

EVIDENCE FOR PRESERVED READING IN 'PURE ALEXIA'

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SUMMARY

We describe 4 patients who developed pure alexia after infarctions of the left cerebral hemisphere. All subjects employed a letter-by-letter strategy (with varying degrees of success) to explicitly identify visually presented words. Although all 4 subjects explicitly denied that they could identify briefly presented words, they all performed significantly better than chance on lexical decision and forced-choice semantic categorization tasks with briefly presented words which they could not explicitly identify. Three subjects regained the ability to explicitly identify briefly presented words; these subjects were more accurate with nouns than functors and words of high as compared with low imageability. Additionally, these subjects were impaired in the processing of suffixes. These data are not accommodated by the 'disconnection' account of pure alexia but are more consistent with the hypothesis that reading in these patients is mediated by the right hemisphere.

INTRODUCTION

In his seminal contributions to the study of acquired dyslexia, Dejerine (1891, 1892) described 2 patients with reading impairment in association with lesions of the left cerebral hemisphere. The first patient (Dejerine, 1891), who had suffered an infarction involving the angular gyrus, was noted to be both alexic and agraphic; the second (Dejerine, 1892) developed alexia without agraphia or significant aphasia in association with infarction of the left medial occipital cortex, periventricular white matter of the left occipital lobe and small portions of the splenium of the corpus callosum. In light of these findings, he proposed that the left angular gyrus contained the word forms or 'optical images of letters' critical for word recognition and writing. Thus alexia with agraphia was attributed to a destruction of the stored word forms; alexia without agraphia or 'pure' alexia, in contrast, was attributed to a disconnection of the visual verbal information in the right hemisphere from the preserved word forms in the left angular gyrus.

Over the years, numerous investigators have confirmed Dejerine's original clinical description (e.g., Bastian, 1898; Foix and Hillemand, 1925). Additionally, although a number of different pathological substrates for the syndrome have been described (e.g., left lateral occipital damage (Damasio and Damasio, 1983);

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a white matter lesion undercutting the left angular gyrus (Greenblatt, 1976)), in virtually every instance the findings have been consistent with Dejerine's disconnection hypothesis in that the lesion severed white matter tracts connecting the preserved right occipital lobe and the left angular gyrus. Lastly, a number of careful investigations of the neuropsychological deficit underlying pure alexia have provided data interpretable within the disconnection framework (e.g., Warrington and Shallice, 1980; Patterson and Kay, 1982). Thus because of the apparent consistency of the clinical, pathological and neuropsychological findings, Dejerine's anatomically based account of the syndrome of pure alexia has remained the most widely accepted explanation of the syndrome.

Recently, however, a number of patients with pure alexia have been demonstrated to have certain capacities which appear to be inconsistent with the traditional disconnection account of pure alexia. Caplan and Hedley-White (1974), for example, described a patient with pure alexia who, although apparently unable to identify words explicitly, could distinguish real words from nonword letter strings. Additionally, several patients have shown the ability to match written words which they were unable to read aloud to objects (Landis *et al.*, 1980) or to auditorily presented words (Kreindler and Ionăşescu, 1961; Grossi *et al.*, 1984). Finally, Shallice and Saffran (1986) reported a patient who was unable to explicitly identify stimuli presented for approximately 2 s and yet could distinguish words from non-words and performed better than chance on certain forced-choice word categorization tasks.

We report data from 4 subjects with pure alexia who, despite their explicit claims to the contrary, were able to distinguish words from nonwords and to derive semantic information from rapidly presented written words which they could not identify. These data are inconsistent with Dejerine's attribution of pure alexia to a disconnection of the literate left hemisphere from visual verbal information restricted to an illiterate right hemisphere. Although there are alternative possibilities, these data provide support for the claim that the right hemisphere is literate (Coltheart, 1983; Zaidel, 1978; Saffran *et al.*, 1980).

SUBJECTS

Case 1

J.G. is a 53-yr-old right-handed meat salesman with a high school education who noted the sudden onset of an inability to read road signs and an inability to see to the right while driving. No weakness was noted and he drove home uneventfully. As his symptoms persisted and he noted that he was unable to remember commonly used telephone numbers, he sought medical attention the next day. Examination on admission revealed a dense right homonymous hemianopia, short-term memory impairment, moderate anomia and profound alexia. CT and magnetic resonance imaging (MRI) scans demonstrated small areas of infarction involving the left lateral geniculate and/or the optic radiation and the splenium of the corpus callosum (see figs 1, 2). Although the MRI scan demonstrated an equivocal small left frontal infarct, the occipital, temporal and parietal cortex was normal.

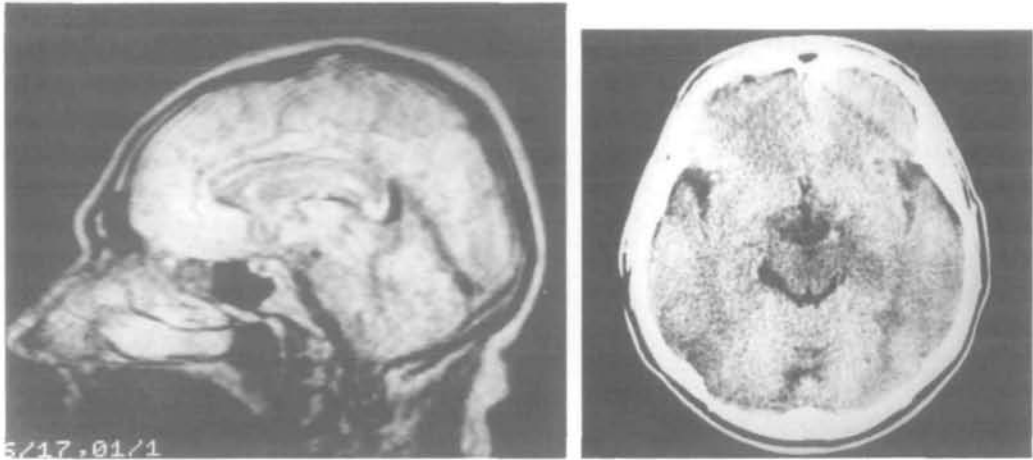


FIG. 1 (*left*). Midsagittal MRI section from *Case 1* demonstrating a lesion of the splenium of the corpus callosum. FIG. 2 (*right*). Axial MRI section from *Case 1* demonstrating a lesion in the region of the lateral geniculate nucleus on the left.

When first examined by the present investigators approximately 7 wks after the stroke, the patient manifested a right homonymous hemianopia but no other elementary sensory deficits. Language testing with the Boston Diagnostic Aphasia Examination (BDAE) (Goodglass and Kaplan, 1972) revealed no aphasia although a mild naming impairment was evident on the Boston Naming Test (Goodglass *et al.*, 1983); he correctly identified 48 of 60 items (5 with a phonological cue). Even when unable to name the item depicted by the line drawing, he typically provided some appropriate information (e.g. 'palette' → 'something to do with artists, you draw from it'). There was no suggestion of a visual agnosia. He named and pointed to named colours normally.

The patient's writing of single words was thought to be consistent with his level of education. He correctly wrote 38 of 40 regular and 35 of 40 irregular words matched for length and frequency. Errors tended to involve single letter substitutions and to preserve phonology; for example, 'subtle' was written as 'suttle' and 'niche' as 'nitch'. He correctly wrote 14 of 15 nonwords. Spelling aloud and naming of spelled words were also at least relatively normal. He correctly named 35 of 40 regular and 34 of 40 irregular words spelled aloud by the examiner. Most errors were word substitutions in which the initial portion of the letter string was preserved (e.g., 'colonel' → 'colonial').

The subject's naming of letters was slow and imperfect; he correctly identified 23 of 26 lower case letters presented individually but often required multiple attempts before arriving at the correct name. When asked to identify letters in words, he erred on approximately 20% of trials. He rapidly and accurately identified 10 ideograms such as '\$', '&' and '%'. He identified written numbers rapidly but imperfectly; he correctly identified 5 single digit numbers, 5 two-digit numbers but only 4 of 5 three-digit numbers.

The patient stated that he was unable to read except by using an explicit letter-by-letter strategy; using this strategy, his performance was not affected by the regularity of print-to-sound correspondences, part of speech or imagery. He correctly 'read' 35 of 39 irregular words and 36 of 39 regular words matched for length and frequency; he identified 28 of 30 nouns and 27 of 30 functors matched for length and frequency. Most errors were attributable to letter misidentifications; for example, he read 'match' as 'march' and 'marker' as 'market'. He read 30 of 40 nonwords correctly; all 10 errors were attributable to grapheme misidentifications.

Both the speed and accuracy of the patient's reading were influenced by word length. The mean time required to correctly identify each of 20 words of 3, 4, 5, 6 or 7 letters is presented in Table 1; also presented is the number of words incorrectly identified.

TABLE 1. SPEED OF ORAL READING AS A FUNCTION OF WORD LENGTH*

Case	No. of letters				
	3	4	5	6	7
1 (J.G.)	9(10)	12.7(10)	17.1(8)	27.1(10)	28.1(8)
2 (T.L.)	2.4(10)	2.9(10)	3.4(10)	4.9(10)	4.4(10)
3 (J.C.)	2.4(10)	5.9(8)	17.2(9)	16.4(9)	29.8(9)
4 (A.F.)	31(2)	83(1)	—	—	—

* In seconds; number correct in parentheses.

J.G. was tested over a period of approximately 8 months. Although the initial clinical examination and formal visual fields revealed a dense right homonymous hemianopia, approximately 3 months after his infarction he noted the return of some vision in the right visual field; J.G. stated that he could detect movement and was aware of 'outlines' or silhouettes in the impaired visual field but could not identify words, letters or small objects on the right. The possible implications of this partial recovery of vision for the subject's reading was extensively tested; a Gerbrands four-field tachistoscope and Apple IIe microcomputer were used to present letter strings (both vertically and horizontally arrayed) for intervals varying from 50 to 150 ms in each visual field. Although he performed significantly above chance on a lexical decision test with stimuli presented in the left visual field (approximately 85% correct), J.G. consistently performed at chance (and never explicitly identified words) with stimuli presented in the right visual field. Thus there was no evidence that the return of vision in the right visual field had any implications for his performance on the reading tests described below.

Case 2

T.L. was an 85-yr-old male, a former bookkeeper, who noted the sudden onset of clumsiness of the right hand and leg and loss of vision on the right while walking. The initial neurological examination revealed a dense right homonymous hemianopia and minimal right-sided weakness; the weakness resolved within 24 h. A CT scan demonstrated a large left occipital infarct involving the forceps major on the left (see figs 3, 4).

When first seen by one of the present investigators (H.B.C.) 10 days after his stroke, he showed a dense right homonymous hemianopia but no other sensory or motor disturbance. Speech and naming as assessed by the BDAE were normal. Spelling aloud and naming of spelled words were normal; performance was not affected by regularity of print-to-sound correspondences, imagery or part of speech.

T.L. identified 23 of 26 single letters but often required multiple attempts. He identified 10 out of 10 symbols and 14 of 15 numbers correctly. He misnamed 3 of 10 colours but matched colour patches flawlessly. He appeared to be unable to read except by using an explicit letter-by-letter strategy. Using this strategy, he demonstrated no effect of linguistic factors such as imagery or part of speech but his speed and, to a lesser extent, accuracy, were clearly affected by word length. The average time required to correctly read words of varying length is shown in Table 1. The data reported here were obtained over a 3 wk interval.

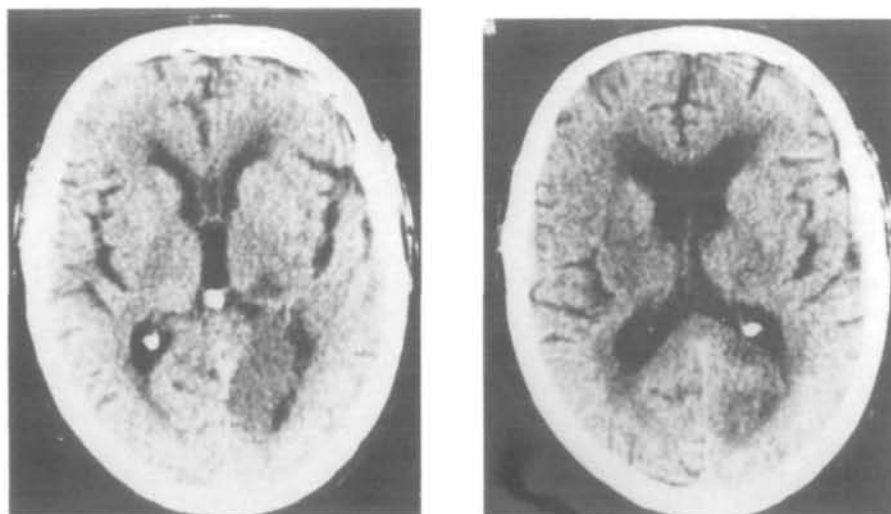


FIG. 3 (*left*). Low ventricular CT scan section from *Case 2* demonstrating infarction of the left inferior occipital lobe. FIG. 4 (*right*). CT scan from *Case 2* demonstrating infarction of the left midoccipital lobe.

Case 3

J.C. was a 26-yr-old female high school graduate who noted the sudden onset of a right hemiplegia, right hemisensory loss and right homonymous hemianopia. A CT scan performed 2 wks later demonstrated a large infarct involving the bulk of the left occipital lobe including the forceps major and extending into the posterior limb of the internal capsule.

When first examined 2 months after her stroke, she manifested a dense right homonymous hemianopia and right hemiparesis. Spontaneous speech was normal and formal language testing with the BDAE demonstrated no aphasia. She correctly spelled aloud 26 of 30 regular and 26 of 30 irregular words as well as 20 of 20 functors. Most errors involved the omission or substitution of a single letter (e.g., 'pitiful'→'pitaful'). On another occasion she was asked to name the same corpus of words spelled aloud by the examiner; she correctly identified 30 of 30 regular words, 28 of 30 irregular words and 19 of 20 functors.

Initially, her writing was abnormal. When asked to write single letters to dictation she correctly wrote 25 of 26 letters with her left hand; however this task required 22 min. Writing of words was characterized by very frequent letter substitution errors which she frequently recognized but was unable to correct despite the ability to name the letter she was attempting to produce; when asked to write the word 'idea', for example, she wrote 'hiem' while correctly spelling the word aloud. She did not improve with anagram letters. She correctly identified 7 of 10 ideograms and read 5 of 5 one-digit, 4 of 5 two-digit and 1 of 5 three-digit numbers. She named colours correctly.

J.C. named 21 of 26 letters correctly but this process was quite slow and she frequently produced a series of incorrect letter names before finding the correct name. She was unable to read aloud any words on sight and attempted to read using an explicit letter-by-letter strategy. Initially, this strategy was ineffective because of frequent letter misidentifications; after approximately 1 month, however, she had improved to the point at which she read 25 of 30 regular and 24 of 30 irregular words as well as 19 of 20 functors using a letter-by-letter strategy. Using this technique, her performance was affected by word length but not by imagery or part of speech (*see Table 1*). She was examined over a 2½ month interval.

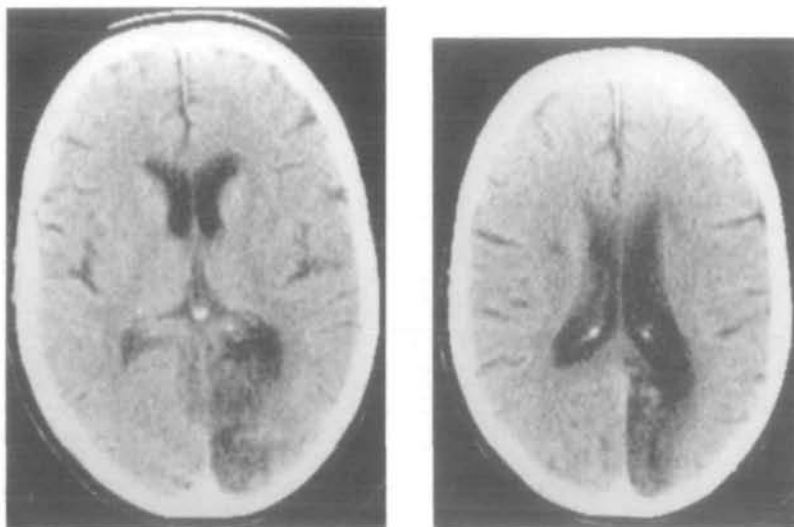


FIG. 5 (left). Low ventricular CT scan from *Case 4* demonstrating infarction in the left occipital lobe. FIG. 6 (right). High ventricular CT scan from *Case 4* demonstrating infarction in the left occipital lobe.

Case 4

A.F. was a 75-yr-old woman with a high school education who developed pure alexia and visual agnosia after a coronary artery bypass graft operation. Although no intraoperative complication was noted, she was slow to regain consciousness. On waking 3 days after the operation she was found to have a dense right homonymous hemianopia and was thought to be unable to recognize visually presented stimuli including faces, objects and words; she identified family members only by voice. An EEG revealed bilateral posterior slowing; a CT scan performed 1 wk after the operation revealed an infarct which involved the left medial occipital cortex and the forceps major (*see* figs 5, 6).

When examined approximately 4 months after her stroke, she was noted to have a minimal right hemiparesis, a dense right homonymous hemianopia and a moderately severe object agnosia. She was not prosopagnosic. Her spontaneous speech was normal and formal testing with the BDAE revealed no deficits that could not be attributed to her visual recognition impairment. She identified only 3 of 10 ideograms. Colour naming appeared to be normal.

Formal testing of her visual recognition impairment suggested that most errors on tests of visual naming were misidentifications based on specific visual features (e.g., wheelchair→'a wagon with wheels'). She performed at chance (43/80 correct) on a forced choice task in which she was required to distinguish real objects from non-objects. She performed normally (43/44 correct), however, on a task in which she was forced to indicate if two irregular, unfamiliar shapes were identical. These results suggest that her deficit is at the level of matching visual information to stored object images or representations.

A.F. correctly spelled aloud 27 of 30 regular, 28 of 30 irregular words and 18 of 20 functors. On a different occasion she was asked to name the same words when spelled aloud by the examiner. She correctly identified 26 of 30 regular words, 27 of 30 irregular words, and 19 of 20 functors. Her writing of single words to dictation was quite similar to her oral spelling. She named single letters accurately (24/26) but slowly with frequent self-corrections. When asked to read words aloud she attempted to use a letter-by-letter strategy. Because of frequent letter misidentifications, however,

this strategy was extremely slow and imprecise. She identified only 3 of 10 three-letter words and 1 of 10 four-letter words. She was unable to identify any of the five, six, or seven-letter words included in the test assessing the effect of word length. She occasionally identified words of 5 or more letters using a letter-by-letter strategy; however, she typically appeared to be guessing on the basis of partial letter information. A.F. was tested over a 3 month interval during which time there was little apparent change in her visual agnosia.

EXPERIMENTAL INVESTIGATIONS

The investigations reported below are motivated by an information processing model which distinguishes a number of distinct processes in reading. First, the stimulus letter string is compared with entries in a stored catalogue of familiar words; if the stimulus corresponds to an entry in the 'visual lexicon', the meaning of the word may be established by accessing the appropriate information in the semantic system. Finally, oral reading (at least for words with irregular print-to-sound correspondences) requires the activation of the entry in the 'phonological output lexicon' or listing of the phonology corresponding to a familiar word. Although a full discussion of these information processing accounts of reading is beyond the scope of this paper, it should be noted that one important consequence of the distinction between the different processing modules is that a reading impairment may be caused by a variety of processing deficits. In the context of these models, therefore, it is important to attempt to define the level(s) of processing at which reading may be affected.

The following experiments were undertaken to assess the integrity of the processing components described above. First, lexical decision tests were performed to determine whether subjects could access stored entries in the visual input lexicon; on this task subjects were asked only to indicate if a letter string was a real word or not. Secondly, a variety of forced-choice categorization and picture-matching tasks were performed to assess the patients' ability to access (at least a portion of) semantic information appropriate to a stimulus. Lastly, the ability to read aloud was investigated; this task differs from the previous tasks in that it may also require access to stored phonological information.

Lexical decision test

Although all subjects denied that they were able to identify words without using a letter-by-letter strategy, a lexical decision test was administered to investigate the possibility that words were being processed without awareness. The ability to discriminate between words and nonword letter strings would suggest that subjects were able to access a catalogue of stored word entries.

Methods. A total of 240 letter strings was presented to each subject; stimuli included 60 high frequency words (mean frequency of 445.8 counts per million; Kucera and Francis, 1967), 60 low frequency words (all 1 count per million), 60 'wordlike' nonwords such as 'shart' (mean 'N' of 10.9; Coltheart *et al.*, 1977) and 60 nonwords with unusual or illegal orthographic sequences such as 'twilk' (mean 'N' of 1.3). Letter strings were unaffixed and varied in length from 3 to 5 letters.

Stimuli in these four experimental conditions were matched for length and presented in random sequence with an Apple 2e and green screen monitor or Apple MacIntosh microcomputer using software which permitted the stimulus duration to be controlled.

For each trial, pressing the spacebar on the keyboard caused a centrally placed fixation point to be replaced by a letter string which persisted for the preprogrammed interval; there was no poststimulus mask. Subjects were instructed to depress a response key on the right if the stimulus was a word or a key on the left for a nonword. Reaction times were measured from the onset of the stimulus to the response. A block of 42 practice trials with feedback about response accuracy was presented before the 240 item test. For all subjects, presentation times were set to be substantially shorter than those required for explicit identification by a letter-by-letter strategy. A stimulus duration of 250 ms was used for Cases 1, 3 and 4; for Case 2 who was most adept at the use of the letter-by-letter strategy, an exposure time of 150 ms was used.

Subjects were told that it was not necessary to identify the stimulus explicitly, but simply to indicate if the letter string was a word; subjects were also told to report any letter string which they believed that they had recognized. As all subjects initially continued to try to identify the constituent letters explicitly, they were repeatedly urged to attempt to derive a 'feeling' for or 'impression' about the letter string and to guess if they were uncertain.

Results. Because of the possibly confounding effects of the left hemisphere lesions on the reaction times of the right hand, only data on response accuracy was formally analysed. The results for each subject, expressed as the percentage of stimuli considered to be real words (percentage of 'yes' responses), are presented in Table 2. All subjects performed better with high as compared to low frequency words and Lo-N as compared to Hi-N nonwords. Differing response biases appeared to lead to some variability in response to low frequency words and Hi-N nonwords. Case 1, for example, tended to reject letter strings about which he was uncertain while Case 2 tended to accept low frequency words and Hi-N nonwords. On rare occasions, subjects correctly identified a stimulus word; no subject identified more than 4 (3.4%) words. Case 2 misidentified two Hi-N nonwords, reporting 'tarch' as 'tape' and 'solt' as 'sole'.

To determine whether subjects differentiated words from nonwords reliably, a bias-free statistic derived from signal detection theory, 'd' was calculated for each

TABLE 2 LEXICAL DECISION TEST*

Case	Words			Nonwords		
	Hi F	Lo F	Hi+Lo	Hi N	Lo N	Hi+Lo
Pure alexics						
1	75	37	56	35	25	30
2	82	78	80	63	38	50
3	78	52	65	28	11	19
4	80	53	67	42	18	30
Deep dyslexics						
P.J.	90	52	71	23	7	15
A.T.	93	43	68	15	7	11

* % 'yes' responses.

subject; for Cases 1-4, d' was 0.675, 0.842, 1.30, and 0.964, respectively. In all instances, subsequent analysis with a Z statistic revealed that the d' values were significantly greater than would be expected by chance ($Z = 4.06, 4.85, 7.36$ and 5.72 , respectively, all $P < 0.05$)

The lexical decision test described above was also administered to 2 subjects with 'deep' dyslexia who correctly read aloud approximately 80% of concrete nouns; as indicated in Table 2, although both subjects were more accurate than the pure dyslexics, they manifested the same pattern of performance.

TABLE 3. PERFORMANCE ON LEXICAL DECISION TEST AS FUNCTION OF LENGTH*

Cases	No. of letters					
	Hi F			Lo F		
Words	3 (n = 8)	4 (32)	5 (20)	3 (9)	4 (29)	5 (22)
1	75	69	85	67	31	32
2	75	91	70	78	79	77
3	63	84	75	55	52	50
		Hi N			Lo N	
Nonwords	3 (8)	4 (32)	5 (20)	3 (9)	4 (30)	5 (21)
1	25	41	30	22	33	19
2	37	78	50	33	47	28
3	37	28	25	22	7	10

* % 'yes' responses.

The effect of word length on performance was also investigated. For each subject, the percentage of correct responses for high and low frequency words and Hi N and Lo N nonwords of 3, 4 and 5 letters is expressed in Table 3. Unfortunately, these data are not available for Case 4. Although the range of letter string lengths is small, no subject demonstrated a significant effect of word length for any of the four types of stimuli.

Two additional post hoc analyses were performed to investigate the contribution of sublexical factors such as the familiarity of letter arrays. First, performance with words and nonwords matched for 'N' was assessed; if responses on the lexical decision test were determined by the familiarity of letter strings rather than lexical information, it would be predicted that performance with words and nonwords matched for sublexical orthographic familiarity would not differ. Stimuli for this post hoc comparison included the 60 high (mean 'N' of 10.9) and 6 low 'N' nonwords (mean 1.3) as well as 40 (20 high and 20 low frequency) Hi-N words (mean of 10.3) and 40 (20 high and 20 low frequency) Lo-N words (mean of 1.7). The data for Cases 1-3, expressed as the percentage of stimuli judged to be a

word, are presented in Table 4. Data for Case 4 were not available. For both Lo-N and Hi-N stimuli, all subjects accepted a significantly greater ($\chi^2 \geq 4.28$, $P < 0.05$) proportion of words as compared to nonwords.

TABLE 4. PERFORMANCE ON LEXICAL DECISION TEST AS FUNCTION OF 'N'

	Case		
	1	2	3
Hi N			
Words	63	83	75
Nonwords	33	63	28
Lo N			
Words	55	75	60
Nonwords	28	38	13

* % 'yes' responses.

In the second analysis, the role of sublexical orthographic similarity was assessed by comparing the performance of Cases 1–3 with high and low-frequency words matched for N count. Normal subjects, whose performance is thought to reflect the influence of lexical information, respond more accurately and quickly to high as compared with low-frequency words on lexical decision tests (Forster, 1976); if these patients also base their responses on lexical information rather than sublexical information, it might be expected that they would respond more reliably to high as compared to low-frequency words matched for N count. Stimuli for this post hoc comparison included 47 high and 47 low-frequency words matched for N count (mean of 5.7 ± 4.2 and 5.8 ± 4.0 , respectively). All subjects correctly accepted a larger proportion of the high as compared to low-frequency words; for Cases 1 and 3 the difference was highly significant (70% vs 40% for Case 1, 83% vs 47% for Case 3; both $P < 0.01$ using a χ^2 test); for Case 2 the difference was not significant (79% vs 68%).

For 2 subjects (Cases 1 and 4), performance on a lexical decision test as a function of exposure time was investigated. For Case 1, the lexical decision test described above was repeated on a number of occasions. Initially, 100 of the 240 stimuli described above were presented using an Apple 2e and a program which sustained stimulus presentation until the subject responded. On this occasion, the test was terminated after 100 items for lack of time; Case 1 required 90 min to complete 100 items. As indicated in Table 4, he responded correctly to 86% of words and 92% of nonwords with unlimited time. Subsequently, the full 240 item test was administered with exposure durations of 50 ms, 250 ms, 500 ms and 2000 ms; all administrations were performed at least 1 wk apart during the first 6 wks of the subject's evaluation; with each administration, the stimulus sequence was rerandomized. On no occasion did the subject explicitly identify more than 4 of

the stimuli. Case 1 was not given feedback regarding the accuracy of his individual responses, although he was told that in general he was doing well. As indicated in Table 5, d' was calculated for each administration. Analysis with the Z statistic revealed that performance was significantly above chance at each exposure time except 2 s.

For Case 4, a different lexical decision test was administered on two occasions; stimuli included 40 words of high imagery (all rated > 5.0 (Paivio *et al.*, 1968) and high frequency (all > 100 counts per million (Kucera and Francis, 1967)) and 40 nonwords derived from high frequency, high imagery words by changing 1 letter; with a 2 s exposure, she performed at chance (54% correct); with a 250 ms exposure, however, her performance was significantly better than chance (74% correct, $\chi^2 = 18.1$, $df = 1$, $P < 0.001$).

TABLE 5. LEXICAL DECISION TEST AS FUNCTION OF EXPOSURE DURATION IN CASE 1*

	50 ms	250 ms	500 ms	2000 ms	Unlimited
Words	49%	59%	55%	51%	86%
Hi F	57	68	70	64	
Lo F	40	57	40	37	
Nonwords	22%	36%	21%	54%	8%
Hi N	27	33	25	68	
Lo N	18	28	18	40	
d'	0.75	0.72	0.93	0.13	2.49
Z	4.36	4.40	5.38	0.775	7.32

* % 'yes' responses.

Although necessarily subjective and anecdotal, the subjects' comments about the test were informative. On most trials, subjects claimed to have 'seen' only 1 letter or insisted that the stimulus had been too fast and that they had seen 'nothing'. Without exception, subjects insisted that they were guessing throughout the test and reacted with surprise and consternation to the news that they had performed significantly better than chance.

Discussion. The fact that subjects discriminated (albeit imperfectly) between words and nonwords on a lexical decision test in which stimuli were presented too briefly to permit explicit word recognition suggests that they were able to derive information about the visual form of the stimulus letter string despite their statements to the contrary. This ability is unlikely to be attributable to the familiarity of sublexical letter strings. Post hoc analyses in which an attempt was made to control for the familiarity of sublexical orthographic units by matching stimuli in 'N' count (Coltheart *et al.*, 1977) suggest that the subjects are not relying on sublexical information but presumably are accessing lexical information. Finally, it might be expected that word length would influence performance significantly if the subjects were responding on the basis of the familiarity of

sublexical components of the visual array; the subjects with pure alexia, like normal readers (Frederiksen and Kroll, 1976; Schiepers, 1980) were not substantially affected by word length. This finding also argues strongly against the alternative hypothesis that subjects were using a strategy of rapid letter identification and 'piecing' the word together using serial letter information; if a letter-by-letter strategy were being used, a clear effect of word length should have emerged in these subjects who demonstrated difficulties even in the identification of single letters.

The finding that Cases 1 and 4 performed *better* with stimuli presented for 250 ms as compared with 2000 ms further argues that the performance with rapid presentation was not mediated by serial letter identification. These data, in conjunction with the observation that at least one of the subjects (Case 1) used an explicit letter-by-letter strategy with stimuli presented for 2000 ms but not for 250 ms raises the possibility that differences in performance with different exposure times reflect the use of different strategies (Landis *et al.*, 1980; Shallice and Saffran, 1986).

Word comprehension

In the light of the previous results suggesting that all 4 subjects were able to access orthographic information about words which they could not explicitly identify, a series of investigations was undertaken to determine if these subjects were also able to access semantic information in the absence of explicit word identification.

Word categorization

1. Animal names

Methods. In the first experiment, subjects were asked to indicate whether a rapidly presented word was an animal name. Stimuli consisted of 25 animal names (e.g., 'mouse'), 25 words judged to be visually similar to the animal names (e.g., 'mount'), and 25 words judged not to be visually or phonologically similar to the animal names (e.g., 'rally'). Visually similar foils shared at least the first 2 letters with the matched animal name. The three types of stimuli were matched for frequency; mean frequencies for the animal names, visually similar foils and unrelated foils were 12.6 ± 23.58 , 13.56 ± 22.1 , and 12.72 ± 23.93 counts per million (Kucera and Francis, 1967), respectively. Animal names and foils differed in length by no more than 1 letter; mean letter lengths for the animal names, visually similar foils and unrelated foils were 5.96 ± 1.0 , 5.92 ± 0.93 , and 5.96 ± 1.0 , respectively. Stimuli were presented with an Apple 2e or Macintosh microcomputer using exposure times as indicated in Table 5. Subjects were instructed to say 'yes' if the word was the name of an animal.

For this and other tests of comprehension, subjects were encouraged to attempt to derive a 'feeling' or 'impression' from the word and *not* simply to identify letters. Emphasis was placed on the importance of the category judgement, not explicit word identification; subjects were asked, however, to inform the investigator whenever they believed that they had recognized a word. Subjects were not told the proportion of stimuli which were animal names and were not given feedback regarding the accuracy of their individual responses.

Results. Data, expressed as percentage correct, are expressed in Table 6. Statistical analysis using a $3 \times 2\chi^2$ demonstrated that all subjects were able to

TABLE 6. ANIMAL NAMES—CATEGORIZATION*

Case	Animal	Visual foil	Unrelated foil	Total
1 (0.25 s)	80	72	72	75
2 (0.1 s)	96	52	60	69
3 (0.25 s)	68	92	96	85
4 (0.25 s)	80	60	72	71

* % correct.

TABLE 7. ANIMAL NAMES—EXPLICIT RESPONSES*

Response category	Case			
	1	2	3	4
Correctly named	1.3	2.6	6.7	0
Incorrectly named	2.7	1.3	6.7	7.9
Unrelated	2.7	1.3	2.7	5.3
Within category substitutions	0	0	4.0	2.7
Partial semantic information	0	0	0	1.3

* % of trials.

distinguish animal names from other words (2 df, $P < 0.01$ for all subjects). As we were concerned with our subjects' ability to categorize words which they could not identify explicitly, a second analysis was performed in which explicitly identified stimuli were excluded; the results of this analysis do not differ significantly from those noted above.

Subjects offered explicit responses to a relatively small number of stimuli. The percentage of stimuli correctly identified and misnamed is presented in Table 7. All word misidentifications were further categorized as within category substitutions ('tiger'→'lion') or semantically unrelated substitutions; most of the latter errors appeared to be visually based (e.g., 'hotel'→'honour'). All but one of the within category substitutions also involved the production of visually similar words. Only stimuli from the target category produced semantically related substitutions. On one occasion Case 4 was unable to report the specific word but offered partial semantic information (e.g., 'rabbit'→'an animal with big teeth').

2. Food names

Methods. A second similar forced-choice categorization experiment was performed in which subjects were asked to indicate whether the referent of a rapidly presented word was edible. Stimuli consisted of 25 food items (e.g., 'grape'), 25 visual foils (e.g., 'graph') and 25 unrelated words (e.g., 'truck'); the three groups of stimuli did not differ in mean frequency (15.0 ± 15.53 , 25.0 ± 55.4 , 15.0 ± 15.52 counts per million (Kucera and Francis, 1967), respectively ($t = 0.87$, ns), or length (mean letter length 5.76 ± 1.03 , 5.84 ± 0.97 , 5.76 ± 1.03 , respectively). Stimuli were presented with an Apple 2e or MacIntosh microcomputer using exposure times as indicated in Table 8. Subjects were instructed to say 'yes' if the rapidly presented word designated a type of food.

TABLE 8. FOOD NAMES—CATEGORIZATION*

Case	Foods	Visual foil	Unrelated foil	Total
1 (0.25 s)	84	76	80	80
2 (0.1 s)	76	56	68	67
3 (0.25 s)	72	72	92	79
4 (0.25 s)	76	68	84	76

* % correct.

TABLE 9. MALE/FEMALE NAMES—CATEGORIZATION*

Case	Male	Female	Total
1 (0.25 s)	74	76	75
2 (0.1 s)	66	74	70
3 (0.25 s)	72	70	71
4 (0.25 s)	84	76	80

* % correct.

Results. Results, expressed as percentage correct, are expressed in Table 8. Once again a $3 \times 2\chi^2$ analysis was performed; all subjects were able to distinguish animal names from other words (2 df, $P < 0.01$ for all subjects). Elimination of those stimuli to which subjects offered an explicit response did not substantially alter the results.

All explicit verbal responses were recorded and categorized as described above; the results of this analysis were similar to those presented in Table 6.

3. Proper names

Methods. In this experiment subjects were asked to judge whether rapidly presented proper names were appropriate for men or women. Stimuli for this test included a randomized list of 50 male and 50 female names varying in length from 3 to 8 letters; mean letter length was 5.82 ± 1.21 for men's and 5.78 ± 1.27 for women's names. Thirty-four of the 50 pairs of male and female names contained the same first 3 letters (e.g., 'Maurice' vs 'Maureen') or differed by only one letter (e.g., 'John' vs 'Joan'). Subjects were told that all stimuli were proper names and were asked to indicate whether the name was appropriate for a man or for a woman. Stimuli were presented with the apparatus described above using exposure times as indicated in Table 9.

Results. The data, expressed as percentage correct, are expressed in Table 9. A χ^2 analysis demonstrated that all subjects categorized the proper names significantly better than chance (1 df, $P < 0.005$ for all subjects). As before, eliminating the explicitly identified items from the analysis did not significantly alter the results of the analysis. Additionally, it should be noted that 11 of the female but none of the male names ended in the letter 'a'; eliminating these names from the data did not effect the outcome of the statistical analysis. Finally, all subjects performed significantly above chance on the 34 pairs of names matched for the first 3 letters or differing by only 1 letter (Case 1, 71% correct; Case 2, 71%; Case 3, 69%; $P < 0.05$ using χ^2 analysis for all subjects).

Subjects' explicit verbal responses were analysed as described previously. The rate of explicit stimulus identification, which ranged from 2 to 9% did not differ substantially from that noted on the previous categorization tasks; subjects did, however, tend to offer more incorrect explicit responses in this task. As noted in the previous categorization tests, most misidentifications appeared to be visually based ('John'→'Joan').

Word-to-picture matching

1. Across category

Evidence for word comprehension in the absence of explicit word recognition was also sought with a forced-choice task requiring the matching of a rapidly presented word to one of two pictures.

Methods. In the first test, the names of items pictured in the Boston Naming Test and Peabody Picture Vocabulary Test (Dunn, 1965) were used to create 31 pairs of words in both words shared at least the first 2 letters; this control was instituted to prevent subjects from using only information derived from a letter-by-letter analysis. Word pairs were matched for letter length (9 pairs, e.g., 'house'→'horse') or differed in length by one (8 pairs, e.g., 'whistle'→'whale') or 2 letters (14 pairs, e.g., 'propeller'→'pretzel'). The drawings appropriate to each pair of words were copied onto a single 11 × 8½ inch piece of white paper.

A randomized sequence of the 62 stimuli was presented briefly using the apparatus described above. Following the brief presentation, subjects were shown the sheet of paper on which the drawing appropriate to the stimulus and its matched word had been copied and asked to point to the appropriate picture. Each word was presented once; no feedback regarding response accuracy was provided. With two exceptions ('snake-snail' and 'broom-brush') pairs of words were drawn from different semantic categories.

Results. The data, expressed as percentage correct, are presented in Table 10. χ^2 analysis revealed that all subjects performed significantly above chance (1 df, $P < 0.25$). Eliminating from the analysis those rare trials in which subjects correctly identified a stimulus word did not appreciably alter the results. The frequency and accuracy of the subjects' explicit naming responses was similar to that reported in previous experiments.

2. Within-category

Methods. A within-category forced-choice word-to-drawing paradigm was performed in which subjects were asked to match animal names to pictures. Using stimuli from the Boston Naming

TABLE 10. WORD-TO-DRAWING MATCHING*

<i>Case</i>	<i>Different category (n = 62)</i>	<i>Within category (n = 30)</i>
1 (0.5 s)	87	90
2 (0.1 s)	69	—
3 (0.25 s)	74	87
4 (0.25 s)	66	73

* % correct.

Test and Peabody Picture Vocabulary Test, 14 pairs of animal names were generated. Because of the smaller number of possible stimuli, matching of the initial portion of the letter string was less rigorous than in the cross-category task above; thus, for 10 of the pairs the names shared only the first letter; 4 of the pairs contained the same initial 2 letter segment. Six of the pairs of animal names were matched for letter length, 2 pairs differed in length by 1 letter, 4 pairs differed by 2 letters and 2 pairs differed by 3 letters ('giraffe'→'goat' and 'beaver'→'butterfly'). A total of 23 different animal names was used; 7 names appeared twice, usually as part of a different pair of names (e.g., the stimulus 'snake' appeared twice, the first time paired on the answer sheet with the picture of a snail and the second with the picture of a spider). The testing procedure was identical to that described above. Subjects were told that a stimulus might appear more than once and were not given feedback regarding the accuracy of their responses during the session.

Results. Data for Cases 1, 3 and 4 are expressed in Table 10; data for Case 2 were not available. Once again, a χ^2 analysis revealed that all subjects performed significantly above chance (1 df, $P < 0.01$).

Discussion. Data from these studies suggest that all subjects were able to derive semantic information from words presented for brief intervals which they were rarely able to identify explicitly; the exclusion of those stimuli which the subjects could identify explicitly did not significantly alter the results.

An alternative explanation of these results is that the subjects adopted a conservative response bias, that they failed to offer an explicit response (i.e., name the word) because they were unsure and did not wish to be wrong. This would predict, however, that when subjects feel sufficiently secure to offer an explicit response, they should be correct. This was not observed; subjects were no more accurate in their explicit responses than with those stimuli they claimed not to have identified. We therefore believe that a conservative response bias is an unlikely explanation for these data.

It is of interest that Case 4, who performed at chance on a forced-choice object/nonobject task performed significantly better than chance on both the across-category and within-category tasks. One possible explanation for this is that she used orthographic information to access stored information about the visual features of the object and based her responses upon expectations regarding specific visual attributes. When presented with the word 'mouse', for example, she may have accessed information that the referent has a long tail and used this piece of information to distinguish between the drawings of a mouse and a moose. It should be noted that this hypothesis is consistent with her poor performance on the object/nonobject task; correct performance on that task required that the subject not only recognize components of an object but the relationships between the components.

Explicit word identification

Over the course of the weeks to months during which these subjects were studied, 3 of them (Cases 1-3) improved from an initial state characterized by an inability to 'see' more than single letters of briefly presented words to a point where they were able to explicitly identify a sizeable proportion of words presented

for 0.25 s or less. Interestingly, Case 4, who was presumed to have suffered bihemispheric damage from systemic hypotension, was the only subject who failed to demonstrate substantial improvement in explicit word recognition.

The improvement in explicit word reading was associated with a clear change in the subjects' behaviour and explicitly verbalized strategy; by the time that subjects could identify rapidly presented words, they seldom named individual letters and denied using their previous strategy of letter-by-letter reading.

A series of investigations was performed in an attempt to elucidate the variables which may have influenced this explicit reading. Specifically, as we hypothesized that the reading of these subjects was mediated by right hemisphere mechanisms, we investigated the effects of part of speech and imagery, variables thought to influence the reading performance of the right hemisphere (Saffran *et al.*, 1980; Coltheart, 1983)

Experiment 1: part of speech

Methods. The possible effects of part of speech were assessed by asking subjects to read aloud a randomized list of 30 functors and 30 nouns matched for frequency (mean log frequency 2.67 ± 0.40 and 2.59 ± 0.27 , respectively) and length (mean letter length 4.97 ± 1.11 and 5.01 ± 1.14 , respectively). As described previously, words were presented with a microcomputer. The exposure times are indicated in Table 11.

TABLE 11. NOUN VS FUNCTOR—ORAL READING*

<i>Case</i>	<i>Nouns</i>	<i>Functors</i>
1 (0.25 s)	77	47
2 (0.1 s)	77	50
3 (0.25 s)	83	40

* % correct.

Results. The percentage of nouns and functors correctly read aloud by Cases 1–3 are shown in Table 11. Cases 1 and 3 identified significantly more nouns than functors ($\chi^2 = 5.71$, $\chi^2 = 10.33$, $df = 1$, respectively, both $P < 0.05$); although Case 2 also identified a greater proportion of nouns, the difference did not reach significance ($\chi^2 = 3.45$, $df = 1$, $0.10 > P > 0.05$).

Errors were classified as omissions, visually based word substitutions, 'unrelated' word substitutions in which no clear visual, semantic or phonological similarity between the stimulus and response was apparent, or 'partial letter information' errors in which only 1 or more letters from the stimulus were reported. For each subject, the percentage of each of these types of errors elicited by functors and nouns is expressed in Table 12; the absolute number of each error type as a function of stimulus class is expressed in parentheses. Although the small numbers make a formal analysis difficult, it would appear that the major difference in the errors for functors and nouns was the greater frequency of functor omissions. No semantic errors were noted.

TABLE 12. NOUN/FUNCTOR ORAL READING—ERROR ANALYSIS*

Error type	Case					
	1		2		3	
	N	F	N	F	N	F
Omission	14(1)	56(9)	17(1)	38(6)	40(2)	53(10)
Visual error	86(6)	38(6)	67(5)	54(8)	60(3)	47(8)
Unrelated	0	6(1)	17(1)	8(1)	0	0
Partial letter information	0	0	0	0	0	0

* % of errors.

TABLE 13. HIGH VS LOW IMAGERY WORDS—ORAL READING*

Case	High	Low
1 (0.25 s)	88	63
3 (0.25 s)	98	65

* % correct.

Finally, 2 normal controls (aged 58 and 67 yrs) were tested with the stimuli and apparatus described above. Exposure times were manipulated to produce error rates approximating those of Cases 1-3. With exposure times of 66 and 83 ms, both normal subjects exhibited error rates of approximately 35%; errors were equally divided between nouns and functors.

Experiment 2: word imagery

Methods. The effect of word imagery on oral reading was also assessed by asking subjects to read aloud a randomized list of 20 nouns of high imagery (> 5.0 , Paivio *et al.*, 1968) and frequency (all > 60 , mean frequency = 177.4 ± 82.8 ; Kucera and Francis, 1967), 20 nouns of high imagery (> 5.0) and low frequency (all < 20 , mean 6.5 ± 4.3), 20 nouns of low imagery (< 3.0) and high frequency (all > 60 , mean 178.6 ± 121.8) and 20 nouns of low imagery (< 3.0) and low frequency (all < 20 , mean 8.9 ± 6.38). All groups of stimuli were matched for word length (mean of 5.6 letters for all groups). As before, stimuli were presented by a microcomputer with exposure times as indicated in Table 13.

Results. Cases 1 and 3 manifested a significant effect of word imagery; both subjects read aloud high imagery words significantly more accurately than low imagery words ($\chi^2 = 12.86$, $df = 1$, $P < 0.001$ and $\chi^2 = 13.87$, $df = 1$, $P < 0.001$, respectively). Collapsing across word imagery, Case 3 was significantly more accurate with high than low-frequency words ($\chi^2 = 6.65$, $P < 0.01$); Case 1 also performed better with high than low-frequency words but this effect was not significant. Unfortunately, data from Case 4 were not available.

Most incorrect responses were visual errors or omissions; 13 of the 14 omissions were noted with low imagery words.

Discussion. Thus all subjects with pure dyslexia who regained the ability to explicitly identify rapidly presented words performed better with nouns than functors and better with high than low imagery words. As previously pointed out by Allport and Funnell (1981), the part of speech effect may reduce to an imageability effect since functors are low in imageability; in any case, these data are consistent with the hypothesis that the reading of these subjects was mediated by the right hemisphere.

Processing of affixes

Experiment 1: oral reading of suffixed words

The distinction between 'open-class' and 'closed-class' words has been found to be a significant determinant of performance on a variety of language comprehension and production tasks in normal (e.g., Garrett, 1980) and brain-damaged (e.g., Friederici and Schoenle, 1980) subjects. In this context, the 'open-class' includes the major lexical items such as nouns, verbs and modifiers; the 'closed-class', in contrast, includes free-standing lexical items such as pronouns, conjunctions, articles, as well as bound morphemes (that is, affixes) which primarily serve grammatical functions.

The previous experiment, in which Cases 1-3 were asked to read aloud nouns and functors, demonstrated that the subjects were significantly more accurate in reading aloud open-class as compared to free-standing closed-class items. The following experiment was performed to determine if these subjects were also impaired in the oral reading of bound closed-class morphemes.

Methods. Forty pairs of words containing the same potential free-standing root morpheme (e.g., 'flow') were generated; 1 of the pair of words was suffixed (e.g., 'flowed'), while the other word was not suffixed but ended in a letter sequence which, in a different context, could be a suffix (e.g., '-er' as in 'flower'). For each word pair, the suffixed and pseudosuffixed words differed in length by no more than one letter. The mean frequency of the suffixed words was slightly higher (22.1 ± 39.1 vs 32.6 ± 43.9 ; Kucera and Francis, 1967), but this difference was not significant. These stimuli were presented in a random sequence; subjects were asked to read each word aloud. Stimuli were presented with a microcomputer using the exposure intervals indicated in Table 14.

Results. The percentage of words correctly read aloud by each subject is presented in Table 14. All subjects read aloud significantly more pseudosuffixed than suffixed words ($P < 0.001$ for all).

As the treatment of the suffixes and pseudosuffixes is of critical significance in

TABLE 14. SUFFIXED VS PSEUDOSUFFIXED WORDS—ORAL READING*

<i>Case</i>	<i>Suffixed</i>	<i>Pseudosuffixed</i>
1 (0.25 s)	30	73
2 (0.1 s)	50	88
3 (0.25 s)	33	83

* % correct.

TABLE 15. ORAL READING OF SUFFIXED VS PSEUDOSUFFIXED WORDS ERROR ANALYSIS*

	Case					
	1		2		3	
	Suffix	P-S	Suffix	P-S	Suffix	P-S
Root						
Omission	1	2	0	0	4	3
Visual error	16	9	7	4	21	14
Suffix (P-S)						
Omission	20(7)	(1)	16(11)	(0)	35(12)	(1)
Substitution	3	(2)	1	(0)	2	(0)
Addition	0	(0)	0	(1)	1	(0)

* Number of errors; suffix omissions but correct reading of the root given in brackets.

the present context, each incorrect response was scored independently with respect to the root morpheme and suffix. Thus, for example, the response 'followed' to the stimulus 'flowed' was scored as correct with regard to the suffix but as a visual error involving the root ('flow'→'follow'); the response 'flower' to the stimulus 'flowed' was scored as a visual error involving the root morpheme and an omission of the suffix. Finally, for suffixed words, the failure to respond to a stimulus was scored as an omission of the root morpheme as well as an omission of the suffix. As each response was scored independently with respect to the root morpheme and suffix, the total number of errors noted in Table 15 may exceed the number of incorrect responses as reflected in the subject's raw score.

The number and breakdown of errors made by Cases 1-3 to suffixed ('Suffix') and pseudosuffixed ('P-S') words is expressed in Table 15. For suffixed and unsuffixed words, most errors which involved the root morpheme appeared to be visually based. For all 3 subjects, the most common errors were suffix omissions; in many cases, the root was correctly read but the suffix omitted (e.g., 'flowed'→'flow'); the number of errors of this type for each subject is indicated in parentheses next to the total number of suffix omissions in Table 15.

In contrast, the analogous error with pseudosuffixed words, the omission of pseudosuffixes to yield a legal free-standing root morpheme (e.g., 'flower'→'flow'), was rare; the precise number of such omissions is recorded in parentheses under the category of suffix omissions for pseudosuffixed words. Case 1 also made 2 errors to pseudosuffixed words which might be interpreted as 'suffix' substitutions ('wallet'→'walls', 'sparkle'→'sparked').

Although the frequency of the suffixed and pseudosuffixed words did not differ, the mean frequencies of the 'suffixes' included in the two groups of stimuli were significantly different (714 ± 274 for the suffixed words, 319 ± 295 for the pseudosuffixed words as measured by frequency counts for the 'suffixes' in the terminal position of 4-7 letter words; Mayzner and Tresselt, 1965; Mayzner *et*

al., 1965). To ensure that the observed difference in performance between pseudosuffixed and suffixed words was attributable to morphological as opposed to orthographic factors, a separate analysis was performed for the 9 pseudosuffixed and 30 suffixed stimuli which ended in '-ed' or '-er'. Case 1 correctly read 9 of 9 pseudosuffixed words ending in '-er' and 14 of 30 suffixed words ending in '-er' or '-ed'. Cases 2 and 3 correctly read 8 and 9 pseudosuffixed words and 16 and 12 of the suffixed words, respectively. Using a χ^2 analysis, performance was significantly better with pseudosuffixed as compared with suffixed words matched for 'suffix' frequency ($P < 0.05$ for all subjects). These data suggest that the difference in performance with suffixed as compared with pseudosuffixed words is attributable to morphological rather than orthographic factors.

Thus when asked to read aloud suffixed and pseudosuffixed words matched for frequency and sharing the same potential root morpheme, subjects manifested a significantly greater impairment in reading aloud suffixed as compared with pseudosuffixed words. These data suggest that the impairment in reading these words reflects impaired processing of suffixes rather than simply a neglect of word endings.

Experiment 2: Lexical decision test with suffixed stimuli

Although the previous experiment demonstrated that Cases 1–3 were selectively impaired in the oral reading of suffixed words, the results do not indicate the functional locus of the impairment. Thus, for example, this impairment could reflect a failure in the production of affixed words or in earlier stages of processing. In an attempt to distinguish between these possibilities, a lexical decision test employing suffixed and unsuffixed words was performed. If our subjects were able to perform this task correctly, their difficulty in reading affixed words aloud would appear to lie in using visually presented affix information for production. Failure on the lexical decision task would imply some deficiency in dealing with affixes at earlier stages in the processing of graphemic information.

Methods. Cases 1 and 3 were given the test developed by Shallice and Saffran (1986). Stimuli for this test included 63 root morphemes between 5 and 9 letters in length. The root morphemes included an equal number of nouns, adjectives and verbs. Each root morpheme was presented on three occasions: in an unaffixed form (e.g., 'elephant'), appropriately suffixed (e.g., 'elephants'), and inappropriately suffixed (e.g., 'elephanting'). For nouns, the appropriate suffix employed was -s, for adjectives appropriate suffixes included -ly, -(i)er, and -(i)est, and for verbs appropriate suffixes included -s, -ed, and -ing. The same suffixes were used to generate inappropriately suffixed words.

Stimuli also included 63 nonwords generated by changing 2 letters in each of the 63 root morphemes; each nonword appeared twice, once unsuffixed and once in conjunction with the suffix appropriate to the word from which it was derived.

The test was administered in three sessions; in each session, 7 blocks of 15 stimuli were presented; each block contained 1 unsuffixed, 1 appropriately suffixed and 1 inappropriately suffixed form of a noun, adjective and verb as well as 3 suffixed and 3 unsuffixed nonwords. Each root morpheme appeared once in each session.

As 2 subjects performed at chance with every category of stimuli on the test described above, a

TABLE 16. SUFFIXED WORD LEXICAL DECISION TEST*

Case	Words			Nonwords	
	Unsuffixed	Correct suffix	Incorrect suffix	Suffixed	Unsuffixed
1 (n = 62) (0.25 s)	63	63	65	19	37
2 (n = 40) (0.1 s)	88	78	75	13	13
3 (n = 62) (0.25 s)	84	79	73	40	32
4 (n = 40) (0.25 s)	85	75	65	18	18

* % 'yes' responses

second version of this test was constructed which was similar in most respects but utilized higher frequency root morphemes.

Stimuli for this study included 40 unsuffixed words (20 nouns, 20 verbs), 40 appropriately suffixed words, 40 root morphemes with inappropriate suffixes (e.g., 'wifed'), 20 unsuffixed nonwords and 20 suffixed nonwords. All root morphemes were greater than 100 counts per million in frequency (Kucera and Francis, 1967) and varied in length between 3 and 6 letters. The same suffixes were used for the appropriately and inappropriately suffixed root morphemes as well as for the suffixed nonwords. Nonwords were derived from high frequency (> 100; Kucera and Francis, 1967) root morphemes by changing a single letter. The test was administered in two sessions.

For all subjects, stimuli were presented with a microcomputer for brief intervals as indicated in Table 16. Subjects were told to indicate if the stimulus was a real word or not; subjects were informed that some 'real' words would have incorrect endings and that these words were to be considered as nonwords. As before, subjects were instructed to attempt to derive a 'feeling' for or 'intuition' about the stimulus rather than to attempt to explicitly identify the stimulus and to notify the experimenter if they believed that they had identified a word.

Results. The data, expressed as the number of 'yes' responses, for all subjects are presented in Table 16. All subjects successfully discriminated between unsuffixed words and nonwords. The critical comparison in this context, however, is between the performance on appropriately and inappropriately suffixed words. No subject reliably distinguished between appropriately and inappropriately suffixed words.

Discussion. These results demonstrate that all our subjects were impaired in the processing of suffixes; more specifically, the finding that the impairment is observed even when oral reading is not required indicates that the limitation must involve processes that occur prior to the programming of verbal output. These results parallel those of Shallice and Saffran (1986) in their study of an alexic patient.

In a broader context, there are several possible interpretations for these results. If, as was hypothesized previously, the patients' reading is mediated by right hemisphere mechanisms, these data suggest that neither affixed words nor a system for determining the legality of roots and affixes is represented in the right hemisphere. In conjunction with the results of the previous oral reading tasks demonstrating an impairment in the reading of functors, these data suggest that

the right hemisphere is deficient in the processing of all aspects of closed-class morphology.

Finally, these data are not predicted by the disconnection account of pure alexia in which the impairment is assumed to be attributable to a failure of input to reach preserved left hemisphere processing mechanisms. Even if an attempt is made to explain the relatively good performance of our subjects on lexical decision tests with unaffixed words by hypothesizing that the disconnection is only 'partial', this theory does not explain why suffixes should be more 'disconnected' than word roots.

GENERAL DISCUSSION

Reading and the right hemisphere

Although in 'classical' accounts, the right hemisphere was considered to be 'word-blind', in recent years evidence has been adduced suggesting that the right hemisphere in normal right-handed subjects may have the capacity to read. On the basis of studies with normal subjects, evaluations of patients after sectioning the corpus callosum, investigations of patients after left hemispherectomy and studies of patients with acquired language disturbances such as deep dyslexia, Coltheart (1980, 1983), for example, has suggested that the right hemisphere supports a lexicon which can be accessed by orthographic input. Additional data supporting this contention is provided by a report of a patient who recovered from alexia due to a left hemisphere vascular lesion but subsequently became profoundly and permanently alexic after a second right hemisphere vascular lesion (Heilman *et al.*, 1979).

The putative right hemisphere language capacities are thought to differ in a number of important respects from those of the left hemisphere. Because split-brain patients are generally unable to perform rhyme judgements on words presented to the right hemisphere, or read aloud words presented to the right hemisphere which they can match to an object, it is often assumed that the right hemisphere does not support speech output mechanisms or the ability to derive phonology from print (Saffran *et al.*, 1980; Zaidel and Peters, 1981; Coltheart, 1983). Investigations of reading in split-brain patients have suggested that the putative right hemisphere lexicon consists primarily of concrete or high imagery open-class nouns; some, but by no means all, studies of normal subjects have also suggested that the right hemisphere lexicon includes primarily concrete nouns (*see* Patterson and Besner, 1984, for a review of this controversial topic). Additionally, investigations of deep dyslexics and split-brain patients has led Coltheart (1980, 1983) to postulate that semantic errors (e.g., 'uncle'→'cousin') are characteristic of right hemisphere reading. Finally, it has been claimed that the right hemisphere reading mechanisms permit greater success with logographic (e.g., Kana) as compared with syllabic scripts (e.g., Kanji) (Sasanuma, 1980).

Data from our patients are in accord with the right hemisphere reading

hypothesis in several important respects. In the following sections dealing with tacit reading, explicit reading and the processing of affixes, the implications of our patients' data for this and competing accounts of pure alexia will be discussed.

Tacit processing

All subjects discriminated words from nonwords and performed better than chance on a variety of semantic categorization tasks with rapidly presented stimuli which they were unable to identify explicitly. Thus these subjects demonstrated the phenomenon of reading without awareness or 'tacit' reading.

Similar phenomena have been demonstrated in normals (Marcel, 1983*a*). To account for this finding in normal subjects, Marcel (1983*b*) proposed that the processing of sensory information is distinct and dissociable from awareness or consciousness. Thus subjects may use the normal processing mechanisms to derive semantic information from rapidly presented visual verbal stimuli but be unaware of this processing because the stimuli do not engage those additional mechanisms which provide the subjective sensation of awareness. One possible account of the tacit reading of subjects with pure alexia (Shallice and Saffran, 1986), for example, suggests that these subjects employ the left hemisphere-based visual word form system normally used to process visually presented words but that this system is partially disrupted, preventing a link to those processes mediating consciousness.

An alternative account is that tacit processing may depend on processing mechanisms which are functionally and anatomically distinct from those normally employed in explicit word recognition. As pointed out by Shallice and Saffran (1986), this is the type of explanation offered for the phenomenon of 'blind-sight' in which hemianopic patients have been shown to process visual input directed to the 'blind' field (Weiskrantz *et al.*, 1974). Such an account may also be proposed to explain tacit reading in pure alexia. As primary visual information is restricted to the right hemisphere in most subjects with pure alexia, one obvious candidate for the locus of tacit reading mechanism in this syndrome is the right hemisphere. It is noteworthy that the explicit denial of the ability to 'see' more than single letters despite evidence of preserved lexical access is reminiscent of phenomena manifested by patients after surgical transection or lesions of the corpus callosum in which it is often assumed that the right hemisphere is processing information and generating motor responses without communication of these activities to the left hemisphere.

Explicit reading

Three of our 4 subjects regained the ability to identify rapidly presented stimuli explicitly. This recovery provided an opportunity to test other predictions of the right hemisphere reading hypothesis. As noted above, data from deep dyslexics and normals have led to the hypothesis that the right hemisphere lexicon consists primarily of open-class words of high imagery. Thus, if the reading of our subjects is mediated by the right hemisphere, better performance

might be expected with nouns than functors and high as compared to low imagery words.

These predictions were, in fact, borne out. Cases 1 and 3 read nouns significantly better than functors; for Case 2 this effect did not quite reach significance. Cases 1 and 3 read high imagery nouns significantly more accurately than low imagery nouns.

There is one respect, however, in which the performance of these 3 subjects on oral reading tasks differs from that predicted by at least one version of the right hemisphere reading hypothesis (Coltheart, 1983): subjects made relatively few semantic errors. Although subjects not infrequently provided some semantic information pertinent to a stimulus which could not be explicitly identified and did exhibit within-category word substitutions on word categorization tests (e.g., 'tiger'→'lion'), semantic paralexias in which subjects were not biased by the experimental context were rare. The explanation for this finding is not clear. One possibility is that the subjects' responses were constrained by convergent input from both the right hemisphere-based semantic system and the (left hemisphere) visual word form system. As these subjects typically were able to identify explicitly at least the initial letter, it might be speculated that this information was available to the (left hemisphere) visual word-form system; thus, even if it is assumed that the right hemisphere-based semantic system does not permit complete specification of the stimulus at the level of the output phonological lexicon, partial information from the visual word form system might constrain the response generated at the phonological lexicon and reduce or eliminate semantic errors.

Alternatively, it could be speculated that, as semantic paralexia errors are typically encountered in subjects with extensive left hemisphere injury, the production of these errors requires both lack of precise specification of the appropriate semantic or output phonological lexical entry and a 'disinhibition' or willingness to respond in the absence of full specification of the appropriate entry; alternatively expressed, it is possible that the extensive left hemisphere injury lowers the response threshold, thereby creating a situation in which subjects are more likely to respond, and therefore, assuming incomplete specification of the target utterance, more likely to produce semantic paralexia errors.

On this line of reasoning, given a 'normal' response threshold, it might be predicted that subjects will not produce semantic errors but will fail to respond; interestingly, in all explicit word identification tasks, omissions, particularly to functors and low imagery words, were the second most frequent type of error.

It is noteworthy that the only subject (Case 4) who failed to regain the ability to identify words explicitly was also the only subject with clinical evidence of bihemispheric impairments. Although she did manifest a well defined infarct on CT scan, it should be noted that this infarct developed in the context of a hypotensive episode suffered during a coronary artery bypass operation; additionally, she failed to recognize family members by sight but could name them from their voices during the first postoperative week and thereafter manifested a visual

object recognition impairment (that is, 'apperceptive visual agnosia') of moderate severity. As both prosopagnosia (which she may have initially manifested) and apperceptive visual agnosia are typically associated with bilateral posterior damage (Bauer and Rubens, 1985), it may be that she suffered ischaemic injury to the right hemisphere due to systemic arterial hypotension, a condition which may not be associated with well defined lesions on CT scan. It might be speculated, therefore, that she could perform above chance on lexical decision tests and semantic categorization tests by accessing a right hemisphere-based lexicon and semantic system but that the presumed ischaemic injury of the right hemisphere prevented sufficient specification of the lexical or semantic entry to permit explicit word identification.

Finally, there are a number of possible explanations for the improvement in explicit word reading in our subjects; our data do not appear to help adjudicate between them. One possibility is that the subjects regained access to the phonological lexicon of the left hemisphere, presumably by means of information transfer across the undamaged body of the corpus callosum; in this event, of course, the subjects' oral reading would not be exclusively dependent upon the right hemisphere but would presumably reflect the right hemisphere lexical-semantic capacities. Another possibility is that the right hemisphere developed the capacity to produce speech; this seems unlikely, however, since corpus callosotomy subjects typically do not develop the capacity to read aloud words presented to the right hemisphere.

Processing of affixes

Previous accounts of the language capacity of the right hemisphere have emphasized its lexical and semantic capabilities (Zaidel, 1978; Coltheart, 1983); in particular, these accounts have stressed the ability to derive meaning from print. Implicit in these accounts is the assumption that the right hemisphere does not support the capacity to decode or generate complex linguistic structures. As functors and bound morphemes, which together comprise the closed-class lexicon, convey relatively little semantic information but are critical for capacities assumed not to be supported by the right hemisphere (that is, syntax comprehension and production), it might be predicted that the closed-class lexicon would not be represented in the right hemisphere. As demonstrated by impaired oral reading of functors as compared to nouns, insensitivity to the appropriateness of suffixes and impaired oral reading of pseudosuffixed versus suffixed words, our subjects showed a significant impairment in the processing of all types of closed-class morphology. These data are consistent with the hypothesis that the reading of our subjects was mediated by right hemisphere mechanisms.

Alternative accounts of pure alexia

Although the previous discussion has emphasized the possible role of the right hemisphere in the residual reading performance of these subjects with pure alexia, there are a number of other accounts of this syndrome which must be considered.

Warrington and Shallice (1980), for example, argued that pure alexia is not attributable to an impairment of visual input to the left hemisphere but to a disruption of the visual word form system, a left hemisphere-based mechanism which serves to process visual verbal information and provide for word identification. As recently suggested by Shallice and Saffran (1986), this account can be extended to accommodate the findings of our subjects. For example, an impairment but not obliteration of the word form system may be associated with some activation of the appropriate entries but this activation may be insufficient for explicit identification; similarly, according to Shallice and Saffran (1986), the weak output of the damaged word form system may be sufficient to activate appropriate semantic entries but not sufficient to inhibit semantic associates and thereby permit precise semantic specification.

This hypothesis, however, is subject to at least two objections. First, it fails to account for the specific pattern of impairments demonstrated by our subjects on tests of explicit word identification. As the distinction between nouns and functors and high and low imagery words has not typically been assumed to be relevant to the visual word form system, it is not clear how the significant effects of imagery and part of speech manifested by our subjects would be associated with damage to this system. The second point concerns the anatomical substrate of the putative visual word form system; although not explicitly stated by Warrington and Shallice (1980), it might be assumed this system is critically dependent on the cortex of the posterior portion of the left hemisphere. At least one of our patients (Case 1), however, had no evidence of damage extending into or undercutting the cortex; thus damage to a cortically represented processing mechanism such as the visual word form system cannot readily account for at least some cases of pure alexia.

Patterson and Kay (1982) proposed that pure alexia is caused by a pathological limitation in the ability to transmit letter information in parallel; they proposed that multiletter segments and words cannot be accommodated by the compromised system but that single letters can be identified and successfully transmitted. On their analysis, the phenomenon of letter-by-letter reading which is often observed in subjects with pure alexia, reflects the operation of the visual word system (or visual input logogen) with sequential as opposed to parallel letter information.

With some modification, this proposal can account for our data; thus, for example, it might be proposed that parallel transmission of letter information is in fact achieved, but that this input to the word form system is 'weak' and does not support full activation of the appropriate entry. The problem with this hypothesis is that aberrant input (that is, serial access) to the visual word form system leads to more adequate output, permitting explicit identification of the word, than normal (that is, parallel) input. As Shallice and Saffran (1986) point out, this seems unlikely. This hypothesis is also subject to the same objection noted above: it provides no principled account of the imagery and word class effects demonstrated by our subjects.

Strategy differences

We have argued that the performance of our subjects is consistent with the hypothesis that the right hemisphere is literate. A proposal that this is a general account of the syndrome, however, must accommodate the observation that most patients with pure alexia have *not* been demonstrated to exhibit the reading capacities demonstrated by our subjects; indeed, the apparent absence of reading ability in patients with pure alexia has been cited as compelling evidence against the right hemisphere reading hypothesis (Patterson and Besner, 1984). There are several important points in this regard.

First, although the vast majority of patients with pure alexia have not shown any ability to process print except by a letter-by-letter strategy, there have been a number of patients with pure alexia who have demonstrated at least some of the phenomena reported here. Landis *et al.* (1980), for example, described a right-handed patient who developed pure alexia secondary to a left posterior glioblastoma multiforme; on 5 of 7 trials, this patient was able to point to the object corresponding to a briefly presented word which he was unable to identify explicitly. Grossi *et al.* (1984) reported a patient with pure alexia following a left occipital infarct who could explicitly identify letters (38/42 correct) but could not identify words (2/50 correct) even with prolonged exposure; in the absence of explicit identification, however, this subject could match pictures, objects and auditory words to 1 of 10 written words correctly (9/12, 9/12, 10/12 respectively). Finally, Shallice and Saffran (1986) reported a patient with pure alexia and letter-by-letter reading who performed above chance on lexical decision tests and at least some tests of semantic categorization with stimuli presented for too brief an interval to permit explicit identification.

Thus there is evidence that at least some subjects with pure alexia can access lexical and even semantic representations for words which they are unable to identify explicitly. In addition, as forced-choice tests of lexical decision and semantic categorization in the absence of explicit identification have not been reported for most patients with pure alexia, it might be argued that the heavy emphasis on oral reading has resulted in a consistent underestimation of the true capacities of these patients.

This explanation alone, however, cannot explain the discrepancy between our subjects and some of the other patients reported in the literature. There are at least two reports of subjects with pure alexia in which seemingly appropriate paradigms were employed but no evidence of implicit reading was found (Warrington and Shallice, 1980; Patterson and Kay, 1982). A number of possible explanations for the discrepancy should be considered. One is that normal subjects vary in the degree to which language is represented in the right hemisphere. Although this hypothesis is subject to the serious criticism that it is consistent with almost any pattern of performance and therefore not testable, this fact alone does not invalidate the hypothesis; Shallice and Saffran (1986) have discussed a number of points which lend credence to the notion that there is variation

among normals in the degree to which language is represented in the right hemisphere.

Another possible explanation for the difference between the performance of our subjects and most subjects with pure alexia is that different strategies may have been employed by different subjects. Our subjects were encouraged not to attempt to explicitly identify words using a letter-by-letter approach but were, rather, urged to develop a 'feeling for' or 'intuition' about the entire letter string. Although definitive evidence of strategy use is not available, it was our strong impression that when subjects attempted to use a letter-by-letter strategy, as they all did initially, there was no convincing evidence of better than chance performance on lexical decision and categorization tasks. With continued exhortations not to use a letter-by-letter strategy, however, our subjects appeared gradually to make a transition to a reading strategy in which the focus was the attempt to achieve what one subject described as a 'sense for the word'. Concomitant with this shift in strategy was an apparent reduction in the explicit use of a letter-by-letter strategy (i.e., subjects reported initial letter information less frequently) and an improvement in performance on lexical decision and categorization tests.

Thus we suggest that our subjects could process visual verbal information in two quite different manners: subjects could identify individual letters and, perhaps using the left hemisphere-based spelling mechanism in a reverse fashion (Warrington and Shallice, 1980; Shallice and Saffran, 1986), use sequential letter information to identify words; additionally, subjects appeared to use a 'whole word' (or more precisely, a root morpheme) mechanism to access a right hemisphere-based lexicon. Perhaps because of an association between left hemisphere-based language mechanisms and conscious awareness of language processing, subjects were explicitly aware of the output of letter analysis mechanism but were not, at least initially, explicitly aware of the output of the right hemisphere-based analysis. We suggest that because of the repeated recommendations of the investigators and the disconcerting but ultimately overwhelming evidence that they performed better when they attempted to derive a 'feeling' for the stimulus, subjects increasingly acted upon the output of the right hemisphere based mechanisms.

Strategy differences were also invoked by Landis *et al.* (1980) and Shallice and Saffran (1986) to account for their data. Landis *et al.*, for example, suggested that initially their patient used visually-presented words to access a right hemisphere-based semantic store; the subsequent use of a letter-by-letter strategy with a goal of explicit word identification, they argued, inhibited or disrupted this right hemisphere-based process. Similarly, Shallice and Saffran (1986) argued that M.L. used a letter-by-letter strategy in tasks requiring word recognition but employed a different strategy when rapid stimulus presentation prevented explicit word identification.

Finally, the hypothesis that strategy differences critically affect performance offers a possible explanation for the apparent lack of implicit word processing demonstrated in the careful investigations by Warrington and Shallice (1980) and

Patterson and Kay (1982). Although in both these investigations, subjects were given forced-choice tests similar to those employed with our subjects, the emphasis appears to have been placed on explicit word identification rather than implicit processing; that is, as they wished to determine if subjects could derive information about words which had not been explicitly identified, they asked subjects to first name the word; only if they failed were they asked to make a judgement about the word (e.g., word vs nonword). In other tasks, Patterson and Kay's (1982) subjects were asked to make judgements before attempting to name words; however, in these tasks stimuli were presented across a desk and it is, therefore, not clear that subjects' standard letter-by-letter strategy was untenable. We would argue that the emphasis on explicit naming in most of these tasks reinforced the subjects' use of the letter-by-letter strategy and discouraged the use of alternative strategies; once again it should be noted that our subjects were constantly urged *not* to attempt to identify words explicitly and their performance appeared to be inversely correlated with the commitment to a strategy of explicit word identification. Thus we would propose that the apparent inconsistency between our data and those of Patterson and Kay (1982) and Warrington and Shallice (1980) is attributable to a subtle but critical difference in methodology which had the effect of encouraging different processing strategies in the different studies.

Therapy

If our account of the influence of strategy differences is correct, the letter-by-letter reading strategy, which is commonly advocated for the treatment of pure alexia, may be counterproductive. Although this strategy may be useful in some subjects, it typically permits only slow and effortful reading. We contend that it would be more appropriate to attempt to encourage subjects to change strategy and access the right hemisphere mechanisms. In this context, it is of note that although subjects with pure alexia usually do not show substantial improvement (Ajax, 1967; Benson and Geschwind, 1976), all 3 of our subjects with unilateral left hemisphere damage improved considerably. However, as all our subjects were tested within several months of the onset of symptoms, this improvement cannot unequivocally be attributed to the strategy change discussed above.

Rothi *et al.* (1985), however, have reported a subject with a 4 yr history of pure alexia and letter-by-letter reading subsequent to a left occipital infarct who demonstrated substantial improvement following a course of therapy designed specifically to encourage the use of a 'gestalt' reading strategy. In a month-long course of remediation involving a variety of tasks in which stimuli were presented tachistoscopically, these investigators demonstrated significant improvement on tests of semantic categorization and lexical decision and improvement of one grade on the Spache Diagnostic Reading Scales (1963).

The case of Rothi *et al.* (1985) is also of note because it provides indirect support for the thesis that the improvement noted by our subjects is attributable to a shift in *strategy* rather than a change in the physiological capacity of

specific brain structures such as the corpus callosum; thus, while the gradual improvement in our subjects might be attributed to gradually resolving ischaemic dysfunction of the corpus callosum or the left occipital pathways implicated in reading, such an explanation would not account for improvement noted 4 yrs after brain infarction.

Finally, these data demonstrating at least relatively preserved tacit processing without subjective awareness attest to the utility of forced-choice and other indirect measures of performance in the assessment of subjects with brain injury. In conjunction with previous investigations of amnesic (e.g., Schacter and Graf, 1986) and prosopagnosic (e.g., Bauer and Rubens, 1985) subjects demonstrating preserved processing without awareness, these data reinforce the notion that a comprehensive understanding of cognitive function must address not only information processing mechanisms but the elusive phenomena of consciousness with these mechanisms are so complexly articulated.

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