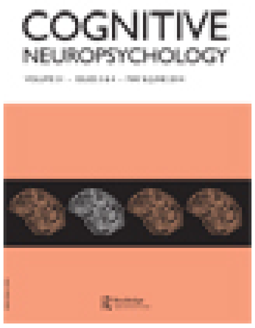

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Digit Dyslexia: A Category-specific Disorder in Development Dyscalculia

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A case study of developmental dyscalculia is presented in which there is impairment of number processing. When reading and writing arabic numbers the syntactic component of the number is processed accurately but lexical processing results in incorrect digit selection. When reading arabic numbers the allocation of lexical items into syntactic frames is particularly poor for digits in the units position. Lexical allocation is unaffected by stimulus length. Despite poor short term memory, word reading is not impaired except for the reading of numeral words for which there is a category specific deficit. Reading errors to numeral words are more frequent than to arabic numbers but the nature of the errors is comparable. This reading deficit coexists with good phonological reading skills. The results are discussed in relation to models derived from studies of the acquired dyscalculias.

INTRODUCTION

A variety of different types of category-specific disorders have now been described in adults who have sustained brain damage (Dennis, 1976; Goodglass, Klein, Carey, & Jones, 1966; Hart, Berndt, & Caramazza, 1985; Hécaen & de Ajuriaguerra, 1956; McKenna & Warrington, 1980; Nielsen,

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1946; Warrington, 1975; 1981; Warrington & McCarthy, 1983; Warrington & Shallice, 1984; Yamadori & Albert, 1973). Some of these have involved dissociations in the spoken naming of classes of lexical items, e.g. between inanimate objects and living things (Warrington & Shallice, 1984). Others have involved dissociations in the comprehension of specific classes, e.g. between concrete and abstract words (Warrington, 1975; 1981).

Despite the documentation of these disorders in adults with neurological damage, the traditional view of the plasticity of the brain in childhood would not lead one to expect analagous deficits to be manifested developmentally. Rather, one would expect that the developing brain, with its capacity for reorganisation, should compensate for any structural abnormality, with residual deficits lacking in specificity. Such a viewpoint derives, in part, from the work of Lenneberg (1967), who argued that at birth the brain was equipotential for language: hemispheric dominance was established gradually and only reached completion by adolescence. The ability of children to recover from head injuries sustained in childhood, which initially affect their language performance, has been taken as evidence in support of Lenneberg's views. However, much recent evidence supports the notion that the brain is not equipotential for language since hemispheric asymmetry is manifest at birth or soon after (Entus, 1977; Glanville, Best, & Levenson, 1977; Molfese, Freeman, & Palermo, 1975). The asymmetry which has been reported in the length of the planum temporale (Geschwind & Levitsky, 1968) has been suggested as a possible anatomical substrate for left hemispheric dominance for language. Moreover, within the left hemisphere frontal lesions in childhood tend to produce nonfluent aphasias whilst posterior lesions produce fluent aphasias (Martins & Ferro, 1987). This suggests early regional organisation, comparable to adults, within the left hemisphere.

Despite these changing views with respect to the onset of lateralisation, the notion of functional plasticity in childhood has remained. The studies of long-term follow-ups of children with hemispherectomy (Dennis, 1980; Dennis & Lovett, 1981; Dennis & Whitaker, 1976) suggest that there may be an upper limit to compensation skills (but see Bishop, 1983): the right hemisphere may never be as competent in syntactic processing and phonological analysis. Yet, the extent of language development in these children is impressive. Sensitive tests are required to delineate deficits. A more common disorder, in which functional plasticity is unable to provide compensation, is developmental dyslexia. Population studies (Rutter, Tizard, Yule, Graham, & Whitmore, 1976, Berger, Yule, & Rutter 1975) suggest that 3-7% of children manifest selective difficulty in learning to read despite adequate intelligence and education.

Recent psycholinguistic analyses of the developmental dyslexias (Campbell & Butterworth, 1985; Coltheart, Masterson, Byng, Prior, &

Riddoch, 1983; Seymour & MacGregor, 1984; Snowling, Stackhouse, & Rack, 1986; Temple 1984a; 1984b; 1984c; 1985a; 1985b; 1988; Temple & Marshall, 1983) and the developmental dysgraphias (Temple, 1985c; 1986a) have revealed conditions analagous to acquired surface dyslexia (Temple & Marshall, 1983), phonological dyslexia (Coltheart et al., 1983) and deep dyslexia (Temple, 1988). Further developmental disorders may also be analagous to disorders in adults, resulting from brain injury.

Recently Temple (1986b) has described a category-specific disorder in childhood which is comparable to the disorders in adults mentioned earlier. The case is of a 12-year-old boy, John, who had an anomic disorder which particularly affected the category of animals, with better development of naming skills for other categories, notably indoor objects. This discrepancy was not a feature of young children with a similar naming age and was not therefore an example of developmental lag. Nor did it result from frequency, familiarity or the type of stimulus material employed. The dissociation was not a feature of cultural experience nor was it exhibited by his twin sister. Further analysis of category-specific disorders in children may provide evidence to address the issue of preformism as well as shedding light on the development and the internal organisation of adult semantic systems. The current paper will address a category-specific disorder affecting number processing in a child with developmental dyscalculia.

In contrast to developmental dyslexia, developmental dyscalculia has been little studied. It has been defined by Kosc (1974) as: "a structural disorder of mathematical ability, which has its origins in a genetic or congenital disorder of those parts of the brain, that are the direct anatomico-physiological substrates of the maturation of mathematical abilities adequate to age without simultaneous disorders of general mental functions". However, despite evidence that developmental dyscalculia may take a variety of forms, there has been no attempt to formulate an appropriate underlying model of these nor to make explicit systematic methods for identifying different types of problems. The paucity of research work in this field contrasts with the enormous literature on developmental reading problems.

Rourke (1982) has looked at the calculation system in developmental dyscalculics. He compared developmental dyscalculics who were good readers and those who were poor readers. The good readers misread signs, aligned rows and columns inappropriately, and missed entire calculation steps. The poor readers avoided unfamiliar operations and had problems with tables, and in recalling appropriate calculation procedures. Unfortunately, these difficulties relate to a variety of different procedural steps. The group conclusions provide little information that addresses the character and development of the individual calculation systems in these children.

Descriptions of the normal development of calculation systems have followed traditional post-piagetian lines delineating stage models. Before learning how to process numbers and entering school, children develop techniques for solving quantitative problems. These skills form system 1 of Ginsburg's (1977) conceptual framework. They are *informal* because they develop outside school and, because they do not require specific information transmitted by culture, they are termed *natural*. Examples include the concept of "more" and the skills, studied by Piaget (1952), of one-to-one correspondence, equivalence, and seriation. Much of Gelman's research has concerned the capabilities of the pre-school child and in particular she has studied the use of counting algorithms (Gelman & Gallistel, 1978). The pre-school counting stage forms system 2 of Ginsberg's (1977) conceptual framework. It is informal but it is *cultural* because it depends upon precise social transmission. Early performance on mental arithmetic suggests the use of a counting algorithm which switches later to memory retrieval from an organised representation of addition facts (Ashcraft & Fierman, 1982). The learning of written symbolism, algorithms, and explicitly stated mathematical principles forms system 3 of Ginsburg's (1977) conceptual framework. It develops through contact with a written culture and is therefore *formal* and because of the social agents involved it is cultural. For a proper development of the number concepts involved in these procedures Piaget believed that the development of object permanance and the principle of seriation were essential precursors. Only at the stage of concrete operations, in his schema, where a diverse set of quantitative principles come to be understood simultaneously, is the child able to carry out such manipulations as formal addition and subtraction. However, according to Gelman, the use of algorithms is local. In one situation a child appears to understand a particular arithmetical concept but in another he does not.

The nature of the mechanisms of arithmetical computation and the representation of numbers in the normal adult brain has received new stimulus from recent studies of acquired dyscalculia. Traditional attempts to classify the acquired dyscalculias into different types had been based largely upon two variables: the functional factor causing the disorder and the lesion location associated with the disorder (Boller & Grafman, 1983). The functional factors proposed include disorders of: attention, memory, intelligence, spatial ability, language, abstraction, and body schema. However, it is not clear that any of these potential concomitant deficiencies are necessary and/or sufficient conditions for the emergence of a calculation disorder. In the numerous papers mapping deficit to lesion site, frontal, occipital, temporal, and parietal areas on both sides have all been implicated. The largest number of patients with acquired dyscalculia have been studied by Hécaen (Hécaen & Angelergues, 1961; Hécaen, Angelergues, & Houillier, 1961). Patients were classified into three groups: alexia or agraphia for digits and numbers, in which the reading and writing impairments affect arithmetical operations; spatial dyscalculia where there is a disorder of spatial organisation for numbers leading to lack of respect of the rules used to place digits in their proper order; and anarithmetia in which neither of these deficits are apparent but there is difficulty performing arithmetical operations. This tripartite classification assumes that normal number processing and calculation involves a number reading and writing ability, a spatial ability, and a calculation ability, but the nature of these posited abilities is left unspecified. It is not clear how each ability is involved in different tasks, nor the sort of impairments which should result from its disruption. It is also a problem that the three types are insufficient to account for the great diversity of number processing and calculation impairments seen in brain-damaged patients. Thus there is heterogeneity in each category.

The new wave of studies of acquired dyscalculia has been carried out using a cognitive neuropsychological perspective, the objective being to formulate hypotheses about the functional architecture of normal cognitive systems which, when "lesioned" in appropriate positions, result in specific patterns of impaired performance (McCloskey, Caramazza, & Basili, 1985; McCloskey, Sokol, & Goodman, 1986).

McCloskey et al. (1985; 1986) draw a basic distinction between a number processing system and a calculation system. The number processing system comprises the mechanisms for perceiving, comprehending, and producing numbers. The calculation system consists of the facts and procedures required specifically for carrying out calculations. The number processing system is of most relevance here. Certain patients exhibit difficulty processing arabic numbers (e.g. 6) whilst verbal number processing is intact (e.g. six). Other patients show the reverse dissociation. Thus different cognitive mechanisms are involved in the processing of arabic and verbal numbers. Certain patients show intact comprehension of numbers by making appropriate magnitude judgements yet read the same items aloud incorrectly. Separate production and comprehension mechanisms are therefore postulated. A further distinction is drawn (within the verbal and arabic number systems) between lexical and syntactic processing components. The lexical processing component is concerned with the processing of individual number words and digits. Patients with impairments of this system make errors of the sort *4051* read as "three thousand and fifty-one". The syntactic component processes the relationships among the elements that comprise a number. Patients with impairments of this system make errors of the sort *4051* read as "four thousand five hundred and one".

In this model "number syntax" identifies the largest power of ten in the number and generates syntactic frames which are placed in working memory whilst lexical processes are carried out. A number input device interprets digits. Each basic quantity in the input semantic representation is assigned to the appropriate slot in the syntactic frame. A number production lexicon retrieves the phonological representations for oral production of the specified sequences in the filled syntactic frames. The syntactic frames, lexical representations, and lexical retrieval processes are qualitatively different for the production of arabic and verbal numbers since information is in the form of digit sequences for arabic numbers but in the form of words for verbal numbers.

In contrast to the number processing system the calculation system processes operational signs which indicate that a specific calculation is to be performed; stores and accesses arithmetical facts; and executes retrieved calculation procedures.

Deloche and Seron (1982a; 1982b) have conducted a number of studies of number processing and looked at transcoding of numbers from one modality to another and one representation to another. They have introduced the notion of stack structure. Stacks are one-dimensional arrays. Items belong to a particular stack and have a specified position within the stack. When a stack error is made the information relating to stack membership is incorrect but position information is correct, e.g. 50 → 5. Position within stack errors indicate that the information relating to stack membership is correct, but position information is incorrect, e.g. 50 → 40 or 60. McCloskey et al. (1986) refer to the former errors as "within-class" errors and the latter as "out-of-class" errors. Both reflect errors in the lexical component of number processing.

The case to be presented describes a boy with developmental dyscalculia which is considered in the light of McCloskey et al.'s schema. The boy has an impairment in number processing in which the lexical processing component is poorly established, regardless of task. Word reading is not impaired except for the reading of numeral words, for which there is a category-specific deficit.

CASE REPORT

Paul was referred, at age eleven, to the Neuropsychology Unit, Oxford, by his general practitioner for assessment of mathematical problems. Birth, motor milestones and early development were all considered normal. There are no siblings. There has been no serious illness, no head injury, and there are no known neurological abnormalities. There have been no seizures and no medication is taken. Paul attends a normal school but from the earliest days, difficulties with arithmetic were reported. Previous intelligence testing had been found to be unexpectedly poor but on Ravens Progressive Matrices, Paul now scores at an I.Q. level of 85, which is at the lower end of the average range.

FIRST ASSESSMENT AT AGE ELEVEN

Most language tests were performed at a normal level for age. Comprehension of vocabulary, on the Peabody Picture Vocabulary Tests, and comprehension of grammar on Bishop's TROG, were normal. Oral fluency was adequate for age. Verbal memory as assessed by the recall of stories was normal. There were only minor errors on the repetition of verbal stimuli from the Benton Aphasia Battery. Some degree of naming difficulty was displayed by a score of 8 years 2 months on the Renfrew Naming Test. However, the upper limit on this test is only 8 years 7 months.

Some specific difficulties emerged. Auditory short-term memory as revealed by recall of a sequence of digits was very poor: digit span was only two forward and two backward. Word span and letter span were three forwards and nonverbal span on Korsi blocks was two. Automated sequences were poorly performed. Only the letters A-P of the alphabet could be recalled and only the months January and September. Counting from 1-20 was accurate except for one missequenced intrusion. Results on the Benton Test of Visual Retention and the Figure of Rey indicated poor copying of nonsense material (at a 7-8 year level) and severely impaired nonverbal memory. No arithmetical concepts and operations had been mastered; only simple addition of numbers less than ten was sometimes possible by counting with fingers upwards from the larger of the two numbers.

Reading and Spelling

Paul's reading is at age level. Text reading on the Neale was at an 11-year level for accuracy and a 10-year 7-month level for comprehension. Single-word reading on the Schonell was at an 11-year age level and single-word spelling was at a 10-year 2-month level. Paul had established a wide sight vocabulary and was able to read such irregular words as *orchestra, physics, choir, forfeit, colonel,* and *antique.* He also has good mastery of phonics, being able to read correctly both pronounceable nonsense words and long unfamiliar words, e.g. *hectographic, chitterling,* and *intertergal.* Relationships between reading and short-term memory or the articulatory loop of working memory have been discussed by many (e.g. Jorm, 1983; Katz, Healy, & Shankweiler, 1983; Liberman, Man, Shankweiler, & Werfelman, 1982; Vellutino, 1978). Poor digit span is one of the clinical characteristics, listed by Denckla (1979), for "pure" developmental dyslexia. It is therefore worth noting in passing that Paul's competent reading levels are attained despite his digit span of 2 and letter span of 3.

Processing of Numbers

An identical set of 40 number stimuli were used in all number tests: the 10 single digits 0 to 9; 10 2-digit numbers, e.g. 78, 21; 10 3-digit numbers, e.g. 176, 252; and 10 4-digit numbers, e.g. 7621, 8433. The full stimulus list appears in Appendix I.

Reading Arabic Numbers Aloud

The stimuli were each written on a single card and presented twice for reading aloud. Results were similar for both presentations. Sixty per cent of the stimuli were read correctly. Examples of errors are given in Table 1. Of the 36 errors, 30 were purely lexical and affected positions within a class; that is, the length of the stimulus and correct multiplier words were selected but inappropriate numeral words were inserted. Thus an ability had developed to process the syntactic relations among the lexical elements but there was impaired development of the lexical processing of individual digits.

The nature of the errors was examined in more detail to determine whether there were any consistencies and patterns; to enable comparison with the model of McCloskey et al. (1986); and in order to be able to compare performance patterns across tasks. The probability of reading a digit correctly was independent of the size of the number (Table 2a). That is, the percentage of digits read incorrectly was unaffected by whether they were in single-digit or four-digit numbers. Longer numbers were more often read incorrectly than short numbers since the cumulative probability of an error was greater with more digits to read.

TABLE 1
Examples of Errors in Reading Arabic Numbers Aloud

1	→	"nine"
85	→	"eighty-two"
34	→	"seventy-six"
711	→	"seven hundred and eighteen"
153	→	"one hundred and twenty-three"
592	→	"two hundred and ninety-two"
9172	→	"six thousand, six hundred and seventy-two"
7621	→	"seven thousand, six hundred and eighty-two"
8483	→	"eight thousand four hundred and eighty-four"

TABLE 2
Probability of Incorrect Digit Response as a Function of Magnitude of Number

a.	*Reading Arabic*	
	1–9	0.15
	10–99	0.23
	100–999	0.20
	1000–9999	0.18
b.	*Writing Arabic*	
	1–9	0.20
	10–99	0.25
	100–999	0.23
	1000–9999	0.45
c.	*Reading Numeral*	
	1–9	0.30
	10–99	0.30
	100–999	0.38
	1000–9999	0.32

TABLE 3
Probability of Incorrect Digit Response as a Function of the Position of the Digit in a Number

✓, ___ ___ ___ : Thousands
___, ✓ ___ ___ : Hundreds
___, ___ ✓ ___ : Tens
___, ___ ___ ✓ : Units

a.	*Reading Arabic*	
	Thousands	0.10
	Hundreds	0.15
	Tens	0.12
	Units	0.28
b.	*Writing Arabic*	
	Thousands	0.20
	Hundreds	0.40
	Tens	0.30
	Units	0.33
c.	*Reading Numeral*	
	Thousands	0.20
	Hundreds	0.20
	Tens	0.30
	Units	0.45

TABLE 4
Reading Arabic Numbers: The Percentage of Lexical Errors Resulting from Digit Response Errors in Different Positions

Error Position	*Thousands*	*Hundreds*	*Tens*	*Units*
One-digit Number	—	—	—	100%
Two-digit Number	—	—	25%	88%
Three-digit Number	—	18%	18%	64%
Four-digit Number	18%	36%	36%	45%

TABLE 5
Mean Error Response as a Function of Stimulus Digit

Digit	*No. of Stimuli*	*No. of Errors*	%
a. *Reading Arabic Numbers*			
1	32	7	22%
2	26	5	19%
3	18	5	28%
4	18	4	22%
5	20	6	30%
6	12	3	25%
7	26	1	4%
8	24	4	17%
9	22	2	9%
b. *Writing Arabic Numbers*			
1	16	5	31%
2	13	6	46%
3	9	5	55%
4	9	4	44%
5	10	3	30%
6	6	0	0%
7	13	4	31%
8	12	0	0%
9	11	4	36%
c. *Reading Numeral Words*			
1	32	14	44%
2	26	5	19%
3	18	4	22%
4	18	8	44%
5	20	8	40%
6	12	3	25%
7	26	8	31%
8	24	4	17%
9	22	12	55%

The percentage of errors in numeral words as a function of the position of a stimulus digit in a number is given in Table 3a. Regardless of the length of the stimulus, errors are more likely to be made to terminal than initial digits. Thus, for example (see Table 4), in 25% of the lexical errors to 2-digit numbers the first digit, in the tens position, was incorrect but in 88% of the errors the final digit was incorrect. The two percentages do not summate to 100% since some errors may result from a mistake in both digit positions. However, the absolute number of errors in the terminal position is not affected by stimulus length. The fourth digit of a four-digit number is no more likely to provoke an error than the second digit of a two-digit number (see Table 4).

It is also possible to calculate the digit error rate as a function of the stimulus digit (see Table 5a). The digit 7 is the least likely to elicit errors, with the digit 5 provoking six times as many errors.

Writing Arabic Numbers to Dictation

Each of the stimulus set was spoken aloud for written response. As with reading, half of the stimuli elicited errors. Examples of errors are given in Table 6. All of the errors, except two, were purely lexical and within class. That is, the length of the stimulus and the syntax of the number was correctly interpreted but inappropriate digits were selected. Once again the ability to process syntactic relations has developed but lexical processing of individual digits is impaired.

Writing errors were further analysed, as for reading errors. The percentage of digits written correctly was unaffected by stimulus length for numbers less than 1000 but error rate doubled between 1000 and 9999 (Table 2b). Slightly fewer errors were made in the initial position than in other positions (Table 3b). The frequency of terminal digit errors was not affected by stimulus length. As before, the second numeral word of a two-digit number was more, rather than less, likely to elicit an error than the fourth numeral word of a four-digit number. The nature of the numeral words

TABLE 6
Examples of Errors in Writing Arabic Numbers to Dictation

"two" → *3*
"nine" → *8*
"twenty-one" → *28*
"ninety-nine" → *91*
"seven hundred and eleven" → *511*
"nine hundred and twenty-one" → *822*
"seven thousand six hundred and twenty-one → *7688*
"eight thousand one hundred and forty-seven" → *8897*
"nine thousand two hundred and fifty-one" → *9281*

eliciting errors was further analysed (see Table 5b). The frequency of occurrence of each stimulus is half that of the previous analysis since the stimulus set was only written once and not repeated. Variations are therefore only suggestive. On all 12 of its appearances the numeral 8 was written correctly whereas on 5 out of 9 occurrences the numeral 3 provoked errors. This pattern of specific numeral words eliciting errors differs from that observed for specific digits, when reading arabic numbers.

For this dictation task poor memory may be hampering performance, since the digit span task indicated recall of only two items. Long numbers are further complicated for retention by the length of their "syntax", e.g. "three thousand four hundred and seventy-six". Two further writing tasks were therefore given: dictation of numeral word strings, derived from the stimulus set minus its "syntax", e.g. "three-four-seven-six"; and dictation of letter strings derived from assigning each of the above digits to a letter, e.g. "C-D-G-F". Nineteen of the numeral word strings were written correctly in arabic form, a similar level of performance to writing the full numbers in arabic form (42% and 47%). In contrast, 31 of the letter strings were written correctly (78%). Paul is thus significantly better at writing letters than digits ($X^2 = 6.45$, $P < 0.02$) and the number writing deficit cannot be attributed to a material-independent deficit of memory. Memory does appear to hamper all performance with four-item stimuli. It is on these that most of the letter string errors are made. Reducing the comparison to performance on 1-3 item stimuli, an even more marked dissociation is shown between numbers and letter strings correct: 53% numbers; 53% digit strings; 93% letter strings.

Reading of Numeral Words

Since reading of arabic numbers is poor but reading of words is good it was initially predicted that the reading of numeral words (e.g. "eight", "thirty-six") would be in sharp contrast to the reading of arabic numbers. All the previously employed stimuli were written in numeral words and presented on two occasions for reading aloud. In contrast to expectation, numeral word reading was as poor as arabic number reading. Examples of errors are given in Table 7. Of the 47 errors, 45 were purely lexical and within class, preserving the length and syntax of the stimulus.

Probability of digit error was unaffected by number length but was slightly higher than for arabic numbers (see Table 2c). On all three number processing tasks the probability of correct digit response as a function of the position of the digit in a number shows trends suggesting greater difficulty with digits in the terminal position than those in initial positions. In reading numeral words the effect is the most marked. Relative difficulty with different numeral word stimuli (Table 5c) suggests least problems with the number eight and most with the number nine.

TABLE 7
Examples of Errors in Reading in Numeral Words

five → "six"
three → "eight"
four → "two"
nine → "three"
seventy-eight → "seventy-two"
seventeen → "eighteen"
three hundred and seventy-one → "three hundred and eighty-eight"
nine hundred and twenty-one → "two hundred and twenty-two"
four hundred and ninety-eight → "four hundred and eighty-eight"
nine thousand, four hundred and thirty-eight → "one thousand, four hundred and thirty-eight"
seven thousand, two hundred and seventy-one → "seven thousand, two hundred and thirty-two"

Previous investigations of the reading of text and single words had revealed no deficits. Nevertheless, reading one stimulus after another, from a closed set of conceptually related items, might cause confusion. Another set of stimuli which form a closed class are colours. A set of unusual-looking stimuli were accordingly constructed by assigning a colour to each of the numerals 0-9 and "translating" the numbers into (partially) colour word sequences. Resultant stimuli included "white thousand red hundred and grey-green", "purple hundred and yellow-brown", and "red hundred and orange-red". These stimuli were also presented for reading aloud but, in contrast to the numeral sequences, these colour sequences were unproblematic. Only two minor errors were made, though it may be of interest that both of these errors were semantic in nature : *grey-blue* → "orange-blue"; *grey hundred and green-green* → "grey hundred and white-green". There was also a self-corrected semantic error to a number syntax word: *grey thousand purple hundred and red-green* → "grey hundred . . . grey thousand purple hundred and red-green". Paul is significantly poorer at reading the stimuli of numeral words than at reading "colour numbers": 33/80 (41%) vs. 38/40 (95%); $X^2 = 29$, $P<0.001$).

Repetition of Numbers

The dissociations shown here are also revealed on repetition tasks. The repetition of numbers is impaired while the repetition of "colour names" and letter strings is unimpaired except for four-item stimuli, where more general short-term memory problems are in evidence. These results and the other number processing results are summarised in Table 8.

The Teen Phenomenom

Caramazza and McCloskey (in press) have provided evidence from cases of acquired dyscalculia that "teens" form a distinct class from ones and tens in the verbal number production lexicon. When they study patients with

TABLE 8
Summary of Test Results

		Stimulus Length					
		1	*2*	*3*	*Sub-total*	*4*	*Total*
Task	(e.g.	7	34	711		1843)	
Reading Arabic Numbers	a)	9	5	3		3	
e.g. 36	b)	8	7	4	60%	5	55%
Writing Arabic Numbers e.g. "thirty-six"		8	5	3	53%	1	42%
Writing Digit Strings e.g. "three-six"		8	2	6	53%	3	48%
Writing Letter Strings e.g. "C-L"		10	10	8	93%	3	78%
Reading Numeral Words	a)	7	6	3		3	
e.g. thirty-six	b)	7	2	1	43%	4	41%
Reading Colour Numbers e.g. blue-green		10	9	9	93%	10	95%
Repeating Numbers		8	5	4	57%	2	47%
Repeating Colour Numbers		10	10	10	100%	0	75%
Repeating Letter Strings		10	10	9	97%	6	87%

Figures in each section give number correct out of ten.
a) first presentation b) second presentation.

disorders of number word production and the error rate to the number one in the teens position (e.g. the 1 in 17), they find that it elicits significantly fewer errors than when the number one is in a units or hundreds position (e.g. 71 or 107). Error responses to numbers in the teens are predominantly other teen numbers. The processing of teen numbers was not specifically investigated here but amongst the stimuli were three containing the digit one as a teen number: 17, 711, 2516; eight containing the digit one as a units number: 1, 21, 371, 711, 921, 7621, 7271, 9251; four containing the digit one as a hundreds number: 153, 176, 8174, 9172; and one containing the digit one as a thousands number: 1843. Each of these numbers occurred on six occasions: twice in reading arabic numbers, twice in reading numeral words, once in writing arabic numbers, and once in repetition. The proportion of times that the number one was processed correctly in each of the units, tens, hundreds, and thousands positions are given in Table 9. When in the units, hundreds, and thousands position, errors are made to the number one, but when in the teens position errors are not made. This is not because the numbers are necessarily read correctly but errors to teen numbers are always other teen numbers, (e.g. 711 → 718 [reading arabic]; 17 → 18 [reading numerals]; 711 → 511 [writing arabic].) There is a significant difference between the processing of ones in the teens position and ones in the units position ($X^2 = 10.4$, Yate's correction applied). Earlier analyses revealed that there was an increased tendency for errors to be made to numbers in the

TABLE 9
Errors to the Digit One as a Function of its Position in a Number

Position	No. of Items	No. of Tasks	No. of Errors	%
✓, — — —	1	6	2/6	33%
—, ✓ — —	4	6	2/24	8%
—, — ✓ —	3	6	0/18	0%
—, — — ✓	8	6	22/48	45%

units position regardless of the digit concerned (see Table 3). Thus the teen-unit comparison here might be a feature of tens-units comparisons for all numbers and attributable to generally lower accuracy for numbers in the units position. Tens-units comparisons were therefore carried out for other numbers. The results are summarised in Table 10. There were no exemplars of the digit 6 appearing in the tens position. For other numbers a discrepancy of the teens-units size did not appear on tens-units comparisons. None of the tens-units comparisons reached significance. This supports McCloskey and Caramazza's notion of teens forming a distinctive class. As McCloskey et al. (1986) have discussed, such effects with respect to "teens" go against any generalised encoding deficit hypothesis of number processing. If there was a general impairment in encoding digits or number words which evoked lexical errors then the errors should appear irrespective of the position of a digit or number word in stimulus. In contrast, their model provides a

TABLE 10
Errors to Digits in Tens or Units Position

Digit	Tens	Units	% Diff.
1	0/18	22/48	
	(0%)	(46%)	45%
2	7/24	11/24	
	(29%)	(46%)	17%
3	3/12	10/30	
	(25%)	(33%)	8%
4	10/24	5/12	
	(42%)	(42%)	0%
5	9/24	4/12	
	(38%)	(33%)	5%
6	—	7/24	
	(—)	(29%)	?
7	6/36	5/24	
	(17%)	(21%)	4%
8	1/24	7/30	
	(4%)	(23%)	19%
9	5/18	11/24	
	(28%)	(46%)	18%

straightforward explanation of the "teens" result. In the model, for example, when reading arabic numbers, the quantity representations in a filled syntactic frame are used to address particular positions within digit lexical classes in the phonological production lexicons. The *1* in a tens-class slot has a special status. It is not used to address a particular phonological representation within lexical classes but carries a specification that a teens procedure should be invoked, which will affect the class of responses accessed for the following digit (e.g. that a 5 in a units slot should elicit "fifteen"). Paul's data suggest that comparable normal syntactic frames, including procedures for identifying teens, may develop despite the absence of accurate lexical number processing mechanisms.

Errors Generated

The error analyses given previously relate to stimuli which generate errors. However, it is also of interest to look at the nature of the errors generated. The figures in Table 11 indicate some consistency in the pattern across tasks.

The digits most commonly produced as errors are 8, 2 and 6, with 8 the highest frequency overall. 1, 3, 4, and 7 are seldom produced as errors. Indeed 4 is only produced once as an error on all three tasks. The consistency across tasks is more marked for these responses than it is for stimuli which elicit errors (see Table 5).

Error Variants

Although a majority of errors are lexical "within-class" errors, a small number of syntactic errors were made. Four of these were "stack" errors or "out-of-class" lexical errors: zero (read as) "thirty"; "one hundred and seventy-six" (written as) 1076; "one thousand eight hundred and forty-three" (written as) 10843; and 921 (read as) "nine thousand and twenty-one". In these errors, despite the incorrect class being accessed, the correct position-within-class information is retained. Such errors provide support

TABLE 11
Digits Produced as Errors

Digit	*Reading Arabic*		*Writing Arabic*		*Reading Numeral*	
1	0	—	1/32	3%	1/64	2%
2	11/35	31%	4/32	13%	23/64	36%
3	0	—	1/32	3%	2/64	3%
4	1/35	3%	0	—	0	—
5	3/35	9%	2/32	6%	2/64	3%
6	6/35	17%	4/32	13%	6/64	9%
7	2/35	6%	0	—	1/64	2%
8	10/35	29%	17/32	53%	28/64	44%
9	2/35	6%	3/32	9%	1/64	2%

for the notion of both class and position-within-class representations. Four errors resulted from lexical errors in the use of multipliers, e.g. 8147 (read as) "eight hundred one hundred and forty-seven". McCloskey et al. (1986) posit a distinct class of multiplier words. Consistent with this assumption of a functional distinction of multiplier words from other number words, none of Paul's errors can be interpreted as a substitution of a multiplier word for a nonmultiplier word or vice versa. Two errors involved the deletion of syntactic words: 648 (read as) "six forty-eight"; nine thousand two hundred and fifty-one (read as) "nine and two hundred and twenty-two". These two errors are the only ones which are not lexical errors in McCloskey et al.'s (1986) terms. Of the ten errors discussed here, four also contained lexical within-class errors. Over all tasks, at least 99% of errors were purely lexical.

DISCUSSION

Arabic and Numeral Production

Paul's reading and writing of numbers and his reading and repetition of numeral words shows a selective competence in processing what McCloskey et al. (1985; 1986) have called the syntactic processing component of number systems. In contrast, the lexical processing component is impaired. Reading of numbers is comparable to patient HY of McCloskey et al. (1986) who made errors on reading aloud both arabic numbers and verbal numbers. Specific numeral words were incorrect but the responses were of the same order of magnitude as the stimulus. Paul also shows a specific lexical impairment in writing numbers to dictation. McCloskey et al. (1986) propose a model in which, subsequent to comprehension mechanisms, production systems for arabic and verbal numbers are entirely separate. In support of this view they have reported patients for whom there is a sharp dissociation between the ability to produce verbal numbers and write arabic numbers, despite intact comprehension. If a similar model applies here it is necessary to postulate at least two deficits in number production, both lexical in nature, the first to verbal number production and the second to arabic number production. The different error patterns over the two production modalities with respect to the specific digits or numeral words eliciting errors and the differing overall error incidence would appear to support such an interpretation.

Processing of Units

Investigation of the probability of incorrect digit response as a function of the position of a digit in a number showed no difference in probability between digits in thousands, hundreds, or tens positions for reading arabic numbers nor in thousands, hundreds, and tens positions for reading numeral words. However, on both tasks probability of error was higher in the units position. On the writing of arabic numbers, where one might have anticipated that short-term memory problems would particularly affect the latter digits, a higher error probability for digits in the units position did not appear. The higher probability of error in the units position on the reading tasks does not have a ready explanation in terms of short-term memory difficulties either. If short-term memory difficulties were at root then one would expect more errors to digits in the units position of four-item stimuli than to those in the units position of two-item stimuli, but the higher probability of errors in the units position is independent of stimulus length. Further, combining the scores across tasks, the difference between errors for the second digit of a two-digit number and the second digit of a four-digit number (19/40 vs. 9/40) is statistically significant ($X^2 = 4.45, P < 0.05$). Thus the lexical impairment in number processing on the two reading tasks is differentially affected by the syntactic position of the lexical item. This suggests that once the syntactic frame is generated in the verbal number production system there is a defect in slotting the final item into the final position in the syntactic frame. Alternatively there may be a defect in the process of retrieving a phonological representation for the final item in the syntactic frame. This suggests separable mechanisms in accessing lexical representations from the different syntactic frame positions. McCloskey et al. (1986) have not discussed such a possibility but the view is supported here by the differing errors elicited by digits in differing positions. The absence of a final digit effect in writing arabic numbers further supports the dissociation between the production mechanisms for numeral words and arabic numbers. Since neither magnitude comparisons nor other assays of comprehension were obtained, alternative accounts in relation to comprehension rather than production mechanisms cannot be refuted unequivocally. Indeed, it seems probable that a comprehension deficit is a further component of Paul's impairment. However, the observed "teen" phenomenon and the units position effect indicate that the deficit in relation to number word production must be at a level where syntactic position has already been specified.

Semantic Representations of Numbers

For Paul there is never refusal in the number processing tasks. Some sort of store is accessed and a production is made. That is, Paul does have a semantic system for numbers but it is either poorly specified or access to or from it is difficult. Shallice (1987) has stressed this distinction between disorders of access or poor establishment of the stored information.

Paul does not produce errors which are not numbers. This is reminiscent of the report by Penfield and Roberts (1959) of specific electrode sites on the cortex, in which, when electric current was applied, there was confusion of numbers while counting. The confusion was illustrated by the patient jumping from one number to another in no obvious sequence. Words other than numbers were not used, i.e. "he had the proper 'set' but was unable to give the correct numbers". After withdrawal of the electrode the patient continued to count correctly. In Penfield and Robert's patient, semantic errors are generated when the electrical circuitry is disturbed in a localised region of the cortex. Yet the underlying storage of number information is not destroyed by this disruption; it is subsequently seen to be intact. It remains possible that Paul's internal store of number information is correctly established but that the mechanisms of access are sporadically disturbed in some fashion comparable to Penfield and Robert's patient. On more than 50% of occasions numbers are processed accurately. Error rate is high but performance overall is not random. A store of some sort exists but this does not speak to the locus of the difficulty when performance fails. Also, in contrast to the patients of Penfield and Robert there are no conditions or tasks in which number processing is perfect. There is thus no clear evidence of a comprehensive store. If the store is established then all routes of access to it are impaired. It might seem more probable that the store or stores themselves are deficient.

Some number sequence information has been established, since only one error is made, by Paul, when counting from 1-20. This consisted of the number 8 reiterated between 12 and 13. However, many researchers consider counting to be an "automatic" task which does not require semantic intervention. Paul is also able to draw the face of a clock and correctly position the numbers 1-12 on its face. Number sequence information can thus be produced both orally and graphically.

The child with animal anomia (Temple, 1986b) also made predominantly semantic naming errors. Other animal names were produced in response to animal stimuli. Moreover insect errors were other insects; water creature errors were other water creatures and there were certain favoured responses, with "wasp" common for insect and "octopus" for sea creatures. The range of responses was narrower than the range of stimuli. Grossman and Wilson (1987) have reported a study of stimulus categorisation by brain-damaged patients in which left posterior patients demonstrated weak category boundaries, sometimes reclassifying items, and left anterior patients showed highly categorical responses and "less differentiation of items within a category". This suggests that brain damage may not merely impair the processing of particular categories of information but may alter the representation of those categories, in some cases narrowing or widening the concept within the category. The category of numbers has a restricted number of lexical items and the boundaries are well fixed. Categorisation tasks were not employed with Paul. However, an analysis of the probability of particular digits being elicited as error responses (Table 11) shows that the accessability of lexical items within the category of numbers is unequal. All digits may provoke errors in numbers (Table 5), but the distribution of these and of responses is uneven: some digits do not appear to be produced as errors on certain number processing tasks (Table 11). Whether these effects result from the nature of the stores themselves or the nature of access to or from them remains unresolved.

Reading Words

Hinshelwood's (1917) view that letter, word, and number reading each depend upon a separate brain centre is supported by the finding that, despite the impairments in number reading, Paul reads words at a normal level for his age. Reading numeral words is a selective category-specific impairment. Further, the incidence of reading errors to numeral words is significantly greater than the incidence to arabic numbers ($X^2 = 5.8$, $P < 0.05$, Yate's correction applied). Nevertheless, the nature of the reading difficulty for arabic numbers and numeral words has common features, suggesting some relationship between the establishment of the two systems. Given the common lexical impairment of number reading, writing numbers to dictation, and repetition of numbers, it could be argued that there has been a central impairment in the development of the lexical representations of numbers. It could further be suggested that the accurate reading of numeral words requires an appropriate semantic representation for numbers, even if established mechanisms for processing numeral words and numbers are ultimately dissociable and/or differentially effected.

However, it is known from studies of acquired and developmental dyslexia that reading aloud does not require semantic access. Evidence supports the notion of a distinct reading route which can accurately read aloud words with regular spelling-to-sound correspondences. Paul shows competent reading of nonwords, a task which requires phonological route reading. He is also able to read correctly many long unfamiliar regular words. In terms of standard psycholinguistic analyses Paul shows no evidence of impairment in his phonological reading route. Why then does he not use this system to aid his numeral word reading? Some numbers are irregular words (e.g. one, eight) which are known to be problematic for phonological analysis since their pronunciation is not logically related to a sequence of rules. If errors were arising from limitations in phonological route reading one would expect there to be greater difficulty on reading irregular number words in comparison to reading regular number words (e.g. five, six, seven). However, the analysis of mean error responses as a function of stimulus digit (Table 5) does not suggest particular difficulty with irregular numerals. Indeed, *eight,* an irregular word, has the lowest error rate and *nine,* a regular word, has the highest error rate. The nature of errors is incompatible with phonological route reading where one would expect to see regularisation errors of the sort one → "own" or eight → "egit". These are never observed. All errors to numeral words are semantic in nature and represent substitutions within a fixed set. One may therefore conclude that a semantic reading route is being employed for the numeral reading task.

Fluent adult readers are believed to read familiar words via a semantic reading route, though Newcombe and Marshall (1980) have argued that concurrent phonological processing serves to block semantic errors for this route, which is intrinsically unstable. In Paul's case, despite good phonological reading skills, semantic errors are not blocked. Phonological reading does not appear to be automatically concurrent with semantic reading. If such reading could be encouraged concurrently error rates might reduce. This suggests an obvious line for potential remediation.

Subsequent to the reported assessment Paul has been involved in an intensive remediation programmer. Further investigation will delineate the nature of the remediation programme involved and its impact upon both number processing skills and calculation abilities. Further study will also investigate the nature of the development of basic number concepts.

Functional Plasticity

The degree of plasticity of the developing brain may have been overestimated. Developmental dyslexia may prove to be merely one of a range of selective disorders of cognition which has been highlighted because of its educational implications. Some other neuropsychological disorders may be less common but it is proposed that not only will developmental dyslexias analagous to acquired dyslexias be further delineated but there will be developmental category-specific disorders analagous to acquired category-specific disorders; and in similar parallels developmental dyscalculias analagous to acquired dyscalculias; developmental constructional apraxias; developmental amnesias; and developmental prosopagnosias. The cognitive neuropsychological perspective has encouraged many new studies of acquired disorders. Its wider use with developmental disorders should not only provide new theoretical accounts of previously described conditions but should highlight novel disorders with distinct theoretical and educational implications. Only when the full range of developmental disorders has been systematically analysed and described can the issue of preformism be resolved and the mechanisms and limitations of functional plasticity be delineated.

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APPENDIX I

Stimuli Used in Number Processing Tasks (Order Randomised)

1	2	3	4	5
6	7	8	9	0
17	21	49	34	73
85	99	56	78	82
176	252	371	498	711
587	921	153	592	648
1843	7621	9438	7271	9172
8483	9251	3529	8147	2516