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Several different interpretations have been offered to explain the mechanism giving rise to the linear relationship between word length and reading time shown by patients with pure alexia or letter-by-letter reading. One interpretation attributes this word length effect to a spatial impairment in which there is a left-right gradient of processing efficiency. This fundamental resource limitation requires that the patient focus on each letter in turn to increase its signal-to-noise ratio and discriminability, especially for letters towards the end of the string. An alternative view attributes the word length effect to a letter activation deficit that disrupts the rapid and efficient processing of single letters. In this paper, we examine these two hypotheses in relation to DS, a letter-by-letter reader. DS is able to distribute her attention to multiple locations in parallel and her performance is unaffected by the absolute or relative spatial location of the letters in a string. She is, however, impaired at reporting the identity of a letter independent of its spatial location and requires an abnormally long time to process each letter. Furthermore, investigations of DS's reading, using Howard's (1991) analyses of reaction time distributions, suggest that she processes each letter in a sequential order. Based on the results of these studies, we propose that prototypic pure alexia is a nonspatial visual disorder that affects the activation of individual letters.

Keywords: acquired dyslexia, orthographic processing, letter activation, pure alexia, letter-by-letter reading.

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INTRODUCTION

Letter-by-letter reading, or pure alexia, is a disorder acquired as a result of brain damage in premorbidly literate adults. The disorder is characterised by disproportionately slow but generally accurate reading of single words and text. The hallmark of this reading deficit, usually associated with left occipital lobe lesions, is the word length effect—an increase in reaction time as the number of letters in the string increases. Letter-by-letter readers may require up to three or four seconds to name even common three-letter words, and for each additional letter, reading time is slowed incrementally (Patterson & Kay, 1982; Warrington & Shallice, 1980).

Many different accounts have been proposed for this impairment, which gives rise to the monotonic relationship between reading latency and string length. One class of explanations proposes that the primary damage is to early prelexical stages of processing, during which visual arrays are encoded prior to obtaining an integrated word form. The high proportion of visual errors in letter-by-letter reading (Hanley & Kay, 1992; Karanth, 1985) and the interaction between word length and degraded visual input (Farah & Wallace, 1991) lend support to the idea that the locus of the deficit is at early stages of processing. These more peripheral explanations contrast with interpretations of pure alexia, which argue that the word length effect derives from damage to more central mechanisms such as the visual word form system (Warrington & Shallice, 1980). Irrespective of whether the impairment arises more peripherally or more centrally, however, patients may still compensate for their impairment in reading through any of a number of alternative processes, all of which can give rise to the hallmark word length effect. Patients may continue to use the normal parallel process that is now error-prone, resorting to a sequential strategy only when the parallel process fails (Howard, 1991; Vigliocco, Semenza, & Neglia, 1992); they may identify letters in a string through implicit or explicit serial letter identification (Kay & Hanley, 1991; Price & Humphreys, 1992); or they may process letter strings "ends-in" but with lowered activation (Bub, Black, & Howell, 1989; Reuter-Lorenz & Brunn, 1990). In this paper, we explore the locus of the underlying deficit in pure alexia and examine to what extent, if any, it is compensated for in word reading.

At present, the number of possible interpretations of the mechanism underlying letter-by-letter reading almost equals the number of patients who demonstrate the deficit. It may be incorrect to assume a common underlying mechanism for all the patients, given the variability both in their reading times and in behaviours such as their ability to access semantics or to show a word superiority effect (Price & Humphreys, 1992). In the last five years, however, most investigators have proposed that the damage is not to the central mechanisms but rather that the deficit arises peripherally at pre-lexical stages of processing. Even within these early stage explanations, however, there is no clear consensus regarding the underlying cause of the deficit. The existing explanations encompass a wide range of possible impairments including, for example, a general deficit in rapidly switching attention between two components of a visual display (Price & Humphreys, 1992) or a fundamental perceptual deficit affecting all types of visual stimuli both orthographic and non-orthographic (Farah, 1992; Farah & Wallace, 1991; Friedman & Alexander, 1984; Kinsbourne & Warrington, 1962a). Another peripheral explanation suggests that the deficit is not general but applies particularly (perhaps *only*) to orthographic stimuli. On this account, the word length effect arises from the loss of automatic and rapid identification of letters leading to slow and inefficient recognition of orthographic input. The deficit may be restricted to the accurate and efficient identification of single alphanumeric symbols (Arguin & Bub, 1992, 1993; Reuter-Lorenz & Brunn, 1990) or it may be manifest as an inability to access word-form representations rapidly and in parallel (Kay & Hanley, 1991; Patterson & Kay, 1982). This orthographic view is not theoretically incompatible with the more general perceptual view, and studies relating the two are becoming more evident (Farah, 1992; Farah & Wallace, 1991; Sekuler & Behrmann, in preparation). Recently, two additional explanations of pure alexia have been proposed, one suggesting an underlying spatial impairment (Rapp & Caramazza, 1991) and one suggesting the use of the impaired, parallel letter process (Howard, 1991). In this paper, in exploring the basis of pure alexia, we consider each of these explanations. We focus first on the spatial hypothesis (Rapp & Caramazza, 1991) and contrast it with an alternative view of a deficit in letter processing. Thereafter, we report experiments that investigate whether letter processing proceeds in parallel in word reading (Howard, 1991).

The Spatial Distribution Impairment

Rapp and Caramazza (1991), in their well-articulated account of pure alexia as a peripheral deficit, argued that the word length effect is not directly attributable to a deficit in the letter identification process per se: instead, they suggested that it is secondary to a deficit that impairs the even deployment of attention across all spatial locations. This unequal deployment causes a differential distribution of noise across the visual array such that attentional resources must be allocated sequentially to each location. The sequential processing gives rise to the left-right gradient of processing difficulty that underlies the word length effect. Empirical support for this view was obtained from their patient, HR, who showed the typical monotonic relationship between speed and word length both in naming latency and in lexical decision (Rapp & Caramazza, 1991). In addition, HR's letter identification accuracy function dropped off from left to right across all string lengths, even in a partial report task in which only a single item was to be identified at any one time. HR's superior performance for information on the left is attributed to this underlying deficit in spatial processing, which is manifest both at a retinocentric and at a stimulus-centred level of representation. Evidence that the impairment arises at the retinocentric representation at which featural information (bars, orientation, etc.) is coded comes from the finding that HR showed a linear increase in reaction time to detect a single target (X) with an increase in the number of background distractors (O). Because the target can be distinguished from the distractors by a single feature, performance should be equally efficient irrespective of the size of the display, as is the case with normal subjects (Treisman, 1988; Treisman & Gelade, 1980). This display size effect in HR is taken as evidence of a limitation in visual processing capacity and suggests that resources are sequentially allocated to different locations rather than distributed across the entire display automatically and in parallel. Further evidence for this spatial interpretation comes from the finding that *absolute* spatial position is a significant determinant of HR's accuracy in letter identification; the further over to the right a letter appears, the poorer is HR's performance.

In addition to this limitation at a retinocentric level, Rapp and Caramazza (1991) argue for a deficit that arises at the level of representation where spatial location is coded relative to the stimulus itself. Evidence for this stimulus-centred deficit comes from the finding that HR's performance was affected by the *relative* spatial position of the target in the array. For example, HR's detection of a target letter was poorest for letters on the right of a stimulus, irrespective of the absolute retinal location of the letter. This finding is consistent with a gradient of processing efficiency at a stimulus-centred level, where information is represented relative to the stimulus itself. Further support for this type of deficit is obtained from the finding that HR's report of a single letter in the identical absolute position in retinocentric space is affected by the surrounding context; she reports a letter in the final position of a three-item horizontal array less well than if it were the final letter in a vertical array or the first letter of a horizontal array. HR shows the same pattern with non-alphanumeric stimuli (bars) as with letters, leading Rapp and Caramazza (1991) to conclude that HR's reading deficit is part of a general impairment in representing spatially arrayed visual stimuli.

This spatial explanation of letter-by-letter reading proposed by Rapp and Caramazza (1991) bears a striking similarity to accounts of neglect dyslexia, a reading deficit in which information on one side of space is reported poorly. In single word reading, patients with neglect dyslexia typically produce letter substitutions (TABLE → "fable"), omissions (TABLE → "able"), and/or additions (ABLE → "table") (see Riddoch, 1990; Halligan & Marshall, 1993, for an overview). Like letter-by-letter readers, patients with neglect dyslexia typically show a serial position effect, with a linear relationship between letter position in the string and accuracy of report (Behrmann, Moscovitch, Black, & Mozer, 1990). This linear pattern of performance has been interpreted as arising from an attentional gradient that takes the form of maximal and minimal attentional distribution on the ipsilesional and contralesional sides respectively (Behrmann et al., 1990; Kinsbourne & Warrington, 1962b; Riddoch, Humphreys, Cleton, & Fery, 1990).

To evaluate the explanation of the characteristic word length effect as a problem in the distribution of spatial attention (Rapp & Caramazza, 1991), we report several experiments examining the spatial processing ability of DS, a patient with letter-by-letter reading. In the process, we compare DS's behaviour with that of a patient with neglect dyslexia and an obvious deficit in spatial attention. We show that, whereas a deficit in attentional distribution may account for the serial position effect in neglect dyslexia, it cannot explain the effect in the case of letter-by-letter reading.

Letter Activation and Sequential or Parallel Processing

Following the spatial experiments, we describe a series of experiments designed to elucidate the nature of DS's reading deficit and conclude that her deficit may be attributed directly to an impairment in single-letter activation. This letter activation deficit may, however, manifest itself in word reading in different ways. First, it could lie in processes following the level of letter activation used in word identification and be specific to *explicit* letter identification (see Warrington & Shallice, 1979, for suggestions to this effect in semantic access dyslexia). There is, however, no real supporting evidence for this position in letter-by-letter reading. Second, it could result in a reliance on sequential letter-by-letter processing, the standard presupposition about how letter-by-letter readers read words (Patterson & Kay, 1982; Warrington & Shallice, 1980). A third possibility, however, has been raised by Howard (1991). He argued that on a purely serial process of word reading, fast response latencies should never occur on long words. If the letters are processed in parallel, however, but are subject to a higher error rate than in normal reading, a second (slow) strategy will need to come into play only when a letter processing error is made. Howard (1991) described the naming latency performance of two letter-by-letter readers in whom the obtained function fitted this impaired parallel processing account. The second focus of this paper is on whether this alternative parallel account can explain DS's performance.

CASE REPORT

DS, a 34-year-old right-handed English-speaking female who reads in a letter-by-letter fashion, has been described in a previous study (Behrmann, Black, & Bub, 1990). She suffered an occlusion of the left posterior cerebral artery in October 1986, and a CT scan performed at the time revealed a left occipital lobe infarction. At onset, DS had a right homonymous hemianopsia, which resolved to an upper right quadrantanopsia at six months post-onset and was still evident at the time of the present testing (June 1991). Throughout the time course of her illness, DS's reading accuracy was relatively good, even immediately post-onset (Behrmann et al., 1990). Although her reading speed improved dramatically over time, latency remained slow relative to normal subjects and she still showed a significant word-length effect. At the time when the present testing was carried out, DS's auditory comprehension and spoken language production were good, although she did show occasional word-finding difficulties in spontaneous speech. She had resumed her premorbid lifestyle as a homemaker, taking care of her two young children. She had also enrolled in a typing course but found this extremely difficult. She still found reading laborious and tiresome, and although she had read for enjoyment premorbidly, she no longer did so.

DS showed no evidence of hemispatial neglect on a number of bedside tests typically used to identify spatial problems. She performed perfectly on symbol detection (Mesulam, 1985), the bells test (Gauthier, Dehaut, & Joanette, 1989), line cancellation (Albert, 1973), and on spontaneous drawing/copying. She showed +0.5% deviation in bisecting horizontal lines where 0% refers to bisection at the midline and positive values refer to deviations to the right. The slight deviation is well within the range of normal limits for this material (Black, Vu, Martin, & Szalai, 1990).

EXPERIMENTAL STUDIES OF DS'S LETTER AND WORD READING DEFICIT

The experiments reported here were administered by means of Psychlab software (Bub & Gum, 1988) run on a Macintosh Plus computer. The procedure adopted was identical for most experiments and any deviations from this standard procedure are described where pertinent. Stimuli were presented in bold black upper-case letters, in 24-point Geneva font on a white background. DS sat at a distance of approximately 40cm from the screen. Each stimulus was preceded by a central black fixation point, which remained on the screen for 500msec and was followed by a 1sec delay. The exposure duration of the stimulus was varied according to the task. All stimuli were presented in DS's intact left field and the visual angles subtended for stimuli of 1, 3, 5, and 7 characters in length were 1°, 1.5°, 2.4°, and 3.6° respectively. On tasks requiring an oral response, reaction time (RT) was measured by a voice activation key, whereas on tasks requiring a key press, RTs were measured from the keyboard. Control data was collected using the identical procedures from a single age- and education-matched female subject, RS.

That DS is a letter-by-letter reader is apparent from the previous report (Behrmann et al., 1990) and from the naming latency data reported in Experiment 9. Experiment 1 is designed to examine DS's letter processing ability, whereas Experiments 2–5 and Experiments 6–9 are directed at the spatial and letter activation hypotheses respectively. Finally, in Experiments 9 and 10, we consider how the observed letter processing deficit affects DS's word processing.

Experiment 1: Single Letter Report

Material and Procedure

In the first part of this experiment, a list of 30 randomly selected single letters was presented for identification. Each letter was presented individually for 17msec (the briefest posssible exposure time subject to screen refresh limits). In the second part of the experiment, 30 arrays, each consisting of 3 letters with a single character space between them (e.g. F M A), were presented individually for identification. A block of 30 different arrays was run at each of 250, 150, and 100msec exposure. Accuracy of letter report was recorded.

Results

DS was able to report all the single letters with perfect accuracy. On the 3-letter arrays, she was able to report 26/30 letters at 250msec, 22/30 at 150msec, and 19/30 at 100msec. The predictable decrement in performance across the string from left to right was noted in her errors: Whereas no errors were made on letters appearing in the initial position of the array, 7 and 16 errors occurred in the medial and final position respectively. The most important observation is that, given sufficient time, DS's single letter identification is good. Accuracy of report, however, drops with limited exposure and when it drops off, it does so in the expected way. The deficit in processing more than a single letter at brief exposure is discussed in detail in later experiments on DS's letter activation ability.

SPATIAL PROCESSING

Experiment 2: Feature Encoding in Retinocentric Coordinates

During early visual encoding, when individual features are picked up, processing is automatic, operating over the entire array independent of the size of the display. Because information is processed from all locations in parallel, the time taken for normal subjects to detect the presence of an "oddball" target such as "X" from an array of "O"s is not affected by an increase in the number of distractor items. Because HR's visual search performance was adversely affected by an increase in the display size, Rapp and Caramazza (1991) concluded that she was impaired at distributing attention in parallel over multiple locations. Furthermore, because the impairment was observed on a simple disjunctive feature search, they suggested that the deficit arose at an early stage of processing, where featural information is coded in retinocentric coordinates.

To determine whether DS showed a spatial deficit like that of HR, we used a typical visual search paradigm in which the target differs from the distractors by a single feature. Both the number of distractors and the location of the target were varied systematically. The first prediction was that, if DS's impairment is spatially determined then, like HR, she should show an increase in RT to detect the target with an increase in the number of distractors. A further, more specific prediction is that if it is indeed a deficit in distributing spatial attention that underlies DS's reading performance, then the ability to detect a target on this task should reflect the left-right gradient observed in reading. Unfortunately, Rapp and Caramazza (1991) do not provide these latter results for HR and so comparisons between her visual search and reading performance is not possible.

Materials and Procedure

DS performed a simple yes/no detection task in which the target (a filled circle, half an inch in diameter) was present on half the trials. She was instructed to use her right hand and to press one key for present trials and a second for absent trials: RT to make the decision was measured. Distractors were unfilled circles of the same diameter as the target. The display size varied from 1 item (target or distractor) present to 3, 6, or 12 items present. The target appeared randomly but with equal probability on the relative left or right and relative upper or lower quadrant of the display and the distractors were randomly distributed. The display remained on the screen until a response was made or three seconds had elapsed. The experiment was run in 4 blocks of 40 randomised trials (80 target present, 80 absent) following a practice block of 24 trials.

Results

RTs for correct responses for DS and the control subject, RS, as a function of display size and target presence, are shown in Fig. 1. Both DS and RS made very few errors (DS: $N = 1$, RS: $N = 5$). Analysis of the RT data, using subject as a between-subject variable, and decision (present/absent) and display size (1, 3, 6, 12) as within-subject variables, showed a significant interaction between subject and decision [$F(1, 3) = 64.5$, $P < 0.0001$]. Post-hoc comparisons (Tukey at $P < 0.05$) showed that, relative to target present trials, RS took, on average, an additional 59msec to respond to absent trials whereas DS required an additional 445msec. The three-way interaction with subject, decision, and display size was not significant [$F(3, 298) = 1.65$, $P > 0.10$]; nor were any other two-way interactions [display size × subject, $F(3, 3) = 1.76$, $P > 0.10$; display size × present/absent $F(3, 3) = 0.57$, $P > 0.5$]. Importantly, there was a main effect of display size [$F(3, 3) = 4.15$, $P < 0.01$] but, as was evident from the analysis, this held to an equivalent extent across DS and RS. The main effects of subject [$F(1, 3) = 377.4$, $P < 0.0001$] and decision [$F(1, 3) = 110$, $P < 0.0001$] were both significant.

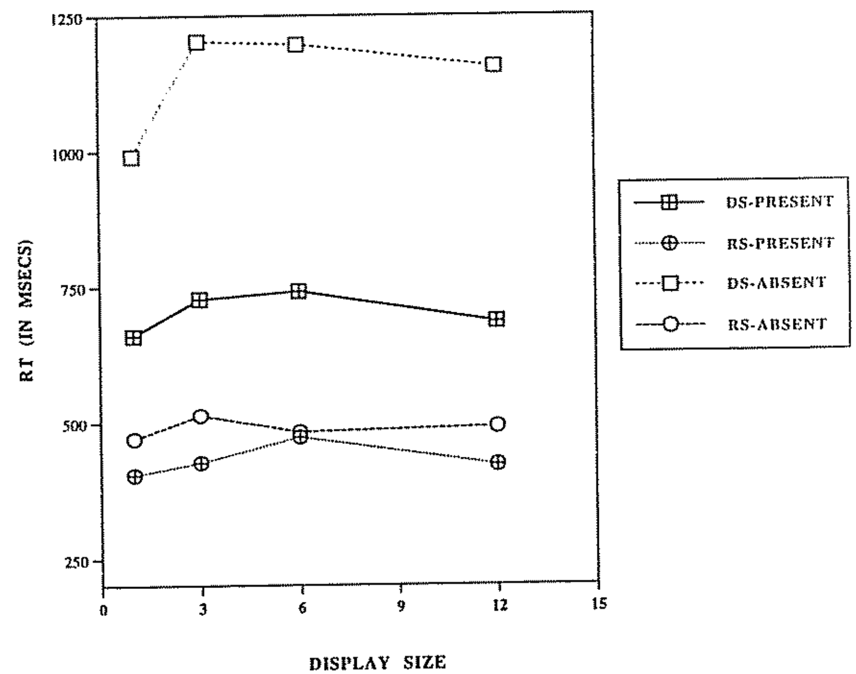

FIG. 1. RTs for correct responses for DS and the control subject on visual search as a function of display size for target present and target absent trials.

To examine the effect of target location on RT, an analysis of variance was conducted on target present trials only with subjects as a between-subject variable and with side (left/right) and vertical location (upper/lower) as within-subject factors. Figure 2 shows RTs to targets as a function of side and vertical location for both DS and RS.

There was a significant difference in RT between the subjects, with RS showing faster response times overall [$F(1, 3) = 124.05$, $P < 0.001$]. There was also a main effect of left/right location, with significantly faster RTs to right than to left targets [$F(1, 3) = 8.37$, $P < 0.001$]. No other main effects or interactions were significant. There was no obvious effect of DS's upper-right quadrantanopsia on search time as RTs for targets in the area of the visual field cut (upper right quadrant) were not significantly different from those for the lower right quadrant (upper = 651msec, lower = 647msec). The faster RT to right-sided targets for both RS and DS may be an effect of spatial compatibility (right hand and right-sided responses), but it is important to note that the right-sided facilitation (relative to the left) for DS was of the same magnitude as for the control subject.

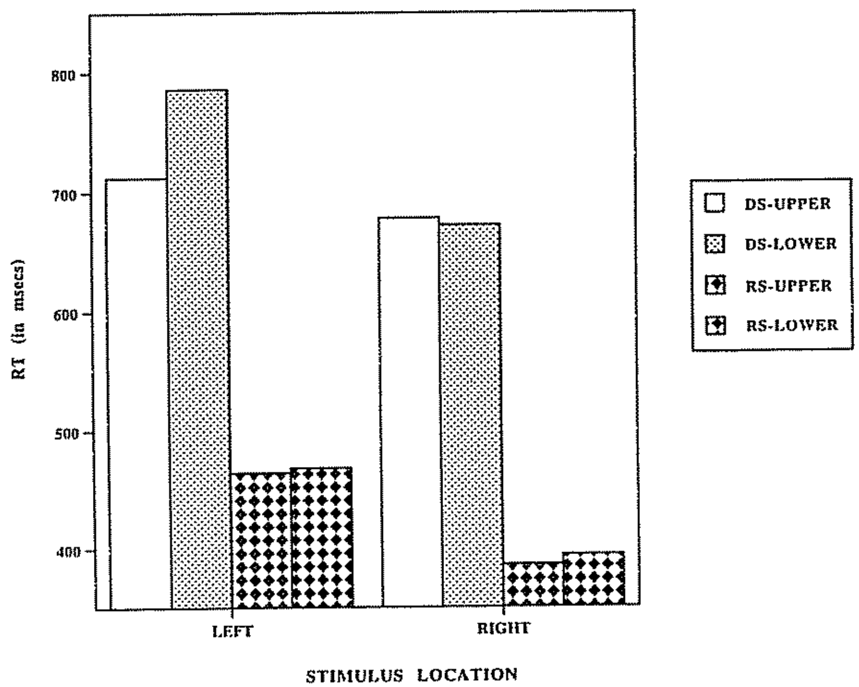

FIG. 2. RTs to target present trials for both DS and the control subject as a function of target side and vertical location.

Discussion

The results of the feature search task indicate that DS's pattern of performance is not significantly different from that of the control subject on the target present trials. The interaction between decision and subject comes from DS's caution in making a "no" response; she appeared to be carrying out an exhaustive search before concluding that the target was not present. Although there is a main effect of number of items for both subjects, the findings are well within the limits provided by Treisman and Gelade (1980) for parallel processing of all items simultaneously. RS shows an increase in RT of 16msec between 1- and 12-item displays, reflecting a minimal increase with the additional distractors. Similarly, DS shows a difference of 26msec (from 659.4 to 685.5msec for 1- and 12-item displays) with an approximate increase in RT of 2msec per additional item. These findings suggest, therefore, that DS, like RS, is able to distribute her attention automatically and in parallel across a display. Because the featural difference was defined by spatial frequency in this task (unlike that in Rapp and Caramazza's task), and because spatial frequency is a low-level feature, any disruption in attentional distribution that might have existed would probably have been detected easily. Similar findings on a variety of visual search tasks using different features for detection have been obtained from other letter-by-letter readers (Arguin & Bub, 1993).

The two important results are that DS's RT does not increase with an increasing number of distractors and that detection time for right-sided targets, relative to left targets, is not different from normal. These findings suggest that, unlike HR (Rapp & Caramazza, 1991), DS does not have a general problem dealing with information on the right, as might be expected from an explanation of her reading deficit in terms of a spatial impairment.

Experiment 3: Extent of Attentional Scan Angle

The finding that DS codes individual features across an array without loss of speed irrespective of display size implies that her reading problem is not related to a *general* deficit in processing in parallel across a visual array. It has been suggested, however, that the disjunctive feature search task is performed pre-attentively (particularly with luminance changes as in Experiment 2) and that visuospatial attention need only be implicated when features of a stimulus need to be conjoined. In the following task, then, we examined DS's ability to identify individual letters, a task that requires, amongst other things, the conjunction of the features of the stimuli. In this experiment, DS was required to report two letters at opposite ends of a string; the strings varied in length between three and seven digits (e.g. W9832751N, B824L). Because of the superior report of initial letters in a string relative to final letters in letter-by-letter readers (and even in normal readers with U-shaped curves; Rumelhart & McClelland, 1982), performance might be expected to be better for the first than for the last letter. If a deficit in visuospatial attention is present, one would expect that DS will have more difficulty reporting the right-sided letter as the number of intervening items increases. If, however, there is no reduction in DS's distribution of visual attention, report of the right-sided letter should not be affected by the number of intervening digits. In a previous study, Warrington and Shallice (1980) used this same letter report task with a letter-by-letter reader. Because their patient reported the extreme letter equally well, independent of the number of intervening items, they argued that the angle of attentional scan was normal and not the determinant of alexia.

Material and Procedure

The stimulus array consisted of a string with two letters on either side of an array of intervening digits. There were a total of 100 arrays, 20 each of 3, 4, 5, 6, or 7 intervening digits, all of which were randomised and presented in a mixed block. The string appeared on the screen for 100msec and DS was to identify the first and last letters. To control for memory load, DS was instructed to report the left-hand letter first on half of the trials and the right-hand first on the remaining half. Order of report was blocked, with instructions given before the block began.

Results

There was no significant difference in DS's accuracy of letter report as a function of order of report (left first or right first) ($\chi^2_{(1)} = 1.98$, $P = 0.15$). Moreover, an analysis with order of instruction (left first/right first) and number correct letter report (left/right) shows no difference as a function of order ($\chi^2_{(1)} = 0.03$, $P = 0.86$). Table 1 shows the number of left and right letters reported as a function of the number of intervening digits in the array. Overall, DS reported 134/200 (67%) letters correctly, with significantly better report of the left than the right letter ($\chi^2_{(1)} = 39.8$, $P < 0.001$). The advantage for the left (or initial) letter is particularly compelling since, with the left visual field presentation, it is the right rather than the left letter that has maximum acuity and falls closest to the fovea. The major finding of this experiment, however, was that there was no significant reduction in report with increasing string length (with even slightly better performance on strings with 7 than with 6 intervening digits: $\chi^2_{(1)} = 2.03$, $P = 0.73$).

TABLE 1
Number of Left and Right Letters Correctly Reported by DS as a Function of Number of Intervening Digits ($N = 20$ Per Cell)

	Number of Intervening Digits					
	3	*4*	*5*	*6*	*7*	*Total (%)*
Left	18	19	18	15	18	88
Right	7	7	10	9	13	46
Total	25	26	28	24	31	

Discussion

DS's ability to report the letters from the extreme ends of an alphanumeric string is not affected by the length of the string, suggesting that the angle of attentional scan or "spotlight" is not restricted in any way. Even though the two items to be reported are predictable, because the strings vary in length, their spatial location is not. These results, therefore, argue against a simple model in which the attentional focus is split and, instead, indicate that DS is able to switch her attention flexibly across strings of different lengths. As such, these findings also rule out a deficit in attentional switching (Price & Humphreys, 1992) as the basis of DS's letter-by-letter reading.

Experiment 4: Horizontal Versus Vertical Orientation of Stimuli

The data presented earlier rule out any effect of the absolute spatial location of the stimulus on DS's performance. In addition to a deficit in retinocentric coordinates, however, Rapp and Caramazza (1991) showed that HR's impairment also arises at a stimulus-centred level of representation, as shown in her performance with strings of different orientations. For example, HR reported correctly a single letter in about 90% of the arrays when the letter appeared at the beginning or end of a vertical array or at the beginning of a horizontal array, even when the physical location of this target letter did not change. However, she reported the letter correctly on only 6% of the trials when the letter fell at the *end* of a horizontal array. That the letter report varies even when the absolute spatial position of the target letter is held constant suggests that performance is affected at a stage of processing in which letters are encoded relative to other letters in the stimulus, i.e. within a stimulus-centred reference frame. The next experiment tests whether a stimulus-centred deficit could account for DS's performance.

Materials and Procedure

In this task, 40 strings of each of 2, 4, and 6 letters appeared to the left of a central fixation point. The letters were separated by a single character space. The strings were arrayed horizontally or vertically so that the final letter (e.g. N *H*, N F S *H*, or N J K M L *H*) occupied the same absolute location on the screen irrespective of the length of the string. The strings were presented individually at 100msec. DS was required to report the identity of the first and the last letter; on half the trials, she reported the first letter first and on the remaining trials, she reported the last letter first. Stimulus length and orientation were randomised and presented in mixed format. Accuracy of report of the noncritical letter (left in horizontal and upper in vertical array) and of the critical target letter was measured.

Results

The percentage of letters reported correctly from the critical and the noncritical position as a function of string length is shown in Table 2. Overall, DS reported 207/240 letters correctly (86.3%) and there was no main effect of the order in which the critical and noncritical letters were reported ($\chi^2_{(1)} = 1.9$, $P = 0.2$). There was, however, a significant joint effect of letter position, string length, and orientation, but this concerned the noncritical rather than the critical letter. DS reported the first (noncritical) letter of horizontal trials significantly better than the first letter of vertical trials ($\chi^2_{(1)} = 5.4$, $P = 0.02$), especially for longer strings. As is evident from the data, this effect arises from the four- and six-letter arrays only and is probably attributable to the greater retinal eccentricity for vertical over horizontal arrays. Because the height of a block capital letter exceeds its width, the visual angle subtended by the vertical arrays is larger

TABLE 2
Percentage Letters Reported Correctly from the Critical and Noncritical Left/Upper Position for Horizontal and Vertical Displays

Letter Position	*Horizontal Arrays*	*Vertical Arrays*
Critical Position		
Two	100	100
Four	95	90
Six	80	90
Noncritical Position		
Two	100	100
Four	89	55
Six	95	40

than that of the horizontal arrays, putting initial letters in long vertical arrays further into peripheral vision. That DS can report the noncritical letter on 6-letter horizontal arrays (which correspond to strings of 11 letters in length because of the spaces between letters) correctly on 95% of the trials is consistent with our claim from Experiment 3 that DS's letter report of the leftmost letter is good irrespective of string length. As visual acuity is compromised (particularly for the vertical strings with which normal readers are less familiar), performance drops off. The major finding with which we are concerned is that report of the critical letter was not affected by stimulus orientation ($\chi^2_{(1)} = 1.8$, $P = 0.17$), number of items in the array ($\chi^2_{(2)} = 3.6$, $P = 0.16$), nor by interactions between these variables when the absolute spatial location of the target was held constant.

Discussion

The absence of an effect of string length on report of the critical letter replicates the finding of the previous experiment in showing that DS can distribute her attention equally efficiently over long and short arrays. This experiment goes further and demonstrates that DS is able to report a letter equally well when it occupies the last position of either a vertical or a horizontal display. Unlike HR (Rapp & Caramazza, 1991) then, DS's report of the critical letter is not affected by the number or orientation of the surrounding items in the array. These findings rule out an explanation of a deficit in the processing of letters whose spatial positions are defined relative to the centre of the stimulus.

Experiment 5: Allocating Attention to Words

Although DS shows no deficit in encoding spatial information from the absolute or the relative spatial locations, it is still conceivable that she has a deficit in distributing attention to real word stimuli. When only two letters must be reported from a random array of alphanumeric characters (Experiments 3 and 4), it may be possible for her to filter out the irrelevant centre material. To determine whether DS has any difficulty in distributing attention equally across words, the next experiment uses only alphanumeric stimuli. In this experiment, we compare DS's ability to report the first and last letters (positions 1 and n) of word and nonword stimuli of increasing length. As a control condition in which spatial extent is minimised but letter report of two items is still necessary, we measured DS's ability to report the letters from the first and second positions of the string (positions 1 and 2). The prediction is that if spatial extent affects performance, letter report should be worse when reporting the first and last letters which require greater distribution of spatial attention ($1/n$) than when reporting the two adjacent letters appearing at the beginning of the string (1/2). In contrast, if the deficit is not in encoding spatial information but rather in the processing of the second-named letter irrespective of its location, then the first letter should be reported best but there should be no difference between DS's reporting of the second and the last letter, i.e. the report of the second letter would be poor independent of its spatial location. Since some letter-by-letter readers perform better with words than with nonwords (Bub et al., 1989; Reuter-Lorenz & Brunn, 1990), we might also expect to see a word superiority effect.

To demonstrate that this task is indeed sensitive to a deficit in spatial processing, we also tested a patient with a deficit of visuo-spatial attention. MG is a 64-year-old, right-handed English-speaking retired executive, who suffered a right middle cerebral artery infarction in August 1990. MG shows significant left-sided neglect: He bisects +4.5% to the right on line bisection and on the line cancellation task he omits 4/15 and 0/15 lines on the left and right respectively. He also fails to detect 9/30 and 1/30 targets on the left and right on the symbol detection task (Mesulam, 1985). For MG, then, position 1 refers to the final right-sided letter in the string (his optimal position), position 2 to the penultimate right-sided letter, and position n to the first letter in the string (on the left). We predicted that he would show an effect of spatial location, reporting letters in position 1 significantly better than those in position 2, and that letters in position 2, in turn, would be reported significantly better than those in position n.

Materials and Procedure

Thirty words and 30 random letter strings (e.g. NDFME), each of 3, 4, 5, 6, and 7 letters in length ($N = 300$) were selected. The words were matched for frequency, with one third of the trials each falling below 20 per million, between 30–90 per million, and over 110 per million for each word length (Francis & Kuçera, 1982). The stimuli were centred over a point located in the fourth character position from fixation in the left visual field for DS and the right visual field for MG. The subjects were required to report two letters in two different conditions. In the 1/n condition, they were instructed to report the first and last letters (e.g. AE in ATHLETE). Because MG has left-sided neglect, his report of the letter in final position is equivalent to DS's report of the first letter. In the 1/2 condition, DS was instructed to report the first and second letters (e.g. AT in ATHLETE) and MG was instructed to report the final two letters (e.g. TE in ATHLETE, where 1 is the final and 2 is the second last letter). The stimuli were presented blocked and condition of report followed an ABBA order: 1/2 words, then 1/n words, then 1/n nonwords, and finally 1/2 nonwords.

The stimuli were presented at a preset exposure duration at which accuracy of report of the first and last letter was 60%. The duration was calculated on a practice set of 30 nonwords of varying lengths. This titration

procedure ensured that the testing conditions were equivalent for the two patients. The same experiment was also presented to the normal control subject, but even at the briefest possible exposure duration (17msec, no mask), performance was at ceiling. The exposure selected for DS was 100msec while the exposure for MG was 200msec. Since MG was only available for a limited time of testing, only 75 trials were completed in each of the 4 cells (rather than 150 as for DS), giving a total of 300 trials for MG and 600 for DS. Two testing sessions were necessary to complete this experiment with DS.

Results

The number and proportion of letters reported correctly from positions 1, 2, and n for MG and DS are shown in Table 3. Overall, MG reported 73% (438/600) letters correctly. Accuracy of final letter report (position 1) was significantly better than that of the second last letter (position 2) ($\chi^2_{(1)} = 39.5$, $P < 0.001$), which in turn was reported significantly better than the leftmost letter closest to fixation in the right field (position n) ($\chi^2_{(1)} = 14.7$, $P < 0.0001$). This deterioration across serial positions, in particular the contrast between position 2 and position n, is consistent with a deficit in visuospatial attention in which the location of the letter significantly affects performance.

The pattern shown by DS was markedly different from that of MG although overall accuracy was similar—DS reported 76% (919/1200) of the letters correctly. The leftmost letter (position 1) was reported significantly better than the letter in position 2 ($\chi^2_{(1)} = 182.4$, $P < 0.001$) and the letter in position n ($\chi^2_{(1)} = 128.5$, $P < 0.001$), but there was no significant difference between the latter two letters ($\chi^2_{(1)} = 0.112$, $P > 0.10$). Thus, on this analysis, DS's report of the second letter is equally poor irrespective of its spatial location in the string.

The effect of spatial position for MG and the absence of a spatial effect for DS is also apparent from an analysis of the percentage of trials on

TABLE 3
Number and Proportion of Letters Reported Correctly from Positions 1, 2, and n for MG and DS

	MG		DS	
	Number	*Proportion*	*Number*	*Proportion*
Position 1	275/300	0.92	551/600	0.92
Position 2	94/150	0.68	186/300	0.62
Position n	69/150	0.43	182/300	0.61

which both letters are reported correctly (see Table 4). These data might provide a more stringent test of the spatial hypothesis since they now reflect the extent to which both of two spatially distant letters are correctly processed. MG reports both letters correctly significantly more often in condition 1/2 (last and second-last letter) than in condition 1/*n* (last and first letter) ($\chi^2_{(1)} = 8.3$, $P < 0.005$), whereas DS shows no such difference ($\chi^2_{(1)} = 0.112$, $P > 0.05$). The superior performance in the condition of adjacent (1/2) over distant (1/*n*) by MG but not by DS supports the view that spatial extent affects MG's reading but does not influence DS's behaviour.

MG reported both letters significantly better from words than from nonwords ($\chi^2_{(1)} = 38.9$, $P < 0.001$), a finding consistent with the observed word superiority effect in neglect dyslexia (Behrmann et al., 1990; Riddoch et al., 1990). The word superiority effect is also seen in DS's performance ($\chi^2_{(1)} = 12.3$, $P < 0.005$). The recognition advantage for letters in words over those in nonwords or pseudowords has been reported in several (Reuter-Lorenz & Brunn, 1990), but not all, cases of letter-by-letter reading (Kay & Hanley, 1991). The word superiority effect could reflect activation of, or feedback from, word or letter-group units to lower letter-level units, or it could merely be a consequence of sequential dependencies in letter identification. The present results do not distinguish clearly between these two possibilities.

Discussion

The findings from this experiment show a clear difference between the performance of MG, a patient with left-sided spatial deficit, and DS, a letter-by-letter reader. MG is able to identify the rightmost letter in a string relatively well but performance drops off markedly across the serial positions, with poorest report of the leftmost letter. This difference as a function of location reflects the impairment in visuospatial processing that

TABLE 4
Percentage of Trials on which Both Letters are Reported Correctly for DS and MG as a Function of String Type and Condition of Report

	MG: Neglect Dyslexia Condition of Report		*DS: Letter-by-letter Condition of Report*	
String Type	*1/2*	*1/n*	*1/2*	*1/n*
Words	84	56	69	66
Nonwords	47	25	57	53
Mean	65.5	40.5	63	59.5

characterises neglect. In contrast, DS does not show this spatial effect, and report of the second letter falls off irrespective of its location. The absence of an effect of location rules out any spatial attentional explanation for DS's performance. That DS reports the first letter better than any other letter suggests that letters are processed sequentially and that this serial processing gives rise to her letter-by-letter reading.

Summary of Spatial Experiments

The hypothesis that a deficit in distributing attention to multiple locations in parallel is responsible for DS's letter-by-letter reading has been refuted in Experiments 2–5. Taken together, these findings show that left-sided letters are processed more efficiently than right-sided letters across a number of different paradigms and reporting formats. DS is able to detect a target with equal speed and accuracy independent of the number of distractors in the display. Her letter report ability is also not affected by an increase in horizontal spatial extent (with increasing intervening digits separating the letters); nor is it affected by the relative spatial location of letters within a string (horizontal or vertical). Finally, in contrast to that of a neglect dyslexic patient, DS's letter report is unaffected by the spatial position occupied by letters in a string and she can allocate her attention flexibly and rapidly to the beginnings and ends of words. Although Rapp and Caramazza (1991) do not suggest that the performance of a letter-by-letter reader and a patient with neglect should be identical, they do argue that in both cases the deficit is spatially determined; they presuppose that the shape and slope of the underlying processing efficiency function may differ between the disorders. It would, however, be very difficult to reconcile the findings that DS shows equally poor performance on positions 2 and *n* of letter strings of different lengths with any interpretation that is spatially based.

SERIAL EFFECTS AND LETTER PROCESSING

The results from Experiments 2–5 suggest that the deficit underlying DS's reading is neither one of impaired spatial distribution of attention nor one of inadequate distribution of processing resources across the letter string. Rather, the problem appears to arise in DS's reporting of the identity of the second letter independent of its spatial location. In these experiments, however, there still remains a confound between letter order and spatial position because letters on the left of the word are also on the left of space. In the following experiments, we deconfound these factors and examine in more detail the serial order effect in DS's ability to process letters.

Experiment 6: Rapid Serial Visual Presentation

In this experiment, we compare DS's ability to report the first and second letter under conditions where the two letters appear in the same spatial position. The strong prediction is that, if the word length effect arises because of a deficit in rapid and efficient single letter processing, reporting two letters will still be impaired even in a situation where spatial location is held constant. One possible reason is that if single letter activation is slow and unreliable, additional time will be required to process a letter satisfactorily. If a second letter appears while the first letter is still being processed, this would produce interference and its effects would need to be inhibited by attentional focusing. If this occurs, either, but not both, of the letters might be processed accurately; strategic factors would determine which. However, if more time is given so that the first letter is processed relatively well before the second letter appears, processing of the first letter would tend to be completed but activation of the second letter would still need to be inhibited. One would therefore expect that report of the second letter would improve provided that the time interval between the appear- ance of the two letters was sufficient and that enough time was available for processing of the first letter to be completed prior to the arrival of the second letter. As detection of two letters presented alone may depend on retrieval from short-term visual memory, a rapid serial visual presentation (RSVP) paradigm was used, in which two letters appeared in the same location separated by intervals of differing duration.

Material and Procedure

A trial consisted of a string of 15 symbols (2 letters and 13 digits), which appeared individually for 100 msec in rapid serial succession all in the *same* spatial location. The 120 trials were divided into 3 conditions: when the 2 letters appeared either temporally adjacent with 0 digits between them (e.g. 15786FH963172), 3 digits between them (e.g. 35785W267B74219), or 7 digits between them (e.g. 943G8357481K749). The SOA between the letters in the 0 digit condition was 100msec from onset of the first digit, while the SOAs in the 3 and 7 digit conditions were 400 and 800msec respectively. Letters did not appear in either the first three or the final three positions of the string so as to avoid primacy and recency effects. Following a central fixation point which remained on the screen for 500msec, and followed by a 500msec blank screen, the first item appeared 2 character spaces (1°) to the left of fixation, followed by the other symbols. DS was instructed to report only the two letters. The same experiment was presented to the control subject, RS, also at 100msec per symbol, and accuracy was recorded.

Results

The number of correct and incorrect responses for the first and second letters as a function of SOA is shown in Table 5 for both DS and RS. The symbols "++" and "−−" indicate that both the first and second letters were reported correctly or incorrectly, respectively. "+−" indicates that the first but not the second letter was reported correctly, and "−+" denotes the reverse. For DS, the probability of reporting both letters shows a significant trend to be higher as SOA increases (Mann-Whitney $U = 2080$; $N_1 = 75$, $N_2 = 45$, $P < 0.05$). For RS, there is a completely nonsignificant trend in the other direction.

When the probability of reporting only the first stimulus correctly is compared with that of the second stimulus for different SOAs, then both subjects show significant effects. Consider the 2 × 3 matrix for trials in which a single target is correctly reported, i.e. +− and −+ on Table 5. The procedure developed by Lancaster (1949) and Irwin (1949) (see Everitt, 1972) can be used to partition the overall chi-squared value. If performance on 100msec SOA is compared with that of 400msec SOA, then the difference in pattern is not significant ($\chi^2_{(1)} = 2.43$, $P > 0.1$). However, the pattern is significantly different for 800msec SOA to that for 100msec SOA and 400msec SOA combined ($\chi^2_{(1)} = 5.8$, $P < 0.02$). Most critically, the strong tendency to produce only the *first* letter at 400msec SOA has completely disappeared by 800msec SOA. RS also shows a significant overall effect of SOA on the incidence of first versus second only reports ($\chi^2_{(1)} = 15.8$, $P < 0.001$). In her case, however, the Lancaster-Irwin partitioning (Everitt, 1949) shows the 100msec and 400msec patterns to be significantly different ($\chi^2_{(1)} = 11.73$, $P < 0.001$), as is also the case for the combined 100msec and 400msec patterns versus the 800msec pattern ($\chi^2_{(1)} = 4.07$, $P < 0.05$).

TABLE 5
Number of Letters Reported by DS and Control on RSVP Presentation as a Function of Increasing SOA between Letters

	DS				*Control Subject*			
SOA	++	+−	−+	−−	++	+−	−+	−−
100	11	14	13	2	26	0	14	0
400	14	17	6	3	26	8	4	2
800	20	4	11	5	23	10	6	1
Total	45	35	30	10	75	18	24	3

Discussion

There are two findings of interest in this study. First, in contrast to RS, DS's ability to report both stimuli is significantly affected by the length of the interval between the targets. Second, DS's ability to report both targets differs from that of RS at 100 and at 400msec but not at 800msec. These results are consistent with the view that DS's letter activation is weak or slow, so that the arrival of the second letter interrupts processing of the first. Given enough time for the first letter to be processed, however, DS's performance is not significantly different from that of the normal control. On this view, because DS's letter processing is slowed at 100msec, processing of the first letter has only just begun when the second letter appears. Processing of the two letters simultaneously is not possible so she identifies either of the two letters with equal probability. At 400msec SOA, however, sufficient processing of the first letter has taken place before the second letter arrives, with the result that performance is better on the first than on the second letter. Finally, at 800msec, there is sufficient time to process both letters. The estimated time required for DS to complete the processing of a single letter is over 400msec, as report of the first item in the 400msec SOA condition (31/40) is still far better than her performance on the second item (20/40) (combining ++ scores with +− or −+, respectively). In that condition DS still remains significantly worse than RS. Neither of these effects is present in the 800msec SOA condition.

Experiment 7: Simultaneous Versus Sequential Letter Processing

Given that DS requires more time than normal for processing the first letter, one would predict that she should have more difficulty matching two letters presented simultaneously, i.e. when there is no interval (0msec SOA) between them, than matching two letters presented sequentially. When the time interval between the letters is sufficient—at least 400msec—she should be able to perform the matching task well. It is possible, however, that in a *physical match* condition where the physical structure of the letters is sufficient for matching (e.g. AA), the advantage of sequential over simultaneous presentation might not be that great. In contrast, the effect of SOA should be more marked when the match is more difficult and depends on a *name match* of the letters using abstract letter codes (e.g. Aa). Thus we would expect an interaction between type of match and SOA, with better performance at longer SOAs when the task requires a name rather than a physical match. To examine this, we tested DS using a variant of the Posner and Mitchell (1967) paradigm employed both by Reuter-Lorenz and Brunn (1990) and by Kay and Hanley (1991). The particular version of the task used is most similar to that of Kay and Hanley (1991).

Materials

Four letters with different upper- and lower-case forms were selected (Aa, Rr, Hh, Gg). The stimuli fell into two conditions where the pairs of letters were the same ($N = 60$) or different ($N = 60$) and the subject was required to make same/different judgments. Trials requiring the response "same" fell into two different conditions. The 30 same *physical match* trials contained 2 letters that were structurally identical and were divided equally into upper- and lower-case trials (e.g. AA or aa). The 30 same *name match* trials contained 2 letters that shared a nominal or letter code (cross-case) but not a physical match (e.g. Aa or Rr)—these still required a "same" response. The 60 different trials were constructed by pairing 2 different letters in the same case (e.g. AR, ar) or in crossed case (e.g. Ar, aR) with equal probability.

Procedure

Following a central fixation point, a single stimulus, subtending a visual angle of 1°, appeared on the screen. Adopting the procedure of Reuter-Lorenz and Brunn (1990) and Kay and Hanley (1991), two SOAs were used. In the *simultaneous* condition both members of the pair appeared on the screen (0msec SOA), whereas in the *sequential* condition, the first stimulus remained on the screen for 500msec prior to the appearance of the second letter. Sequential and simultaneous trials were mixed and randomised and 2 blocks of 120 trials were run. Unlike previous experiments (Reuter-Lorenz & Brunn, 1990; Kay & Hanley, 1991), in which the two letters appeared horizontally adjacent, in this experiment the two letters appeared vertically, one directly above the other. This vertical presentation was used since any shift in eye movement with a horizontal display could place one stimulus in the blind field, making the comparison between stimuli more difficult, particularly under conditions of limited exposure duration. In both simultaneous and sequential conditions, after presentation, both stimuli remained on the screen until the response key was pressed. DS was instructed to press one key for the "same" (includes physical and name match conditions) and a second key for "different" decisions. Reaction time and accuracy was measured for DS. The control subject also completed this experiment.

Results

Few errors were made by the subjects (DS: 8/240 or 97% correct; RS: 4/240 or 98% correct). All eight errors made by DS were on sequential presentation, two on name matching trials and the remaining six on different trials. A one-way ANOVA with case (lower/upper, e.g. AA and aa) showed no significant difference on DS's RT [$F(1, 1) = 0.25$, $P > 0.5$]

and thus the data are pooled across case for the rest of the analysis. Mean reaction times for both DS and RS for physical, name, and different trials for simultaneous and sequential conditions are displayed in Fig. 3. An ANOVA of the data with trial type (physical, name, and different matches) and condition (simultaneous/sequential) as within-subject variables were conducted separately for DS and for RS. Although the name and physical match conditions are more comparable as they both require "same" responses, the data for the "different" trials are also included.

As can be seen from Fig. 3, there is a significant effect of condition [$F(2, 2) = 11.47$, $P < 0.001$] for RS with faster physical matches than either name or different matches. This pattern holds equally across simultaneous and sequential presentations [$F(1, 2) = 2.12$, $P > 0.10$], with the advantage of physical matches over name matches being 29 and 53msec for the two conditions respectively. These results reflect the same qualitative pattern shown by Posner and Mitchell (1967) as well as that of the

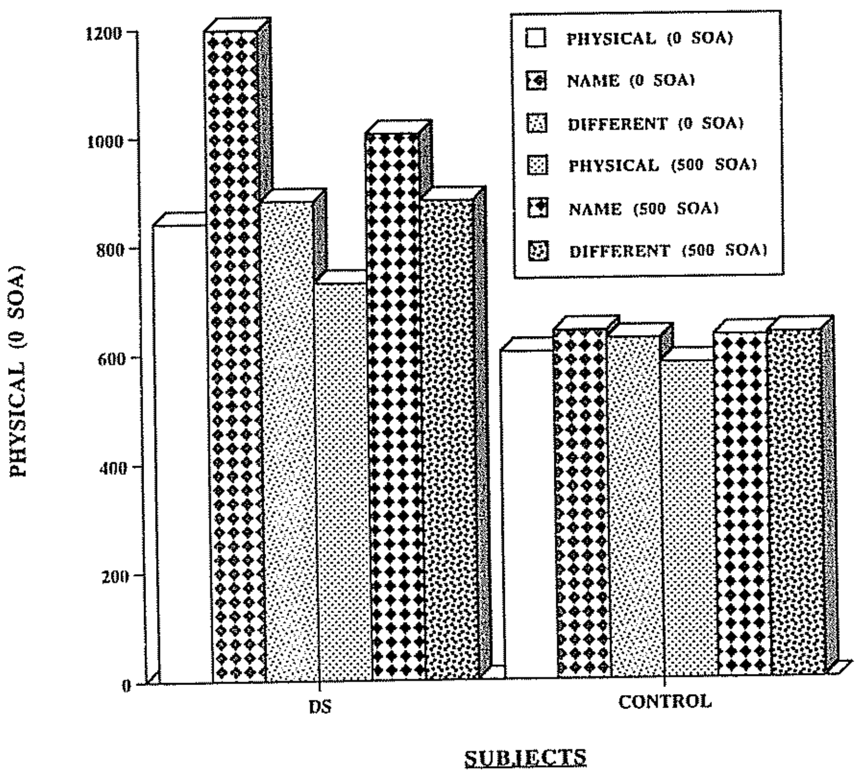

FIG. 3. Mean RT for DS and control subject to make same/different decisions for physical, name, and different trials in simultaneous and sequential conditions.

control subjects described in Reuter-Lorenz and Brunn (1990). The most interesting finding for DS is the presence of the predicted interaction between condition and SOA [$F(2, 2) = 5.2$, $P < 0.05$]. Main effects of condition [$F(1, 2) = 3.15$, $P > 0.05$] and of SOA [$F(1, 2) = 2.12$, $P > 0.05$] were also significant. Post-hoc testing (Tukey with $P < 0.05$) of the interaction reveals a significant difference only on the name match condition, with faster RTs in the sequential (1011.7msec) than in the simultaneous condition (1198.2msec) [$F(2, 2) = 11.5$, $P < 0.0001$]. There was a significant advantage in decision time for physical relative to name matches; 371 and 272msec in the simultaneous and sequential condition respectively. In addition, physical matches were carried out significantly faster than different matches in the sequential condition only.

Discussion

The most interesting result from this experiment is the disproportionate benefit of sequential over simultaneous presentation for the name match condition for DS. These findings suggest that although DS may be able to make reasonably fast judgements about the physical description of the letters, even under simultaneous presentation, she requires additional time in the range of 500msec for processing the abstract (name) identity of a single letter. This time estimate is approximately what was predicted from the previous RSVP experiment where, even at a 400msec interval, performance on the two letters had improved but had not yet reached ceiling.

DS's pattern of performance on this task is different from that obtained with both PD (Kay & Hanley, 1991) and WL (Reuter-Lorenz & Brunn, 1990), and the way in which those differences arise is informative. Whereas PD also shows an interaction between condition and SOA, WL only does so under somewhat different experimental conditions. WL performed the task in two different ways: (1) with blocked instructions (only physical but not name matches were "same" in some blocks) and (2) with mixed instructions, as used here and by Kay and Hanley (1991). WL does show an interaction between SOA and matching condition but only under blocked instructions (not surprising, given that only physical but not name matches require "yes" responses). Under these conditions, the RT for name matches over and above that of physical matches was 558 and 448msec for simultaneous and sequential presentation. WL does not, however, show the relative advantage for sequential (299msec) over simultaneous (290msec) presentation on name matches relative to physical matches on mixed instructions, as is the case for DS. That physical matches are performed faster than name matches led Reuter-Lorenz and Brunn (1990) to conclude that WL was poor at making abstract letter name matches and that this inability to form abstract representation of multiple characters rapidly was the basis of his reading deficit.

Although PD (Kay & Hanley, 1991) also showed a condition by SOA interaction, the form of the interaction is also different from that of DS. DS shows a cost in RT both in sequential and simultaneous trials for name matching relative to physical matching, but this cost is exaggerated in the simultaneous trials. In contrast, the cost for name matching over physical matching for PD was only evident on simultaneous but *not* on sequential trials; on sequential trials, name and physical match RTs were not significantly different. PD's major deficit, therefore, arises only on simultaneous presentation where more than a single stimulus must be processed. These findings led Kay and Hanley (1991) to conclude that the deficit underlying PD's reading problem is one of an inability to process two items simultaneously.

It is clear that PD has a major deficit in simultaneous processing; she may also have a basic deficit in processing even a single letter. Evidence for this is that PD's sequential name match, although better than the simultaneous name match, is still far slower than that of the control subject (in the order of 60msec, see Kay & Hanley, 1991, Fig. 5, p. 267). Because the data analysis is done separately for PD and the control subject, we do not know whether the observed difference is statistically significant. This observation, together with the finding that PD occasionally misidentifies letters presented singly or in words, suggests that she may have a letter-processing deficit as well as a deficit in simultaneous processing.

Evidence for a letter-processing deficit in DS is quite clear—she is impaired in physical as well as name matches relative to the control subject, even under sequential conditions where only a single stimulus is present at any one time. An explanation of impaired simultaneous letter processing, therefore, cannot account for DS's performance; instead, the findings suggest that for her, letter activation is either slowed or reduced relative to normal processing. In the next experiment, we attempt to obtain estimates of the time DS requires to process multiple letters in parallel when they are all presented simultaneously.

Experiment 8: String Matching

In the previous experiment, we found that when the time to process a single letter was adequate, DS was able to derive the name or identity of the stimulus accurately. Under short SOAs, however, she required considerably longer than normal to decide the identity of a letter. This task, however, requires at most (in the simultaneous condition) that DS consider two letters at a time. One might expect that, even when the stimulus appears for an unlimited exposure duration, as the number of letters displayed increases, DS would experience greater difficulty in letter processing. To obtain estimates of the time needed by DS for processing single letters in words, we examined her ability to make same/different judgements on pairs of letter strings presented simultaneously and varying in length. The procedure followed that of Friedrich, Walker, and Posner (1985) and that used by Kay and Hanley (1991) to examine the left-to-right processing of their patient, PD.

Materials

A list of 72 pairs of letter strings was drawn up, half of which were words and half random letter strings with an equal number of trials of 4-, 5-, and 6-letter pairs. Half the pairs were identical strings (e.g. book-book or bkoo-bkoo) and half were different. The different trials consisted of 12 pairs at each of the 3 lengths, where the 2 items of each pair differed by a single letter. The point of difference for words was equally divided into the beginning (e.g. book-cook), middle (e.g. care-cane), or end (e.g. meal-meat) of the string. The middle of the 4-letter word was in position 2 or 3 and the middle of the 6-letter word was in position 3 or 4. The different random strings were constructed by scrambling the letters of the words and maintaining the point of difference; for example, the 4-letter same pair "book-cook" became "bkoo-ckoo."

Procedure

A central fixation point, which remained on the screen for 50msec was followed by a delay of 1000msec. Thereafter, the pair of letter strings appeared to the left of fixation, one immediately above the other, with the final letter appearing two character spaces from fixation. The strings remained on the screen until a response was made. DS indicated her choice, using her right hand, pushing one key for "same" and a second key for "different" responses; RT and accuracy were recorded. The identical procedure was used with RS, the control subject. The data were analysed separately for DS and RS. The critical variables of interest are whether string length affects RT and whether the position of the point of difference in the string affects decision time.

Results

The mean reaction times for RS and for DS to produce "same" and "different" responses as a function of string length and string type are shown in Figs. 4a and 4b respectively. An ANOVA with string type (word/nonword), decision (same/different) and string length (4/5/6) was performed for DS and the control subject separately. As can be seen from Fig. 4a, RS made "same" judgements faster than "different" judgements [$F(1, 1) = 8.82$, $P < 0.005$] and was slower as word length increased [$F(1, 2) = 3.8$, $P < 0.05$]. Although performance did not vary for words and nonwords [$F(1, 2) = 2.3$, $P > 0.10$], there is a trend towards an inter-

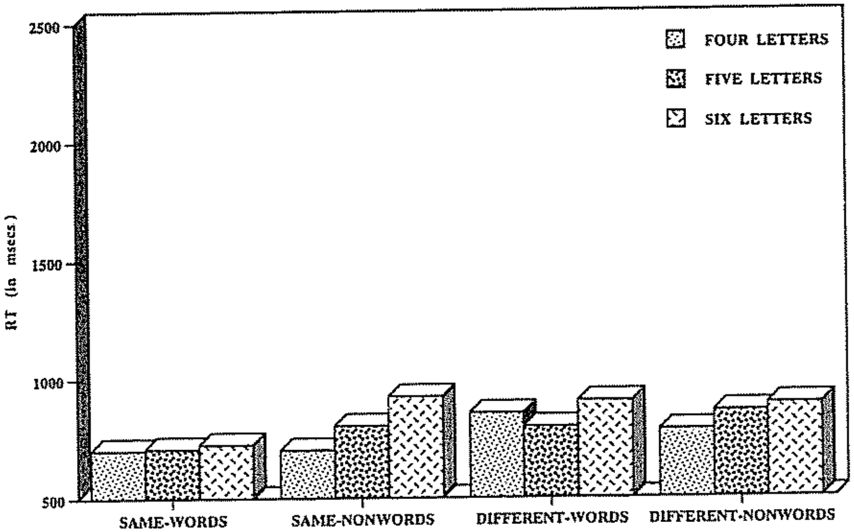

FIG. 4a. RTs for RS on string matching for "same" and "different" strings as a function of string length and string type.

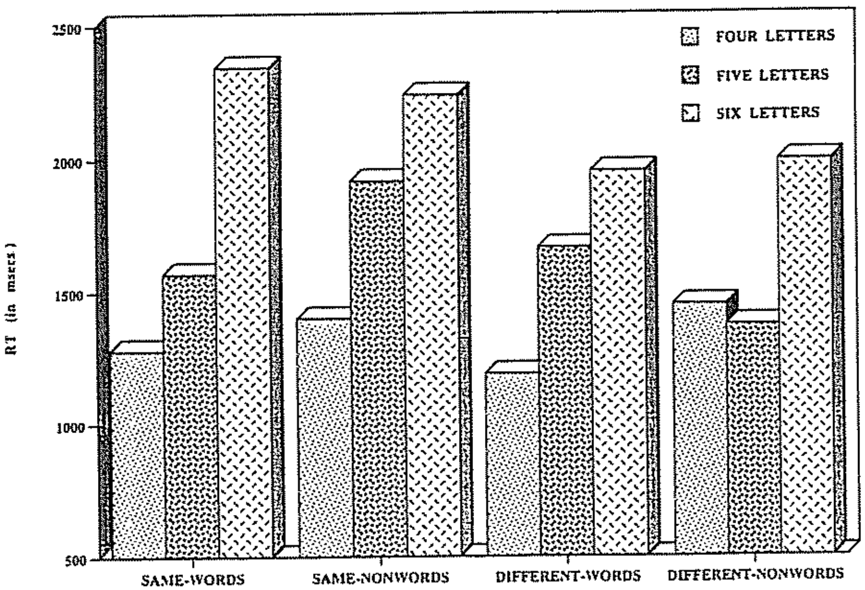

FIG. 4b. RTs for DS on string matching for "same" and "different" strings as a function of string length and string type.

action between length and string type [$F(1, 2) = 3.0$, $P = 0.08$], with a greater length effect for nonwords than for words. No other main effects nor higher-order interactions were significant. These findings mirror those of the original normal subjects tested by Friedrich et al. (1985) and by Kay and Hanley (1991). Like RS, for DS there was a significant effect of word length [$F(1, 2) = 19.25$, $P < 0.0001$] but not string type [$F(1, 2) = 0.27$, $P > 0.5$] on RT. The finding that matching on words and nonwords did not differ seems, on the surface, to be inconsistent with the result from Experiment 5 of a word superiority effect. The absence of this effect here may be attributed to the task differences: Letter matching was required in the present task, and so DS could focus on the elements rather than on the whole word. Experiment 5 was designed specifically so that the entire word could be spanned, increasing the probability of a word superiority effect. There was no difference between "same" and "different" decisions [$F(1, 2) = 3.10$, $P > 0.05$] and no interactions between any variables were significant. The major result here is that RT is affected by the length of the letter string in both RS and DS.

Figures 5a and 5b show the RTs to detect the difference as a function of string length and position of difference (beginning, middle, and end) for RS and DS respectively. A three-way ANOVA with string type (word/nonword), length, and position of difference shows no main effects for RS: string type [$F(1, 2) = 0.15$, $P > 0.5$]; position of difference [$F(2, 2) = 2.51$, $P > 0.05$]; string length [$F(2, 2) = 1.05$, $P > 0.10$]; nor does it show joint effects of any of these variables on RTs. For DS, however, the interaction between length and position [$F(2, 4) = 3.4$, $P < 0.05$] and the individual main effects of length [$F(2, 2) = 10.98$, $P < 0.0001$] and position [$F(2, 2) = 19.98$, $P < 0.0001$] are significant but string type is not [$F(1, 2) = 0.01$, $P > 0.5$]. Planned post-hoc tests (Tukey at 0.05, corrected for multiple comparisons) of length and difference position (collapsed across word and nonword) reveal a significant difference between RTs to detect the difference at the end relative to the beginning for all string lengths. On four-letter strings alone, RTs to the beginning and middle positions were not significantly different, nor were decision times for the middle and end positions. On the five-letters strings, all three positions differed from each other, and on six-letter strings, the beginning and middle, but not middle and end, positions were significantly different. Overall, these findings support the hypothesis that, for DS and for RS, as strings increase in length, so does time to detect the difference. Furthermore, as the position moves from beginning to middle to end, so it takes longer for DS but not for RS to detect the difference.

Although both DS and RS show an effect of string length on performance, the magnitude of the effect differs markedly between them. The time it takes to scan the letters of a pair may be estimated by comparing RTs

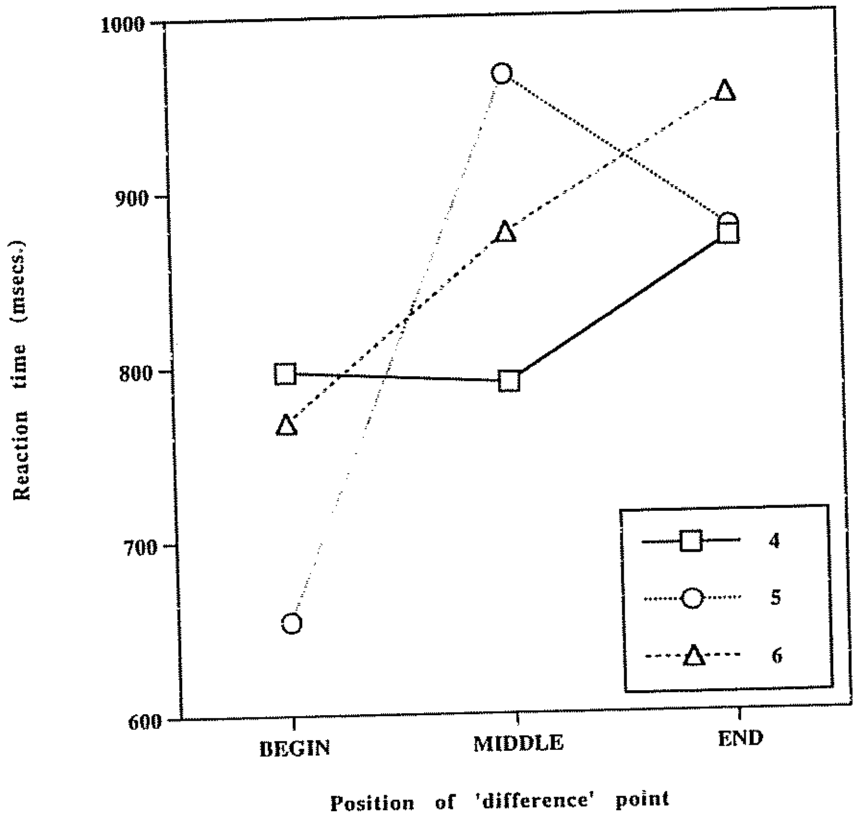

FIG. 5a. RTs for RS to detect a letter of difference as a function of string length and position of difference.

when the difference arises at the end of a four- and at the end of a six-letter string. Length effects (on different trials: end letter of length 6 − end letter of length 4, divided by 2, where 2 is the difference between 4 and 6 letters) of 336msec and 41msec per additional letter were obtained for DS and RS respectively. Interestingly, both DS and RS also take longer to make the "different" judgement on the beginning letter of the pairs of different length where it might be sufficient to focus only on the first letter. Subtracting the RT for "different" 4-letter strings from that of 6-letter strings (beginning letter of 6 − beginning letter of 4), the difference is 71msec and 240msec for RS and DS respectively. That there is a difference even for the initial pairs of letters suggests that some processing may be taking place beyond the initial letter. A final estimate of the serial processing time may be obtained from taking the absolute RT difference between 4- and

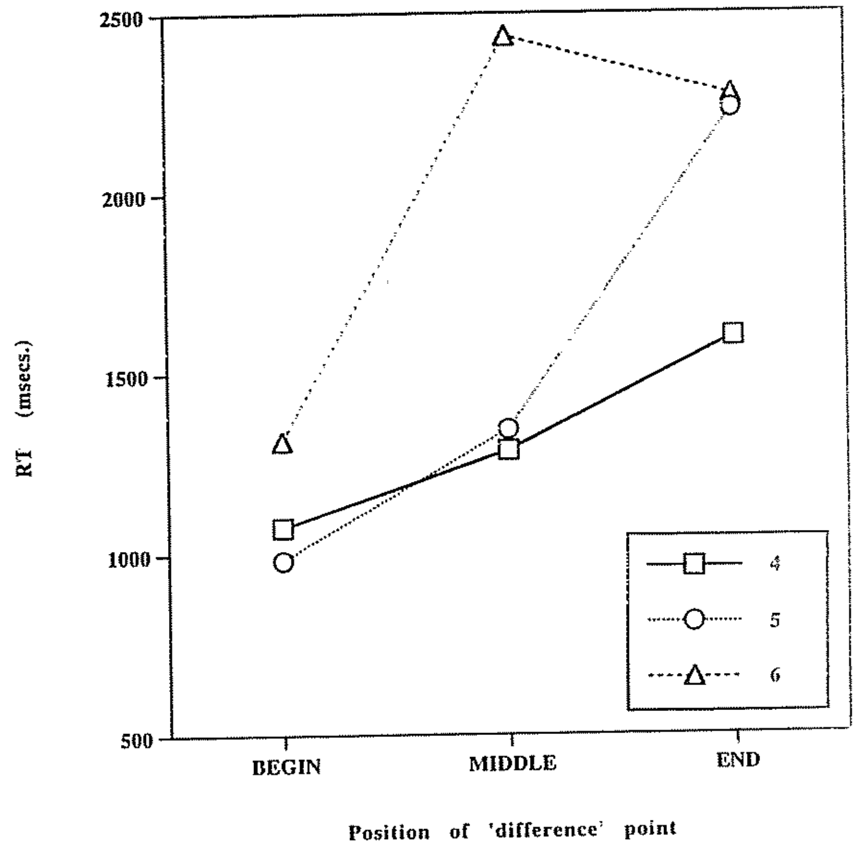

FIG. 5b. RTs for DS to detect a letter of difference as a function of string length and position of difference.

6-letter strings on "same" trials (collapsed across string type as this variable is not significant). DS takes an extra 945.4msec (477 per additional letter) whereas RS takes 62msec (31 per additional letter).

Discussion

The most important result from this experiment is that DS takes significantly longer than normal to make decisions about letters in strings as string length increases. Moreover, decision time is slowed as a function of where in the string the point of difference arises. As the difference moves towards the end position, so RT is slowed incrementally. The calculation of the increase in processing additional letters, estimated from "same" and "different" trials, is somewhere between 350–500msec of additional processing time for DS.

PD (Kay & Hanley, 1991) shows an almost identical pattern of results to those of DS on this task, with no word superiority effect and only significant effects of string length and position. DS is considerably faster than PD both in base reaction times and in the increase required per additional letter; whereas DS required 477msec (difference on RTs for "same" 4 and 6-letter pairs), PD needs in the order of 600msec for each additional letter (see Kay & Hanley, 1991, Fig. 3, p. 261). Like Kay and Hanley (1991), we take the increment in processing for each additional letter with better performance on the left than the right to mean that DS processes letter strings in a serial left-to-right fashion. Not all letter-by-letter readers process letters in this strictly sequential fashion. Bub, Black, and Howell (1989) and Reuter-Lorenz and Brunn (1990) have shown that their letter-by-letter readers process a string "ends-in," with extreme left and right letters processed faster or more accurately than internal letters. The differences between subjects could arise from strategic differences in how they control scanning or it could be explained in terms of a degree of parallel processing in the subjects which, while reduced by comparison with normal subjects, is still sufficient to produce some rapid detection of differences at end positions.

Summary of Serial Effects

The results of Experiments 6–8 provide converging evidence supporting the hypothesis that DS has an impairment in letter processing with slowing or reduction in the activation of single letters[2]. The critical result is that even when a single letter appears in isolation without surrounding letters (RSVP and sequential presentation with 500msec SOA), DS performs more poorly than the normal control subject. Estimates of the additional time required by DS comes from the RSVP experiment, where performance is not yet at ceiling at 400msec SOA. In the simultaneous/sequential matching task, at 500msec SOA, performance is significantly better than at 0msec, but letter matching (particularly name matching) is still slow relative to normal times. Finally, when several letters appear concurrently for same/different judgement, DS requires somewhere between 350–500msec additional time to process each letter pair. These results support the view that single letter processing is slowed and that strings are processed in a strictly sequential left-to-right fashion.

[2]We attempted to obtain further evidence for this hypothesis using an alphabetic decision task similar to that of Jacobs and Grainger (1991) and Arguin and Bub (1993). The subject indicates whether a target is a letter or a non-letter keyboard character, e.g. "@" or "$," through a key press and RT is measured. Prior to the target, a prime appears. The prime may be physically identical (e.g. C C), perceptually similar (e.g. G C), dissimilar (e.g. T C) or unrelated (e.g. • C) to the target. The prediction in the case of DS is that if she has an impairment in single letter activation, she should show weak or possibly no effect of priming. Whereas our control subjects, like those of Jacobs and Grainger (1991), show strong facilitation for identical as well as weaker facilitation for similar and dissimilar trials relative to unrelated, DS's results could not be easily interpreted.

WORD PROCESSING

How does the slowed letter activation relate to DS's ability to read words? The sequential processing pattern obtained with strings of letters would fit naturally with accounts in which the increase in reading latency with word length arises from a sequential letter identification process (e.g. Warrington & Shallice, 1980). However, it is also compatible with the proposal of Howard (1991), that when words are not read correctly by the impaired parallel processing procedure, the reading strategy is changed to one involving sequential letter processing. In this section, we first characterise DS's word reading and then we evaluate whether letters are read primarily sequentially or by an impaired parallel procedure.

Experiment 9: Naming Latency

Materials and Procedure

A total of 120 words, 40 each of 3, 5, and 7 letters in length, were presented individually in lower case, mixed within a block and in randomised order. Half the stimuli were abstract and half were concrete. Half the items were low frequency (less than 20 per million, $M = 6.5$, SD 5.2; Francis & Kuçera, 1982) and half were high frequency (more than 19 per million, $M = 87$, SD 79). A month later, 60 of the same words were re-presented to DS, but this time they were presented in a typeface which was more script-like or cursive (Los Angeles 24) than the standard typeface (Geneva 24) originally used. Each word remained on the screen for an unlimited exposure duration until a response was made and reaction time (RT) and accuracy were measured.

Results

DS made two errors on print reading, both on 3-letter words, and no errors on script reading, yielding an overall accuracy score of 99%. Mean naming latencies for the correct responses for both print and script, plotted as a function of word length, are shown in Fig. 6.

DS showed the typical monotonic relationship between word length and RT for words in both fonts. A four-way ANOVA with font (print, script), concreteness (abstract, concrete), frequency (high, low) and word length

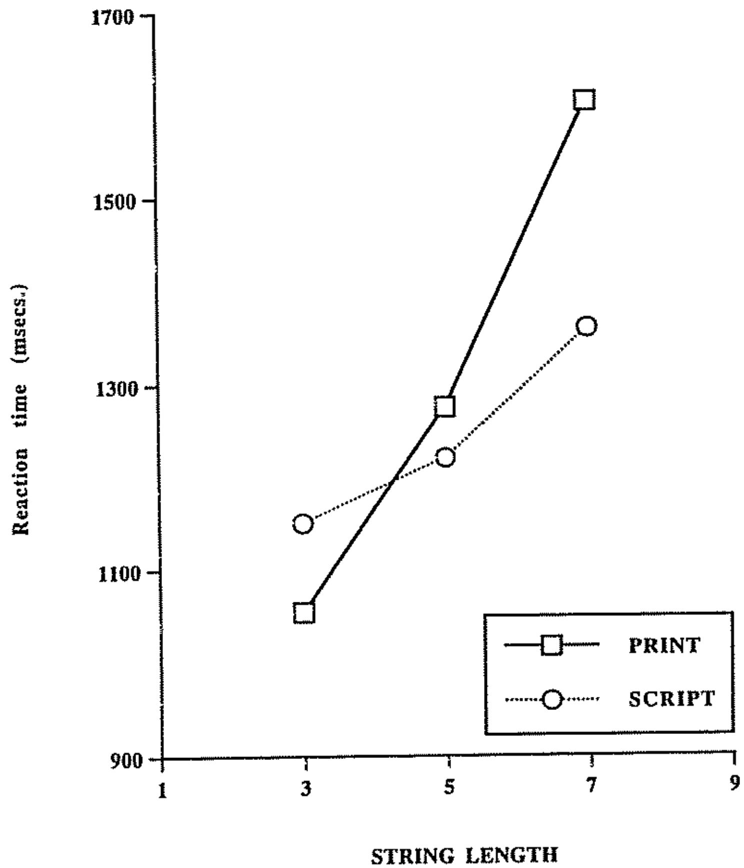

FIG. 6. DS's response latencies (msec) for reading aloud print and script words as a function of string length.

(3, 5, and 7) as within-subject factors showed a significant effect of word length [$F(2, 3) = 16.52, P < 0.001$] and frequency with faster RTs for high ($M = 1209$msec) than for low frequency words ($M = 1306$msec) [$F(1, 2) = 5.52, P < 0.001$]. There were no other significant main effects nor interactions. The mean RTs for 3-, 5-, and 7-letter words (collapsed across print and script) were 1078, 1259, and 1510msec respectively.

A surprising result is the absence of a difference between RTs for words presented in print and in script, since most previous studies of letter-by-letter reading have obtained a drop in performance from print to script (Hanley & Kay, 1992; Shallice & Saffran, 1986; Warrington & Shallice, 1980). The absence of a font effect may be attributable to the fact that the script typeface was not sufficiently difficult and taxing for DS, who is a relatively mild letter-by-letter reader.

Experiment 10: Lexical Decision

Materials and Procedure

The same 120 words (print only) used for naming latency were presented to DS for lexical decision together with 120 nonwords formed by changing a single letter in the 3- and 5-letter words (e.g. APE-AFE, BRIBE-BLIBE) and 2 letters in the 7-letter words (e.g. BALLOON-BAFLOAN). DS was instructed to use the middle and index fingers of her dominant hand to press the "." key for "yes" and the ":" key for "no" responses. The strings remained on the screen for an unlimited duration until a response key was depressed.

Results

DS's accuracy in lexical decision was 93%, with an equal number of errors occurring across each string length. Mean RTs for both "yes" and "no" responses as a function of string length are shown in Fig. 7.

The results of an analysis of variance with string type (word/nonword) and length (3, 5, 7) revealed significantly faster decision times for words than for nonwords [$F(1, 8) = 9.7, P < 0.01$] as well as a significant effect of string length [$F(2, 8) = 6.7, P < 0.05$], but no interaction between them ($P > 0.05$). The means for 3-, 5-, and 7-letter word decisions ("yes") were 1048, 1358, and 1522msec respectively.

Summary of DS's Word Reading Behaviour

The results of the naming latency and lexical decision tasks demonstrate a monotonic increase in response time as a function of increasing string length. Unlike some other letter-by-letter readers, DS does not show access to semantic information for words presented too briefly for explicit report[3]. She is a relatively mild letter-by-letter reader, taking an average of 1078msec to respond to a 3-letter word in naming (see Shallice, 1988, Table 4.1, for times for other patients). A regression line plotted with DS's naming RT against word length reveals a linear fit with an intercept of 742msecs and a slope of 108msec for each individual letter in the stimulus. Although DS is a mild letter-by-letter reader, the slope of 108msec

[3]There are now several reports of letter-by-letter readers who have demonstrated access to semantic information for words they were unable to report explicitly (Bub & Arguin, in press; Coslett, Saffran, Greenbaum, & Schwartz, 1993; Coslett & Saffran, 1989; Shallice & Saffran, 1986). A list of 100 words, 4–6 letters in length, half of which referred to body parts (e.g. ELBOW, SHIN) and half to food (e.g. PEPSI, FISH) were presented in DS's left visual field at 500msec, an exposure duration too brief for her to identify all the constituent letters. DS was instructed not to try and read the word (see Coslett et al., 1993) but to perform a binary semantic classification without identifying the letters. DS read correctly 55 of the 100 words. Of the remaining 45, she categorised correctly only 24 (53%), a result not significantly different from chance.

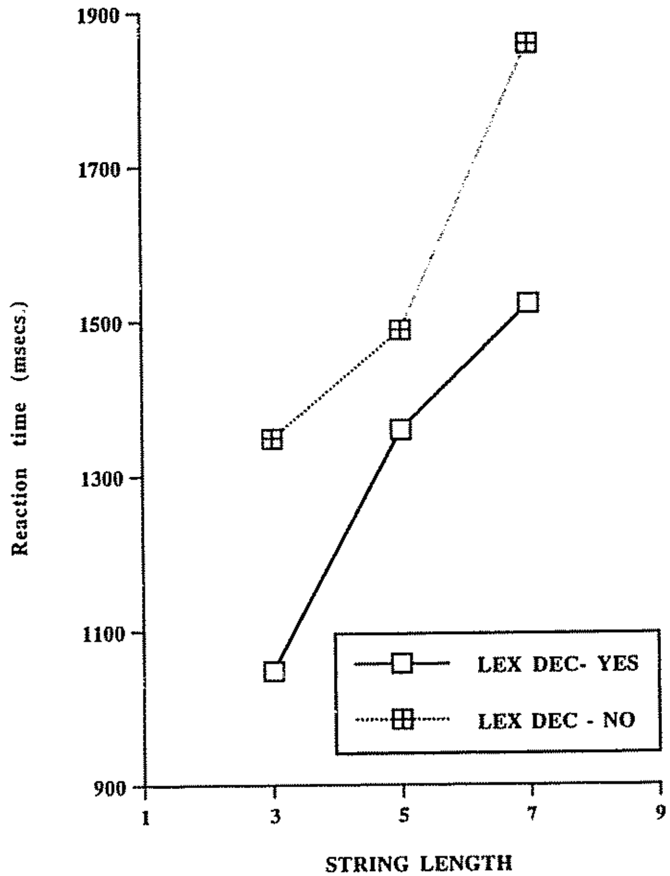

FIG. 7. DS's response latencies (msec) for both "yes" and "no" responses in lexical decision as a function of string length.

contrasts with the finding that normal subjects typically show a maximum increase (if any at all) of 28–30msec in RT for each additional letter in the string even when presented to the left visual field (Young & Ellis, 1985; see also Henderson, 1982). The difference between DS and normal readers is perhaps even more dramatic in lexical decision, where normal readers typically do not show any effect of word length (Frederiksen & Kroll, 1976; Koriat & Norman, 1984). On a linear regression analysis with lexical decision RT and word length, DS's "yes" responses revealed an intercept of 717 and a slope of 119msec for each additional letter. DS's pattern fits the typical profile of letter-by-letter reading, with marked effects of word length on reading RT. This profile has generally been used to support a sequential processing view of word reading in these patients.

The distribution of naming times has been used by Howard (1991) as a test of an alternative perspective that challenges the sequential view. In particular, he argued that the impaired parallel processing model would predict that when the log probability of a correct response is plotted against word length, there should be a linear relationship passing through the origin. On this independent but parallel letter processing account, the log probability of the subject making a "fast" response should decline linearly from the origin as word length increases, with the gradient representing the probability that an individual letter is misidentified. To test whether this function captures DS's fast reading times, we used Howard's test of impaired parallel processing to examine the distribution of RTs in DS's data.

What counts as a "fast" response is not theoretically defined by Howard (1991), but for patients who respond more quickly than his, the operational definition he used seems appropriate. To delineate the fast reading responses in DS's performance, a cut-off equal to twice the fastest RT was employed (following Howard, 1991) and the proportion of correct naming responses with a RT faster than this cut-off was calculated for each word length. Because the type of font did not affect DS's reading times, the response times for print and script were pooled, and a cut-off of 1.35sec was used to separate fast from slow responses. Figure 8 shows the relation between log probability of a fast response and word length for DS. The expected function according to Howard's impaired parallel account (1991) is also plotted for comparison.

It is clear from these results that DS's responses are approximately linear with log probability over the 3–7 letter range, but that the best fitting line for her data does not intercept the y-axis at the origin as predicted by Howard (1991). Moreover, if one extrapolates from DS's performance on 3-letter words to values expected on Howard's account for lengths 5 and 7, the extrapolated values of 78% and 71% fast responses are significantly different from the obtained values of 63% and 40% respectively (5 letters $\chi^2_{(1)} = 7.9$, $P < 0.01$; 7 letters $\chi^2_{(1)} = 27.2$, $P < 0.001$). Indeed, as log probability cannot exceed 0, the observed function must actually be concave downwards. The results of DS's naming times, therefore, do not support the impaired independent parallel processing account of Howard (1991), and favour a view of serial processing.

As Howard (1991) assumes that fast responses occur if and only if all the individual letters are correctly processed independently, one would expect that the proportion of fast responses would not be affected by word frequency. Table 6 displays the median frequencies of fast and slow responses as a function of word length for DS. A significant difference in frequency between fast and slow responses was observed for each word length (Mann-Whitney U test: 3 letters 405.5, $P < 0.001$; 5 letters 584.5, $P < 0.001$; 7 letters 598, $P < 0.01$).

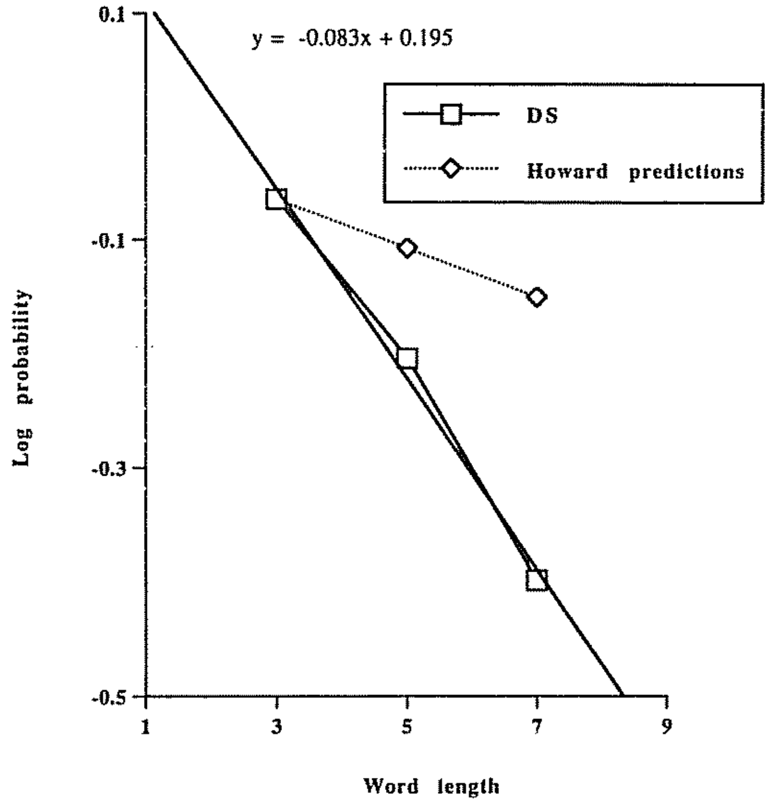

FIG. 8. The relation between the log probability of DS's fast reading responses as a function of word length collapsed across print and script. The dotted line shows the expected function according to Howard's (1991) independent parallel processing theory. Also shown is the best fitting straight line, which clearly does not pass through the origin.

TABLE 6
Median Frequencies and Number of Items (in Parentheses) for DS's Fast and Slow Reading Responses as a Function of Word Length

	Word Length (Number of Letters)		
	3	*5*	*7*
Fast	51.5	49.8	74.4
	(50)	(45)	(32)
Slow	28.1	35.6	27.9
	(9)	(14)	(28)

The finding that frequency plays a significant role in determining which responses are "fast" provides further data to conflict with Howard's version of the impaired parallel letter processing hypothesis. The concave downward function of DS's fast responses as a function of word length is, however, compatible with a number of possible alternative explanations. For instance, a serial processing model may explain these data if the time for processing individual letters has a distribution that is strongly skewed and if frequency-related guessing is assumed. As they stand, however, these results also do not rule out more complex hypotheses related to Howard's results (1991), in which a mixture of parallel and serial processing may be operating.

GENERAL DISCUSSION

Many alternative interpretations have been presented for the letter-by-letter reading characteristically observed in pure alexia. In a few cases, empirically supported arguments have been presented that specific patients who read in this manner have different underlying functional deficits (e.g. Price & Humphreys, 1992; Vigliocco et al., 1992). However, in general, single-case accounts of the behavioural pattern have restricted themselves to discussing a particular patient and, in the absence of a well-developed theory, the number of interpretations of the disorder can increase without constraint. An alternative heuristic, which is implicitly adopted by a number of people working on letter-by-letter reading, is to presuppose that most of the patients exhibiting the behaviour have a common underlying deficit or one of a small number of such deficits. Behavioural differences between these patients are then explained as manifestations of different strategic adaptations to the primary condition (see Coslett & Saffran, 1989; Coslett et al., 1993, for a strong version of this position). We will adopt this position as a starting premise, as this allows alternative interpretations to be treated as compatible with a unitary explanation rather than as accounts of a variety of qualitatively different conditions. Moreover, this allows us to extract common principles that might underlie pure alexia even in the face of obviously different overt patterns of performance.

In order to examine the nature of the mechanism underlying the word length effects in pure alexia, we have taken as our case DS, who shows the hallmark feature of letter-by-letter reading following a left occipital lobe lesion. She shows relatively preserved single word identification and the characteristic monotonic relationship between reaction time and increasing word length in reading (Experiments 9 and 10). Unlike some pure alexic patients (Coslett et al., 1993), DS does not have access to semantics for words she cannot identify. In a series of experiments (Experiments 2–5 and Experiments 6–8), we initially examined two current hypotheses, both of which have been put forward to explain the underlying deficit in patients with this pattern of behaviour. On the spatial hypothesis, the increase in RT with word length arises because of a deficit in the distribution of attention to multiple spatial locations in parallel. According to Rapp and Caramazza (1991), the decreasing left-to-right spatial gradient requires that the patient attend serially to each letter in order to increase letter discriminability and the signal-to-noise ratio. On the letter activation account, the deficit arises in the processing of single letters, independent of spatial location. There are several variants of this letter activation hypothesis outlined later, after the discussion of the empirical data. It is important to note that the orthographic or letter activation hypothesis is perfectly consistent with views proposing that letter-by-letter reading arises from a basic impairment in perceptual processing (Farah, 1992; Farah & Wallace, 1991; Friedman & Alexander, 1984; Kinsbourne & Warrington, 1962a; Sekuler & Behrmann, in preparation). In this paper, however, we have restricted our focus to the orthographic deficit per se in order to study letter processing and its effects on word processing in these patients.

In Experiments 2–5, we show that DS is able to distribute her attention in parallel to a number of different locations for feature detection and for letter report when letters appear both in the context of words and of random letter strings. In addition, letter report is unaffected by the absolute or relative spatial location of the target letter. Arguin and Bub (1993) reached a similar conclusion, showing that, like DS, their pure alexic patient DM could detect the presence of a target equally well independent of the number of items in the display. These findings of flat RT functions with increasing number of distractors challenge the spatial gradient view suggested by Rapp and Caramazza (1991) as a satisfactory explanation of the pattern of letter-by-letter reading. We also show that DS's performance is markedly different from that of a patient with a documented spatial deficit (hemispatial neglect). The most striking results from this set of experiments are that, for DS, report of the second letter, although significantly worse than that of the first letter, is unaffected by the variation in its own spatial location. This set of findings rules out a deficit in the distribution of resources across a spatial array as the mechanism giving rise to DS's serial reading pattern.

The alternative hypothesis of an impairment in on-line letter processing as the underlying functional deficit in pure alexia is investigated in Experiments 6–8. The results support the view that DS is impaired at processing the identity of a single letter relative to the control subject even when the letter appears in isolation. The slowed letter processing affects the report of the second letter in the RSVP task (Experiment 6), gives rise to the slower decisions on name matching even under conditions of relatively long SOA (Experiment 7), and manifests as poorer detection of differences between letter strings as a function of string length and of position of the "different" target on the string matching task (Experiment 8).

An impairment in on-line letter activation may itself arise from a number of different sources. Kay and Hanley (1991), for example, propose that the deficit comes about because of an inability to deal with more than a single letter at a time (see also Kinsbourne & Warrington, 1962a), whereas Price and Humphreys (1992) propose that the deficit comes about because of an inability to switch attention between two items displayed simultaneously. Evidence from DS's behaviour suggests that the problem is at an even more basic stage of processing and is related to the identification of the letters rather than to a process that controls or switches between them. First, DS is able to switch attention flexibly and efficiently, as seen in her ability to report letters from extremes of letter strings irrespective of the length of the string (Experiments 4 and 5). Second, even when a single letter appears in isolation, DS is impaired in letter identification relative to the control subject. Converging evidence from several experiments indicates that the problem is in activating letter identities or letter forms rapidly and efficiently. Estimates of the additional processing time needed for letter activation, obtained over a number of different tasks, is in the order of 350–500msec. An obvious implication of this view is that, if activation is slowed, when more time is available for letter processing, performance should improve. Improved letter matching under sequential presentation and improved letter report in the RSVP experiment with longer intervals between letters support this view.

The findings from the experiments suggest that the primary deficit for DS is not a spatial one and we have argued that the deficit appears to be one of slow or reduced letter activation. This view has been proposed by others to explain the deficits in their patients. Reuter-Lorenz and Brunn (1990) and Bub et al. (1989) have claimed that a deficit in letter identification is causally related to pure alexia. Letter processing itself, however, has a number of component processes, each of which might be damaged selectively following a lesion. For example, perceptual processing of letter features is required, followed by some form of featural integration. Once this is achieved, activation of the letter form or structural description is necessary (McClelland & Rumelhart, 1981). One specific account of the letter processing deficit has been provided by Arguin and Bub (1993) who have suggested that the deficit in their patient, DM, arises from the process of selection of the target form. Simulations using only the letter features and letter forms of the Interactive Activation Model (McClelland & Rumelhart, 1981) provide computational support for this account. When the weights from features to letters are modified by reducing the inhibition and increasing the activation relative to the "normal" network, time to reach threshold for similar letters is markedly increased relative to identical and dissimilar letters.

Although there is accumulating evidence for a fundamental deficit in on-line letter processing in pure alexia, the outstanding question concerns the direct implications of such a deficit for oral reading. Whereas some authors argue that letter processing and word processing can be independent (Warrington & Shallice, 1980), others have suggested that the letter processing problem is causally related to the observed reading deficit (Howard, 1991). Evidence for a causal connection between the two comes from the finding that reading speed and accuracy seem to depend on the accuracy of identifying single letters (Shallice, 1988). This relationship is also seen for DS—the time course of letter processing for DS in the RSVP task, where only single letters appear, is remarkably similar to that observed in the string matching task where letter strings appear. Furthermore, the accuracy of both DS's letter processing and her word reading speed, although impaired, is reasonably good compared with other letter-by-letter readers (see Howard, 1991; Shallice, 1988, Table 4.1, p. 74 for comparisons).

Aside from overall reaction-time comparisons, however, Howard (1991) has argued that a number of different reading modes may be adopted by different letter-by-letter readers, who may compensate for their deficit by either parallel or sequential processing in word reading. In the case of DS, slowed or weakened activation of single letters during orthographic processing necessarily entails a letter-by-letter strategy with sequential processing from left to right. Furthermore, plots of the probability of correct "fast" responses as a function of word length provide no evidence for an impaired parallel reading process in which individual letters are unreliably but independently identified. The shape of the function is markedly different from that predicted by Howard (1991) for the impaired parallel process and cannot be accommodated by a view of independent (albeit parallel) letter processing (see Fig. 8)[4]. Instead, the findings are consistent with a more hybrid view in which there is non-independence between processing of letters in word identification, but letter activation is weaker or the spatial range of the parallel interaction is less than for normal subjects. The reduced additional letter time in word processing experiments (100–120msec) by comparison with letter processing experiments (350–500msec) support the non-independence claim. The slightly concave downward function of log probability of correct "fast" responses against word length (Fig. 8) supports the reduction in letter activation capacity compared to normal subjects. It is, however, consistent with a model in which the first few letters are processed serially and then guessing takes place or with a model in which lower criteria are used for letter processing in words relative to processing letters that do not appear in words.

As stated previously, the account proposed here of slowed letter processing is also compatible with an account of letter-by-letter reading as a visual perceptual deficit. Indeed, DS has participated in another study in which her perceptual abilities were tested directly (Sekuler & Behrmann, in preparation). On three "perceptual speed" subtests of the Ekstrom, French, and Harman (1976) kit of factor-referenced cognitive tests, shown to be sensitive to the perceptual deficits in letter-by-letter reading (Farah & Wallace, 1991), DS's performance was well below the normal limits on two separate administrations of the tests. For example, on the "Finding 'A's test," DS was able to detect the presence of 'A's in only 19 words in a 2-minute period. On the "Number comparison test," she was able to match only 14 number strings in a 1½-minute period, and selected the target pictogram out of an array of 5 on only 24 trials in a 2-minute period on the "Identical pictures test." These scores are more than 2 SD below average. These results suggest that DS's slowed letter processing may be a direct manifestation of a more general slowing in visuoperceptual functioning.

[4]A serious problem in the analysis provided by Howard (1991) is that the apparent shape of the fast response vs. word length curves is strongly influenced by points where the observed probability (P) of a fast response is close to 0. As P approaches 0, $|\log P|$ increases rapidly so that the estimates provided of the actual probability of a fast response becomes unreliable.

CONCLUSION

DS's letter-by-letter reading is well explained by an impairment at or before letter processing, resulting in a difficulty in parallel on-line access and compensated for by a process of serial identification of single letters. This basic position is similar to that of a number of previous authors (e.g. Arguin & Bub, 1993; Bub et al., 1989; Friedman & Alexander, 1984; Howard, 1991; Reuter-Lorenz & Brunn, 1990; Shallice & Saffran, 1986). The strength of the argument in the present case is twofold. First, when procedures typically used to test letter processing in the past (e.g. tachistoscopic presentation of single letters) are employed with DS, she performs perfectly and yet her letter processing difficulty is manifest under more stringent testing conditions. Secondly, aspects of her performance are superficially suggestive of alternative accounts such as the word-form hypothesis (Warrington & Shallice, 1980), the spatial processing impairment (Rapp & Caramazza, 1991) or the simultaneous form processing impairment or attention-switching hypothesis (Kay & Hanley, 1991; Kinsbourne & Warrington, 1962a; Price & Humphreys, 1992). However, on further investigation, the impaired letter processing hypothesis is the more adequate of the rival explanations for the critical aspects of her performance. Moreover, some phenomena (e.g. RSVP results, Experiment 6) cannot be explained by any of the rival hypotheses.

The one pure alexic patient for whom a good empirical argument has been made that letter processing is intact is Kay and Hanley's (1991) patient PD. They argue that PD's letter-by-letter reading arises from an inability to identify letters in parallel and not from a primary deficit in letter processing, as we are suggesting. The critical result on which they based this conclusion was that of the sequential/simultaneous condition, where PD performed significantly differently on name and physical matching only in the simultaneous condition but not in the sequential condition. The outstanding question, however, is whether name matching on sequential presentation was normal or not. As the analyses were conducted using within-subject procedures rather than between PD and the control subject, this remains an open issue. Moreover, if the critical letter processing were slower than normal but still less than 500msec (the interval duration), the same pattern of data would still be obtained for PD. Some evidence suggesting that PD might indeed have some letter processing problems comes from the misidentification errors he makes on single letters and the finding that he makes about 10% letter misidentification errors in word naming. Indeed, Kay and Hanley (1991, p. 252) suggest, and we agree, that he does have some letter identification problems but "what is clear, (though), is that his reading problems go beyond difficulties in recognising single letters."

We therefore propose that the default explanation for the functional deficit underlying pure alexia should be that of an impairment that results in less efficient letter processing, and alternative accounts for patients should be considered only when that hypothesis has clearly been found to be wanting. Although many letter-by-letter readers undoubtedly have impairments in addition to the prototypical one, we are not aware of any letter-by-letter reader whose letter processing can convincingly be considered normal. Even for those cases in whom individual letter recognition is considered to be accurate (e.g. RAV, Warrington & Shallice, 1980), identification may well be slowed. Only when more stringent assessment of this process is carried out can a definitive conclusion about normal processing be reached.

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