comprehension of complex utterances. Description of speech-language pathology evaluation is given in the Appendix. Following usual standards, YM could be classified as presenting anomic aphasia.

During the clinical examination, YM was asked to read 27 informally presented Arabic numbers from 1 to 5 digits. He produced 6 incorrect responses, each plausibly resulting from the substitution of a digit for another. For example, 38 was read as "vingt huit" (28), and 72 as "soixante dix neuf" (79). We present in the following section the subsequent experimental exploration of YM's number reading deficit.

NUMBER READING

Method

The patient read aloud 5 lists of numbers on different days. A total of 1948 numbers, from 1 to 8 digits long (Table 1), were presented, horizontally centred, on sheets of paper; each sheet contained about ten numbers. The sessions were recorded on tape and later transcribed.

Results

Three patterns emerged from an informal inspection of YM's errors. First, most errors resulted in the production of a number of the same magnitude as the target number, that is, a number with the correct number of digits (e.g. 916 → "quatre cent seize" [416]). This could be described as the *substitution* of one or more digits occurring in the course of the reading process. Second, such errors seemed to affect more frequently the leftmost digit of the target numbers than the following digits, suggesting a *positional bias* in the production of errors. Third, the digit that YM produced instead of the misread one was not selected completely at random. As shown in Table 2, it was often the case that YM was influenced by the previously uttered name. This behaviour enters in the scope of *recurrent perseveration* (Sandson & Albert, 1984), that is, the unintentional repetition of a previous response to a subsequent stimulus.

In order to evaluate and develop these informal observations, we submitted the data to detailed analyses which are now presented.

Errors were initially classified as substitution errors (syntactically correct productions with correct length, but incorrect number words; e.g. 3 → "neuf" [9]; 217 → "deux cent soixante-dix sept" [277][1]) vs. other errors. The latter were few and were analysed separately. Substitution errors were transcribed in Arabic notation and fed into a computer for automated analyses. Self-corrected productions or incomplete productions were also entered into the database. Thus, the production 234 → "deux cent cinquante . . . deux cent trente quatre" [250 . . . 234], where the patient apparently stopped in the middle of saying 254, was entered as 254. When the attempted correction was still wrong, the final error was used. For example the production of 364 → "huit cent . . . six cent soixante quatre" [800 . . . 664] was entered as 664. Self-corrections concerned only 51 (12%) of the 425 trials with an error.

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[1]Note that our class of substitution errors include actual verbal omissions, e.g. 545 → "cinq cent quarante" (540). These omissions appear in our analyses as substitutions of digit zero.

1. Substitution Errors

Three hundred and sixty-eight numbers (18.9%) contained one or more substitution errors. Table 1 gives the percentage of substitution errors as a function of stimulus length in digits, and as a function of digit position. Globally, error rate increases with number length ($r^2 = 94.8\%$, $P = 0.001$). Errors are not distributed randomly across positions, but tend to occur preferentially on the leftmost digit (separate chi^2 tests for stimulus length between 2 and 5, $chi^2[1\ d.f.] > 7.19$, $P = 0.01$). The percentage of errors on the leftmost digit seems to be constant (about 12.5%) for 1- to 3-digit numbers, and jumps to about 22% for longer numbers.

As shown in Table 1, about one third of these errors can be accounted for by perseveration, i.e. substitution of one digit by the digit standing at the same position in the previous number in the list; this is much higher than the 10% figure expected under the hypothesis of a random substitution. Note that two definitions of digit position can be used: *absolute position*, i.e. units, tens digits, hundreds digits, etc., vs. *relative position*, i.e. position relative to the left of the number. Do perseverations occur at the same absolute position or at the same relative position? In most lists, consecutive numbers often had the same number of digits, in which case the two definitions are confounded. However, we found a number of cases which could only be accounted for by perseveration at a given *relative* position (see Table 2). These cases also suggest that perseveration occurs at the digit level, not at the verbal level: digit 7 is persevered irrespective of its variable pronounciations ("sept" or "soixante-dix").[2]

Are some items more susceptible to error than others? Table 3 gives the percentage of errors as a function of the digit read. Globally, error rate varies widely across digits ($chi^2[9\ d.f.] = 84.2$, $P < 0.001$), with digits 0 and 1 being about 4 times less error-prone than digits 3, 9, or 5. We computed error rates separately for positions 1, 2, and 3 modulo 3, where digits respectively play a role of units, decades, or hundreds identifiers. Error rate tends to increase from position 1 to position 3. It is noteworthy that for most digits, aside from this global increase, error rate is not differentially affected by position. Thus 3 remains one of the most error-prone digits at positions 1, 2, and 3, despite different realisations as "trois"

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[2]Several other instances of prolonged perseverations were found. Series such as those reported in Table 2 are unlikely to be found merely by chance in a large corpus of responses. In our lists, about 200 numbers started with the digit 7. YM misread a first digit on 20% of the trials (Table 1), and the substituted digit then had a 17.5% probability of being a 7 (Table 4). Hence, the chance probability of observing 4 consecutive substitutions of the leftmost digit by digit 7, immediately following a correctly read number starting with digit 7, is about $200 \times (0.20 \times 0.175)^4$, i.e. 0.0003. The probability of observing similar series with other digits is even lower (Table 4).

TABLE 1
Errors in Reading Arabic Numbers

Stimulus Length (Digits)	*No. of Stimuli*	*Percentage of Substitution Errors*									
		Globally	*As a Function of Position*								
			8	*7*	*6*	*5*	*4*	*3*	*2*	*1*
1	95	12.6%								12.6% (4.2%)
2	495	17.0%							12.9% (4.6%)	6.7% (1.2%)
3	1060	18.6%						13.0% (4.8%)	5.1% (2.4%)	2.5% (0.3%)
4	218	26.6%					21.6% (6.9%)	3.2% (0.9%)	2.8%	2.8% (0.5%)
5	50	34.0%				20.0% (6.0%)	14.0% (2.0%)	10.0%	2.0%	—
6	20	35.0%			25.0% (10.0%)	—	—	10.0%	—	10.0%
7	9	22.2%		22.2% (11.1%)	—	—	—	—	—	—
8	*1*	*0.0%*	—	—	—	—	—	—	—	—

(a) The only 7- and 8-digit numbers that we tested were millions. Hence, these categories are not fully comparable with the others, and were not included in statistical analyses.

(b) The total over positions can be superior to the global percentage of errors, since there may be more than one error per number.

(c) The number in parentheses gives the percentage of errors that can be accounted for by perseveration (same digit as in the previous number at the same position relative to the left).

TABLE 2
Examples of Prolonged Error Perseverations in Number Reading

Visual stimulus	78	233	6534	52	6453
Verbal response	78	733	7534	73	7453
Visual stimulus	11	852	970	949	
Verbal response	11	152	170	149	

For convenience, verbal responses have been transcribed into Arabic numerals. The first example is particularly compelling in suggesting that (a) perseverations depend on digit position relative to the left, not on absolute digit position (i.e. units, tens, etc.); and (b) they occur at the digit level rather than at the verbal level: the persevered 7 is realised very differently ("sept" or "soixante-dix") depending on its position.

or "trente". Again, this suggests a deficit at the digit level rather than in a later verbal component.

Digits 0 and 1 behave differently, however. The distribution of errors across positions differ for digits 0 and 1 vs. digits 2 to 9 ($chi^2[2\ d.f.] = 18.7$ and 27.6 respectively, $P < 0.001$); whereas error rate increases from position 1 to position 3 for digits 2 to 9, it decreases for digit 0, and is approximately stable for digit 1. In units position, 0 and 1 are not significantly different from other digits ($chi^2[1\ d.f.] = 2.85$, $P < 0.10$; $chi^2[1\ d.f.] = 1.91$, $P > 0.10$), whereas they differ markedly in the tens position ($chi^2[1\ d.f.] = 11.4$, $P < 0.001$; $chi^2[1\ d.f.] = 14.4$, $P < 0.001$) and the hundreds position ($chi^2[1\ d.f.] = 4.43$ [Yates correction applied]), $P < 0.05$; $chi^2[1\ d.f.] = 11.4$, $P < 0.001$).

TABLE 3
Percentage (and Absolute Number) of Substitution Errors as a Function of the Digit Presented

	Digit Read										
	0	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*2..9*
Overall	2.3	3.0	10.3	12.8	6.2	10.4	8.6	5.0	6.6	10.9	9.4
	(10)	(19)	(60)	(72)	(34)	(60)	(49)	(28)	(37)	(59)	(399)
P 1 mod 3	3.7	3.9	7.3	7.8	6.5	3.5	8.6	4.1	7.0	7.4	7.0
	(9)	(8)	(17)	(18)	(14)	(8)	(20)	(9)	(16)	(17)	(119)
P 2 mod 3	0.7	1.6	7.2	12.8	6.9	12.2	8.2	3.6	5.7	11.8	9.7
	(1)	(4)	(14)	(25)	(13)	(23)	(15)	(7)	(11)	(22)	(130)
P 3 mod 3	0.0	4.1	19.3	19.5	5.0	18.4	9.0	8.1	7.0	14.6	15.2
	(0)	(7)	(29)	(29)	(7)	(29)	(14)	(12)	(10)	(20)	(150)

P 1 mod 3 = Position 1 modulo 3 (units, thousands, millions). P 2 mod 3 = position 2 modulo 3 (tens, tens of thousands). P 3 mod 3 = position 3 modulo 3 (hundreds, hundreds of thousands).

TABLE 4
Number of Times a Given Digit Appeared as a Substitution Error

Digit	*0*	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*
Occurrences	6	27	48	55	29	27	64	75	74	23

Finally, Table 4 gives the number of times a given digit was substituted for the correct digit. The distribution is not flat (chi^2[9 d.f.] = 121, $P < 0.001$); for example, digit 7 is about 3 times more likely to be chosen than digit 9; digit 0 is hardly ever produced as an error. Of course, digits 0 and 1 are special, since they often yield verbal omissions if substituted for another digit. However, even if 0 and 1 are excluded from the analysis, significant irregularities remain in the distribution (chi^2[7 d.f.] = 64.7, $P < 0.001$).

The 9 × 9 digit substitution matrix (excluding digit 0) was submitted to a multiple regression analysis with the following factors: odd-even agreement (whether the correct and the substituted digits had identical parity), numerical proximity (absolute difference between the two digits), and visual similarity (as measured in Campbell & Clark, 1988). Error rate increased with visual similarity ($r = 0.42$, $P = 0.0002$) and numerical proximity ($r = 0.25$, $P = 0.03$), irrespective of odd-even agreement ($P = 0.55$). In a stepwise regression, visual similarity entered first, followed by numerical proximity. When numerical proximity was forced to enter first, visual similarity still accounted for a significant amount of variance ($F[1,70] = 14.8$, $P = 0.0003$). Altogether, the two factors accounted for 20.5% of variance.

Separate substitution matrices were also calculated for positions 1, 2, and 3 modulo 3; error rates were highly correlated between these three positions ($P < 0.001$), even when digits 0 and 1 were excluded from the analysis ($P < 0.05$). For example, in 49.9% of his errors on digit 5, YM produced digit 7; this bias for the 5 → 7 substitution held regardless of the different realisations of the digit 7 as "sept" or "soixante" + teen.

2. *Other Errors*

Fifty-seven numbers (2.9%) yielded non-substitution errors. Of these, only 4 were incorrect French number names (805 → "huit cent . . . huit cinq"; 261 → "deux cent six cent un"; 5493 → "huit cent quatre cent quatre-vingt treize"; 3760 → "trois cent sept cent soixante"). The last two could be interpreted as multiplier errors ("cent" instead of "mille"). There were 9 errors involving a similar substitution of multiplier "million" for "mille".

The remaining 44 errors could all be interpreted as misperceptions of stimulus length or "parsing errors", e.g. 72 → "sept cent . . . soixante douze" (700 . . . 72). Thirteen of them, however, could also be interpreted as a substitution of multiplier "mille" for "cent", or the converse; e.g. 200 → "deux mille" (2000). Nineteen parsing errors were later self-corrected. For the remaining ones, misperception of length was compensated by digit duplication (60 → "six cent soixante" [660]), digit addition (14 → "cent quatre-vingt quatorze" [194]), or digit deletion (5198 → "cinq cent quatre-vingt dix-huit" [598]). Substitution errors sometimes occurred with these length errors (5/44 = 11.4% for the leftmost digit).

OTHER EXPERIMENTS

The deficit appears to concern only a production component. Satisfactory comprehension of multi-digit Arabic numbers was suggested by YM's performance in numerical comparision, verification of additions, and other mental calculation tasks. Number writing to dictation was also fairly well preserved.

Number Comparison. A list of 44 pairs of numbers with equal length (1 to 4 digits) was presented 5 times. The numbers in a pair were presented side by side. On 2 runs, YM was simply asked to point to the larger number in each pair, and made no error whatsoever. On 2 other runs, he was asked to read aloud the 2 numbers before pointing to the larger one. On the fifth run, he was asked to read aloud columnwise the list of the left numbers, and then the list of the right numbers. Again, YM never made any comparison error. However, he made numerous reading errors. Among the 88 pairs that he both read and compared, 38 contained at least one error. Six of these reading errors resulted in a reversal of the relative magnitudes of the 2 numbers, but YM nevertheless selected the truly larger stimulus.

Verification of Additions. YM was asked to read aloud and check 25 horizontally written additions of 1- or 2-digit numbers, 14 of which were correct and 11 of which were incorrect. He misread 25 numbers (15 additions). By contrast, only 3 problems were incorrectly verified. All 3 were incorrect by one decade, and were misclassified as correct.

Mental Calculations. The same 25 addition problems were also presented without the results, which YM was asked to produce either verbally or in Arabic numbers. He made 9 errors with the verbal task, and 6 errors with the written task. Three errors in the verbal task may be attributed to a failure of producing the correctly computed result (19 + 5 → "deux cent quatre" [204]; 55 + 9 → "six cent quatre" [604]; 78 + 22 → "mille" [1000]). YM was also tested on addition and multiplication tables. The experimenter read all possible additions and multiplications of digits 1 to 9 (81 problems each). YM responded orally. He made respectively 10 and 8 errors, which is close to the error rate in number reading. Most errors were within the correct range for additions, and within table for multiplications (see patient MW in Caramazza & McCloskey, 1987). In brief, the calculation ability appears fairly preserved relative to the number production system.

Number Writing to Dictation. Within the number production system, McCloskey and Caramazza (1987) distinguish Arabic and verbal components. It seems that only the verbal component was affected in YM. When asked to write on dictation 84 Arabic numbers from 1 to 6 digits long, he made only 3 errors (2012 → 200012; 6300 → 630; 8217 → 827). Within the verbal output system, a further distinction may be drawn between written and oral components. However we did not have time to study YM's written verbal production of numbers, so we may only identify a deficit in the oral component.

DISCUSSION

Competing Explanations for YM's Leftward Bias

The most striking characteristic of YM's deficit is the strong tendency for reading errors and perseverations to occur mostly on the leftmost digit of the target number. That the spatial layout of the display governs reading performance suggests an impairment at the level of visual encoding. However, this apparently contradicts several other observations, such as the relative preservation of the number comparison task. It therefore seems appropriate to rule out three alternative accounts that may explain the error pattern in nonspatial terms.

First, the effect may be an artefact of number word frequency. The frequency of numerals is inversely related to the magnitude that they express (Francis & Kuçera, 1982; Dehaene & Mehler, Note 1). For example, "fifty" is less frequent than "five". Variations in word frequency are known to affect naming and reading performance. They might explain that in reading, say, number 55, the leftmost digit would yield more errors that the rightmost one. However, this explanation works only for 2-digit numbers. With 3-digit numbers, which represent the bulk of our experimental material, the same words are used to express the first and last digits. Yet there were 13.0% errors on the hundreds digit, and only 2.5% on the units ($chi^2[1\ d.f.] = 81.0$, $P < 0.001$). Another prediction of the frequency hypothesis is that at any given position, larger digits should yield more errors than smaller ones, since they correspond to less frequent number words. Table 3 clearly shows that it is not the case. Hence, the leftward bias cannot be explained by a word frequency artefact.

Second, the bias for the leftmost position could be interpreted in temporal rather than in spatial terms: the first pronounced item would be more error-prone than the following ones. To separate the two interpretations, YM was asked to read 1- to 3-digit numbers, the digits of which were vertically aligned. In this condition, contrary to the prediction of the temporal hypothesis, error rates were not significantly higher for the first pronounced digit than for the other digits ($chi^2[1 \text{ d.f.}] = 0.02$; see Table 5).

TABLE 5
Errors in Reading Arabic Numbers Printed Vertically

		Percentage of Substitution Errors			
			As a Function of Position		
Stimulus Length (Digits)	*No. of stimuli*	*Globally*	*3*	*2*	*1*
1	7	42.9%			42.9%
2	7	14.3%		—	14.3%
3	93	24.7%	8.6%	10.8%	7.5%

At all positions, the error rate approached the 12.6% figure obtained in reading single digits. This suggested that YM read each digit as an independent item, before combining all digits into the complete number name. If indeed reading a single vertical number amounts to reading several independent digits in succession, then perseverations, which in horizontal reading occur from one number to the next, should now appear from one digit to the next *within* a single vertical number. Therefore, we should expect a higher rate of within-number digit repetitions, such as 257 read as 227, in the vertical reading condition than in the normal reading condition. Indeed, in normal reading, only 17.8% of incorrectly read 3-digit numbers contained digit repetitions, a percentage close to the 20% figure expected under random conditions; however in vertical reading, the percentage raises to 39.1% ($chi^2[1 \text{ d.f.}] = 9.37$, $P < 0.01$) (Table 6).

Finally, there remains an alternative account of the leftward bias. Larger error rates would be associated with higher powers of ten. Two alternative versions of this hypothesis may be conceived: a quantitative one and a syntactic one. Within the number production system, large quantities could be affected more than small ones; hence digit 5 in 508 would yield more

TABLE 6
Percentage of Within-number Consecutive Digit Repetitions (e.g. 227, 366) in 3-Digit Numbers

Condition	*Stimuli*	*Errors*
Normal reading	204/1060 = 19.2%	35/197 = 17.8%
Vertical reading	22/93 = 23.7%	9/23 = 39.1%

Expected percentage under random conditions: 20%. Within-number consecutive digit repetitions, or digit perseverations, are more frequent than chance only in the vertical reading condition ($chi^2[1 \text{ d.f.}] = 4.13$, $P < 0.05$).

errors than digit 8, simply because it represents a larger quantity. The syntactic variant of this explanation does not appeal to quantities at all, but merely to number syntax. Characteristic error rates would be associated to the words expressing decades, hundreds, thousands, etc. This is similar to Temple's (1989) account of a rightward bias in number reading errors: naming digits would be "differentially affected by the syntactic position", due to a "defect in slotting the final item into the final position in the syntactic frame" (op. cit., p. 110).

Both variants fall to the same objections. First, they cannot explain the results from the vertical reading condition. Second, they should predict a constant rate of errors for any given power of ten, regardless of number length. But performance at any given power of ten actually *improves* when number length increases (see Table 1). For example, at the tens position, error rates decreases from 12.9% in 2-digit numbers to 2.8% in 4-digit numbers.[3]

In short, the critical parameter explaining the leftward bias in the error pattern appears to be *spatial* position. We have ruled out alternative explanations in terms of word frequency, temporal position, or associated power of ten.

McCloskey et al.'s Model

Our patient YM shows a number reading problem very similar to patient HY's, which McCloskey et al. (1986) have analysed and modelled. It therefore seems appropriate to look for an explanation of YM's deficit within the framework proposed by McCloskey et al. (1986). An outline of their spoken-verbal-number production process is shown in Fig. 1. Their first

[3]Due to small sampling, the error rates for numbers longer than 4 digits are less reliable. For 2- to 4-digit numbers, the decrease in error rate is not due to the longer number being more likely to end with zero. The proportion of numbers ending with zero was controlled in this subset of stimuli.

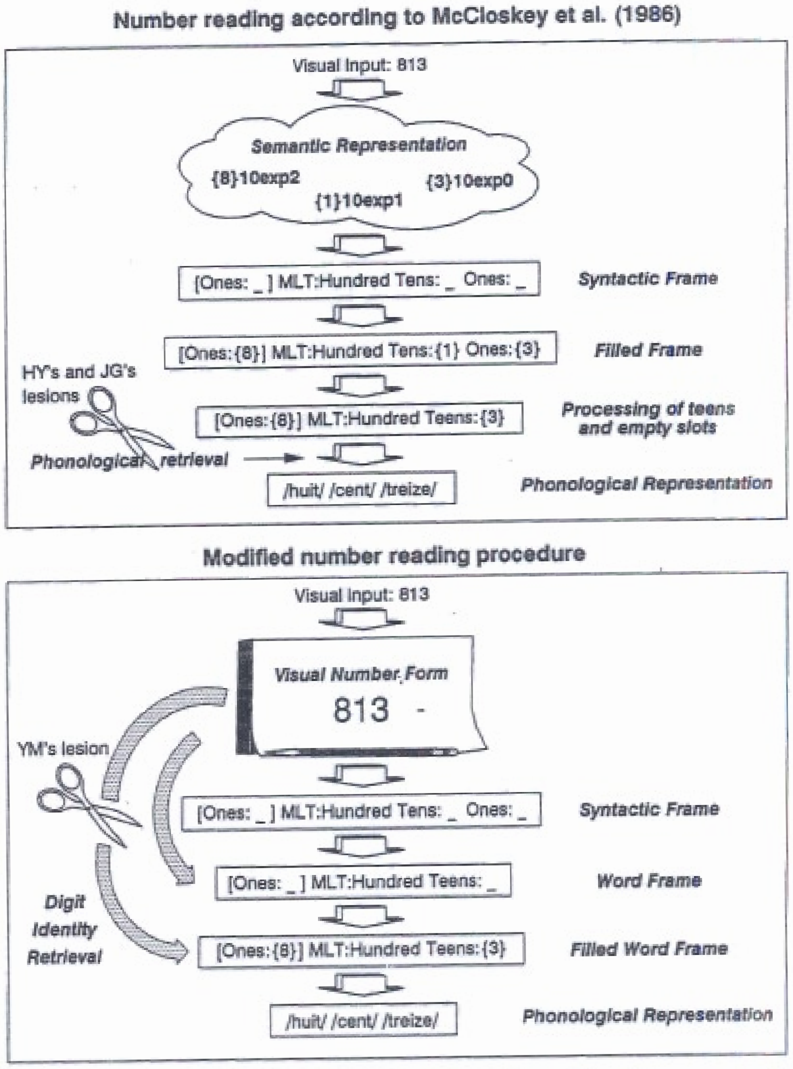

FIG. 1 Processing models of Arabic-to-verbal number transcoding. The upper model is adapted from McCloskey et al. (1986) (see text for details). The bottom model introduces modifications necessary to account for YM's performance. The input to the reading process is a visual buffer, the visual number form, rather than a semantic representation. This visual number form is accessed twice. In a first pass, syntactic information is extracted to compute the syntactic frame, then the word frame. In a second pass, impaired in YM, specific digit identities are retrieved in order to fill the empty slots in the word frame and access the phonological representation. Impairments of phonological retrieval, which is identically represented in both models, may still account for the deficits observed in patients HY and JG by McCloskey et al. (1986).

processing stage is the mapping of the input into a semantic representation of the number, specifying the quantity associated with each power of 10. On the basis of the largest power of 10 present, a syntactic frame is generated. The frame specifies the default sequence of words for a number of that magnitude. For example the sequence for a 3-digit number would be a ones word followed by the multiplier for hundreds ("cent" in French), followed by a tens word and a ones word. Each slot of the frame is then filled with the quantity from the appropriate power of ten in the input. The final step is the retrieval of phonological representations. Special procedures ensure appropriate access to the phonological lexicon in the case of teens; empty slots and multipliers words referring to empty quantities (e.g. "hundred" in 8,022) are also filtered out.[4] Eventually then, phonological representations are retrieved on the joint basis of class information (ones, teens, or tens) and position-within-class information.

McCloskey et al. (1986) explained patient HY's performance as a failure in using position-within-class information during phonological retrieval. The performance of another patient (JG) was similarly understandable as a failure in using class information. Could a similar deficit in phonological retrieval account for our patient YM? A major problem for this explanation is that YM's confusions, in contrast to HY's and JG's, depended largely on visual parameters. We have already discussed the spatial basis of errors. Also remember that 17.6% of the variance in the digit confusion matrix was accounted for by the visual similarity of the substituted digits. Assuming that processing is strictly serial, and that YM's processes were intact up to access to the phonological lexicon, one should not expect visual factors to govern errors. The syntactic frame is an abstract representation, at the level of which any visual information should not be available anymore.

In short, although YM's errors may initially appear as word substitutions similar to patient HY's, the loci of the deficits are probably distinct in the two cases. In contrast to YM, HY's performance was little affected by visual factors and was not position specific. In addition, HY made some between-class substitution errors that argue strongly for an impairment of lexical access (e.g. 12 → "twenty"). It seems safer to conclude that YM and HY have different deficits.

What type of lesion could, then, account for YM's errors? Another possible locus of impairment within McCloskey et al.'s model is the

[4]In French, there are more special cases that need to be dealt with before phonological retrieval. First, a "1" in the position of hundreds or thousands is not pronounced (100 → "cent"; 1,000 → "mille"). Second, a "7" or a "9" in the tens position requires both access to the phonological lexicon (retrieving "soixante" or "quatre-vingt"), and a specification to access the lexicon in the teens class, not in the ones class, for the next word (e.g. 73 → "soixante treize", literally "sixty thirteen").

abstract internal representation of quantities within the verbal number production system (see Fig. 1). A lesion at this level might explain that YM tended to substitute digits that are close in magnitude. However, this effect of numerical proximity accounted for only 6.25% of variance in the digit substitution matrix. Furthermore, the spatial bias and the strong effect of visual similarity elude this explanation.

Is YM's Deficit Visual?

A final level at which the deficit could occur in McCloskey et al.'s model is the visual input. Digit identities would be misperceived, especially on the left of the numbers. Occasionally, the visual trace of a preceding digit would over-ride a more recent input, yielding perseverations. That substitutions occur at the level of *digits*, as opposed to words or other more abstract representations, is strongly supported by two experimental observations. First, in consecutive perseverative errors, such as those in Table 2, a persevered digit can be successively realised with different words, with the same within-class position but belonging to different word classes (e.g. "sept" and "soixante"). These errors often would not be considered as perseverations at all if described at the word level. Second, error patterns are correlated across number lexical classes. Thus "sept" (7) is often substituted for "cinq" (5), "dix-sept" (17) for "quinze" (15) and "soixante" + teen (70) for "cinquante" (50). This recurring pattern of errors would be a straightforward consequence of a bias in digit substitution.

However, the hypothesis of a lesioned visual input also encounters difficulties. It predicts that any task with a visual presentation of numbers should be equally affected, which is not what is observed. YM made no errors at all in 220 comparisons of pairs of visually presented numbers. At the same time he still made many errors in reading aloud the stimuli. If those reading errors merely reflected a global visual deficit, YM should have made at least 6 comparison errors, e.g. when 56 62 was read "soixante-seize, soixante-douze" (76 72). YM's flawless performance on comparison suggests that only number production was affected. A similar, though weaker, argument can be made about YM's calculation abilities. Additions and multiplications were only slightly impaired. More calculation errors were made when a verbal response was required than when the patient merely had to check a calculation. This suggests that the calculation errors were not entirely caused by an impaired visual input. YM might have had a mild calculation deficit in addition to his reading problem.

Preservation of Number Syntax

Even if YM's deficit appears manifold, some stages of processing are clearly intact. YM's syntactic frame generation seems to be spared: 86.6% of his reading errors were legal number names with the correct number of digits (substitution errors). This percentage rises to 92.2% if one includes errors that seem to involve the selection of an incorrect multiplier. Only 4 errors (0.94%) were truly agrammatical.

The preservation of number syntax relative to lexical information can best be appreciated by examining performance in reading digits 0 and 1. In French, 0 entails access to the phonological lexicon only if it occupies the units position and if preceded by 1, 7, or 9; it then realises as "dix", either in isolation or in "soixante-dix" or "quatre-vingt-dix". In all other contexts, 0 is not realised verbally. Similarly, 1 has a phonological realisation only at the units position. When it occupies the decades position, it serves as a syntactic marker indicating that the name of the next digit should be retrieved from the teens class. When in the hundreds position, it is not verbally realised (100 is read as "cent", literally "hundred", not "one hundred" as in English). If YM's syntactic process were preserved, then one should expect smaller error rates for digits 0 and 1 when they do not contact the phonological lexicon. This is exactly what is observed in Table 3: digits 0 and 1 yield far less errors that the other digits, only in positions 2 and 3 (decades or hundreds), but not in position 1 (units).[5]

A Revised Model of Number Reading

We may now clearly state the central difficulty in explaining YM's reading performance within McCloskey et al.'s (1986) model. On the one hand, processing appears intact at least up to the syntactic level. On the other hand, performance is largely driven by seemingly low-level visuo-spatial factors. This constitutes a logical paradox for McCloskey et al., who postulate an absolute separation between comprehension and production components in reading. In their account, once a semantic representation of the number is formed, visual representations in principle cannot intervene in further stages of the reading process.

Models of number reading which do not include such a bottleneck stage of semantic encoding (Deloche & Seron, 1987) may avoid this paradox. In

[5] In French, digits 7 and 9 in the tens position play both a syntactic and a lexical role (see footnote 4). Table 3 shows that they do not behave like 1 in the decades position, but rather behave like the other digits. This suggests that YM's reading is impaired on any digit accessing the phonological lexicon, even when this digit also has an additional syntactic role.

these models, it is not meaningful anymore to draw a strict line between comprehension and production components. It then becomes conceivable that visual factors influence late verbal production processes.

Along these lines, we propose that the workbench storing the input data for number reading is visual rather than semantic in nature. This store encodes several visuo-spatial characteristics of the stimulus, including the shape and the relative positions of the digits, presumably in a stimulus-centred co-ordinate system (Caramazza & Hillis, in press). For example, the digits of a vertically printed number still appear in a vertical array at this level. Further processing stages then pick out from this store the information they need (number length, digit identities), and may thus be affected by visual factors. We propose to name this store the visual number form, by analogy with the visual word form, which is the level at which a string of characters is identified as an orthographic entity (Shallice, 1988). Presumably, the visual number form is an input stage common to any task involving number manipulations, including reading, magnitude comparison, calculation, etc.

We may now propose an explanation for the paradoxical sparing of syntax, given the visual characteristics of the deficit. We need only assume that reading requires two successive accesses to the visual number form. A first pass extracts syntactic information, as conveyed by number length and digits with a syntactic role. In a second pass, the identity of the remaining digits is picked out to allow lexical access. Only the second pass would be deficient in YM.[6]

In more detail, our modified reading procedure works as follows (Fig. 1). Number length is processed initially to prepare the standard syntactic frame, specifying the default sequence of words for a number of that length (e.g. the sequence ONES:_ Multiplier:Hundred TENS:_ ONES:_ for a three-digit number like 813) This default frame is then transformed into a specific word sequence or *word frame*. This word frame contains a complete specification of the output lexical classes to be accessed. For example, the word frame for number 813 is ONES:_ Multiplier:Hundred TEENS:_. In contrast to the standard syntactic frame, the word frame now specifies that the last word must be retrieved from the teens class. For 800, the word frame is simply ONES:_ Multiplier: Hundred; slots not to be realised phonetically have been suppressed.

Preparation of a complete word frame requires the identification of only some of the input digits. These are the *syntactic markers*, which modify the default mapping principle from digits in the position of units and hundreds

[6]As is visible in Fig.1, our model allows for a flow of information from one processing stage to several of the later ones. Nevertheless, only unidirectional bottom-up communications are allowed. Thus, the model escapes the objections often raised against top-down architectures.

to names in the "ones" stack, and from digits in the tens position to names in the "tens" stack. In French, the syntactic markers are the silent 0 and 1, and the digits 1, 7, and 9 in position 2. We propose that these markers consitute a separate psychological class, an idea that bears some similarity to the hypothesis of separate lexicons for closed-class and open-class words in language processing (Garrett, 1978). They are picked out selectively from the visual number form, during the first pass, in order to compute the word frame.

Once the word frame is completed, its empty slots must be filled with the appropriate digit identities. The identity of individual digits is retrieved by a second pass through the earlier-defined visual number form. For example, the word frame for 813 is filled as ONES:{8} Multiplier:Hundred TEENS:{3}, a word plan which directly permits phonological access to the final sequence /huit/ /cent/ /treize/ in French. We assume that the *digit identity retrieval* procedure is the locus of YM's impairment: his retrieval procedure suffers from spatial bias, perseverations, and confusions of visually similar digits.

CONCLUSION: THE NATURE OF NEGLECT DYSLEXIA

We have reported a detailed analysis of a corpus of number reading errors yielding some insights into the organisation of number processing pathways. In the patient's errors, number syntax was spared. Errors consisted mainly of digits substitutions and/or perseverations, and were governed by visual factors such as digit position and shape similarity. We propose that a representation with visual characteristics, the visual number form, is accessed repeatedly at several stages of the reading process. Access for syntactic purposes is intact in YM, whereas access prior to lexical retrieval is disrupted selectively.

The positional bias exhibited by YM—reading errors occurring mostly on the leftmost digit—is the most striking spatial feature of his deficit, and deserves further discussion. Positional bias in reading is the hallmark of the so-called neglect dyslexia (Kinsbourne & Warrington, 1962). This disorder is normally only a by-product of visuo-spatial neglect: neglect patients produce reading errors involving the extremity of words corresponding to their neglected field.

There are two major reasons not to accept (without qualifications) the term of neglect dyslexia in YM's case. First YM had no clinical signs of left hemineglect. Although the splenium of corpus callosum was probably invaded by the tumour, he had a massive *left* temporo-parietal lesion with upper right quadrantanopia, so, if anything, right neglect would be expected. Second, the hypothetical neglect would have to interact very specifically with the digit identity retrieval process, and not disturb other visual inputs.

Costello and Warrington (1987) face the very same two difficulties with patient JOH. JOH presents with a clinically evident right-sided hemianopia and visuo-spatial neglect, paradoxically associated with an isolated left neglect dyslexia. He is similar to YM in two respects. First, the neglected side in reading is opposite to the expected one (although both JOH and YM had callosal lesions). Second, we have argued that YM's positional effect did not occur at the visual input level but specifically when accessing the visual number form in the process of reading. Costello and Warrington (1987) similarly conclude that JOH's disorder stems from a faulty access to a preserved visual word form. In a recent paper, Katz and Sevush (1989) describe two similar patients, JM and LS, with mild right side visual neglect. Like JOH, they both make reading errors on the left side of words. Patient JM was asked to read 2-, 4-, and 6-digit numbers. Fourteen of the 16 errors that he produced affected the leftmost digit of the string.

The interpretation of positional bias as an attentional disorder is more natural when the deficit occurs on the side opposite to the lesion. For instance, Hillis and Caramazza (1989) study two patients (DH and ML) with damage to the graphemic buffer. These patients exhibit opposite bias as a function of the position of letters in a word. The two patients have opposite hemispheric damage and show signs of visual neglect. The authors propose that, within the spelling system, DH and ML have selective damage to only one internal representation, namely the graphemic buffer. The right hemisphere patient (ML) would neglect the leftmost region of the graphemic buffer and the left hemisphere patient (DH) would neglect its rightmost region. Quite similar is the conclusion of Baxter and Warrington (1983). Their patient ORF is a left-hander with a right hemisphere lesion, who presents with phonological dysgraphia and makes more errors at the beginning of words, i.e. on the side contralateral to the lesion.

A similar situation has been documented in the domain of Arabic number reading and writing. Patient Paul (Temple, 1989) presents with a developmental digit dyslexia. His errors are more frequent to the rightmost digit than to the other positions in target numbers. In the absence of any evidence of right-sided neglect, and of any visible cerebral damage, an interpretation of this pattern of deficit as a restricted neglect dyslexia would be rather vacuous.

In brief, patients YM, JOH, JM, LS, Paul, ORF, ML, and DH have in common a distinctive pattern of deficit. First, in the linguistic domain, the damage selectively affects the operation of an input or output buffer: the visual word (or number) form for YM, JOH, JM, LS, and possibly Paul, and the graphemic buffer for ML, DH, and possibly ORF. Second, in accordance with the spatial organisation of these peripheral representations, the deficit follows a gradient from left to right. Whether the terms of neglect dyslexia or positional dyslexia (Katz & Sevush, 1989) should be used to designate such cases is a secondary issue. Actually, it highlights the fact that the neglect syndrome, like classical aphasia syndromes (Badecker & Caramazza, 1985), is ill-defined and functionally non-homogeneous.

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APPENDIX

YM was administered a French version of the Boston Diagnostic Aphasia Examin ation (Goodglass & Kaplan, 1972; Mazaux & Orgogozo, 1982), excluding the assessment of writing. He was given a 3 on the overall severity rating scale. Aditory comprehension was good except in the complex ideational material subtest (3/12). Fluency, automatic speech, music and repetition subtests were normal, except low-probability sentence repetition (4/8). He scored 8/10 in the word reading and 7/10 in the sentence reading subtests. The two errors in word reading were /ioé/ . . . /vioé/ for "violet", and no answer at all for "échelle". The word reading subtest includes two written number names ("sept cent quarante" and "dix-huit"), which he read correctly. Picture confrontation naming was more obviously impaired (54/108). Interestingly, he was perfectly accurate when naming actions (6/6), and much worse when naming objects, symbols, colours, and simple geometric patterns (8/24). This advantage of actions over objects ($chi^2[1\ d.f.] = 6.10$ with Yates correction, $P = 0.014$) is congruent with the performance of 4 of the 5 anomic patients described by Miceli, Silveri, Villa, & Caramazza (1984). YM could name 7 out of 10 body parts on confrontation. He could only produce 2 names of animals in the fluency in controlled association subtest. He scored 31/41 in the reading comprehension test (the reading sentences and paragraphs subtest could not be completed entirely).

YM scored 27/36 on a French translation of the Modified Token Test (DeRenzi & Faglioni, 1978), thus being classified as having "mild comprehension impairment".