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Visuoperceptual deficits in letter-by-letter reading?

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ABSTRACT

A longstanding and controversial issue concerns the underlying mechanisms that give rise to letter-by-letter (LBL) reading: while some researchers propose a prelexical, perceptual basis for the disorder, others postulate a postlexical, linguistic source for the problem. To examine the nature of the deficit underlying LBL reading, in three experiments, we compare the performance of seven LBL readers, matched control participants and one brain-damaged patient, OL, with no reading impairment. Experiment 1 revealed that the LBL patients were impaired, relative to the controls and to OL, on a same/different matching task using checkerboards of black and white squares. Given that the perceptual impairment extends beyond abnormalities with alphanumeric stimuli, the findings are suggestive of a more general visual processing deficit. This interpretation was confirmed in Experiments 2 (matching words and symbol strings) and 3 (visual search of letter and symbol targets), which compared the processing of linguistic and non-linguistic written stimuli, matched for visual complexity. In both experiments, the LBL patients displayed qualitatively similar effects of length and left-to-right sequential ordering on linguistic and non-linguistic stimuli. Moreover, there was a clear association between the perceptual impairments on these tasks and the slope of the reading latency function for the LBL patients. Taken together, these findings are consistent with a significant visuoperceptual impairment in LBL that adversely affects reading performance as well as performance on other non-reading tasks.

1. Introduction

Letter-by-letter (LBL) reading refers to the disorder in which, following brain damage, premorbidly normal readers read slowly, in an apparently serial left-to-right fashion (Behrmann, Plaut, & Nelson, 1998), with the result that reading latency increases linearly with word length (Patterson & Kay, 1982; Warrington & Shallice, 1980). The pattern of increasing response time with increasing string length is mirrored in the accuracy data—the errors of these patients typically arise towards the end of words, consistent with the laborious and sequential encoding of letter strings. In many but not all cases, LBL reading arises in the context of 'pure alexia', in which the reading impairment occurs in the absence of obvious impairments of writing or spelling (e.g. Dejerine, 1891). LBL (again, primarily in the context of pure alexia) is usually a consequence of left occipitotemporal lobe damage (Binder & Mohr, 1992; Cohen et al., 2003; Damasio & Damasio, 1983) and, in some cases, there may be accompanying lesions in the white matter tracts such as the splenium of the corpus callosum (Dejerine, 1891; Geschwind, 1965).

Despite the many very detailed studies of LBL reading, there remains considerable debate regarding the functional impairment underlying this disorder. Some theories implicate impaired letter processing (Arguin & Bub, 1993; Arguin & Bub, 1994a, 1994b; Bachoud-Levi & Bartolomeo, 2003; Behrmann & Shallice, 1995; Kay & Hanley, 1991; Reuter-Lorenz & Brunn, 1990) which, in turn, may be a consequence of a purely linguistic difficulty or of impaired visuoperceptual processing (Behrmann, Plaut, et al., 1998; Johnson & Rayner, 2007). It is this latter notion, that LBL fundamentally arises from a visual impairment, which is addressed in the current work. However, there are several other hypotheses that have been proposed. On other accounts, LBL arises from faulty access to lexical orthographic forms (Miozzo & Caramazza, 1998; Montant, Nazir, & Poncet, 1998; Patterson & Kay, 1982; Shallice & Saffran, 1986) or the lexical representations themselves may be damaged (Warrington & Shallice, 1980). Some views adopt a 'disconnection' explanation in which, by virtue of the left posterior lesion, visual information (coming from the left visual field) is processed first of all by the right hemisphere and then transferred to phonological representations in the left hemisphere and it is during this transfer that processing is affected (Bowers, Arguin, & Bub, 1996; Bowers, Bub, & Arguin, 1996; Chialant & Caramazza, 1998; Damasio & Damasio, 1983; Dejerine, 1892; Epelbaum et al., 2008; Geschwind, 1965). The right hemisphere hypothesis (Coslett & Saffran, 1989, 1994) is sim-

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ilar to these last 'disconnection' theories, but also accounts for the successful performance of some LBL individuals on implicit tasks by suggesting that this is an emergent property of the intact right hemisphere processing (Shallice & Saffran, 1986).

1.1. The visuoperceptual hypothesis

The present article tests the hypothesis that LBL may fundamentally arise as the result of a prelexical visual processing impairment. Perhaps the first proposal of a general perceptual deficit in LBL was suggested by Farah and Wallace (1991) who demonstrated an interaction of visual quality and word length on the reading performance of a patient who read LBL, and, using additive factors logic[1] (see Sternberg, 1969), argued that the word length effect observed in their patient arose as a result of a visual level impairment. As part of this work, Farah and Wallace (1991) encouraged all researchers to evaluate the perceptual performance of their LBL readers systematically and even proposed that fine-grained testing may uncover perceptual difficulties in all such individuals. Subsequent studies have confirmed this initial finding of a visual deficit. For example, in a relatively large series of LBL patients, Behrmann, Nelson, and Sekuler (1998) reported that their patients were impaired not just in processing alphanumeric stimuli but also in processing pictorial stimuli and that this was true especially as visual complexity of the stimuli increased. Deficits in LBL readers have also been revealed in some perceptual tasks which are unrelated to alphanumeric process in any obvious way (Sekuler & Behrmann, 1996).

There is evidence then, that, at least on some occasions, LBL reading is associated with a more general visual impairment. The difficulty remains in knowing what sort of visual impairment; some studies have documented visual impairments in patients with LBL reading in the speed of visual identification and span (Friedman & Alexander, 1984; Kinsbourne & Warrington, 1962; Starrfelt, Habekost, & Leff, in press) especially when many items appear rapidly (Ingles & Eskes, 2007), in the absence of salient visual cues (Sekuler & Behrmann, 1996), in feature discrimination (Humphreys & Price, 1994), and in the capacity or switching of visual attention (Buxbaum & Coslett, 1996; Price & Humphreys, 1992). In recent work, Arguin, Fiset and colleagues have argued that letter confusability, likely attributable to an underlying visual impairment which disrupts the ability to discriminate between similar letters, is at the root of LBL reading (Fiset, Arguin, Bub, Humphreys, & Riddoch, 2005; Fiset, Gosselin, Blais, & Arguin, 2006). In support of this claim, they showed that the hallmark feature of LBL, the word length effect, is abolished when this source of visual letter confusion is removed, giving rise to the suggestion that it is the confusability of the visual input that is critical in determining LBL reading (Fiset et al., 2005).

The focus of this article is to compare the visual processing skills of a relatively large group of seven LBL readers with those of matched normal subjects and a brain-damaged individual who has no reading impairment. To do so, we compare the performance of these individuals on processing linguistic and non-linguistic stimuli, matched to words for their visual characteristics, and we document the length effects and the reaction times to targets appearing in different parts of the string. One prediction is that a more general visual impairment, if present, might also affect the processing of non-linguistic stimuli. A stronger version of this claim is that the profile of the impairment would be the same on linguistic and non-linguistic stimuli, i.e. we would observe the hallmark characteristics of LBL reading on both stimulus types: notably, reaction times would increase with longer strings, processing would proceed from left to right and performance would be adversely affected as complexity increases. We also evaluate, as far as possible, whether there might be a relationship between the visual impairment that we document and the pattern of LBL reading and we do so by exploring the association between performance on alphanumeric and symbol detection in search tasks and in reading tasks.

1.2. Visual complexity as a factor

To evaluate whether visual processing is affected in LBL readers, it is essential to use stimuli that are visually as complex as words. Although visual complexity is a commonly used term in the literature, opinion remains vague about how best to define and measure it and researchers often rely on subjective ratings of observers (Snodgrass & Vanderwart, 1980). The measurements used in the present article are based on the work of Ichikawa (1985), who used dots in a 4×4 pattern matrix to examine the factors underlying judgements of pattern complexity. He identified a quantitative factor relating to the concentration or the number of clusters of dots and a structural factor that was linked to the symmetry of the display. Although this method was applied to patterns, the conclusions about the factors that are important in defining visual complexity can also be applied to other visual stimuli and we take these factors into account here.

Here, we use checkerboards, words and symbols, designed to resemble letters visually. The visual complexity of the checkerboards is measured by their size (i.e. number of constituent squares) and, as size increases, performance should be increasingly affected. The visual complexity of the letters and symbols is measured by the number of strokes that comprise them and, again, the prediction is that as the number of strokes increase, so should performance degrade. In fact, the number of strokes required to draw a character has already been used with linguistic stimuli in Chinese and Japanese (Buessing, Bruckmann, & Hartje, 1987; Coney, 1998; Hartje, Hannen, & Willmes, 1986). Symmetry is also taken into account by using only asymmetrical checkerboards. Letters and symbols are matched for symmetry.

An effective way of investigating not only whether a visual impairment is present, but also whether it is possibly related to LBL reading, is to compare the processing of linguistic and non-linguistic stimuli matched for visual complexity. Observing similar patterns in processing both stimulus types, although not definitive, would be highly suggestive of a causal link. This is because a visual impairment would be expected to impact in a similar way on the processing of visually similar stimuli, regardless of whether or not they have linguistic associations. Direct comparisons between the processing of linguistic and matched non-linguistic stimuli by LBL readers have not been made before (although there are several comparisons of letter and digit processing), yet they seem to hold a possible key to establishing whether links exist between visual processing and reading. The need to compare linguistic and non-linguistic stimuli that are closely matched requires careful selection of appropriate tasks (clearly, reading cannot be used with non-linguistic stimuli!). Here, we employ two tasks that can be carried out with both words and symbol strings: visual matching (deciding whether two stimuli are same/different) and visual search (searching for a target among distractors) and we compare performance across the two stimulus types.

2. Methods

2.1. Participants

Seven LBL readers, all of whom are native English speakers, participated in the following studies. The first two patients, DK and EL, were tested in the United States and completed only Experiments 1 and 2, while the other five patients, tested in Britain, completed all tasks. The biographical and neuropsychological details of each case are described below in Table 1, followed by word reading evidence confirming

[1] Although Sternberg's additive factor has been quite widely criticised (e.g. McClelland, 1979; Pieters, 1983) it continues to offer a useful framework providing one is aware of its limitations (Sternberg, 1998; Sanders, 1998).

Table 1
Biographic details for the LBL readers and brain-damaged control subject.

Patient	Age[a]	Gender	Occupation	Nature and time of damage	Additional information
DK[b]	69	M	Grocery store clerk	1995; Left posterior cerebral artery	Mild memory loss; right homonymous hemianopia
EL[c]	50	F	Special Education teacher	1996; Left posterior cerebral artery infarct	Right superior quadrantanopia with macular sparing; picture naming affected by visual complexity (Behrmann, Nelson, et al., 1998)
JC	56	M	Member, Fire service	1998; Left occipital and inferior temporal lobe infarction	Right homonymous hemianopia; some anomia; severe reading difficulty; left school aged 16
MC	72	M	Accountant/Auctioneer	1999; Bifrontal haematoma; large left temporo-parietal infarct extending into occipital lobe	10 years education; difficulty with spelling and object naming; acalculic; right homonymous hemianopia
PA	49	F	Factory worker	1999; Left MCA aneurysm; subarachnoid haemorrhage, craniotomy	10 years education; anomia, difficulty writing and spelling
PD[d]	43	M	Metal worker	1982; AVM in posterior thalamus; left thalamic haemorrhage ruptured into ventricle	10 years education; right homonymous hemianopia; right hemiparesis and hemianesthesia. Mild anomia and spelling difficulty
PL	82	F	Seamstress	1999; Left temporal haematoma with midline shift	10 years education; anomia; spells letters out loud during reading
OL	53	M	Construction worker	2004; Right middle cerebral artery infarct	10 years education; No evidence of hemispatial neglect

[a] Age at testing.
[b] DK has participated in previous studies and details are available in Behrmann, Nelson, et al. (1998), Behrmann, Plaut, et al. (1998).
[c] EL has participated in previous studies and details are available in Behrmann, Plaut, et al. (1998), Montant and Behrmann (2001) and McKeeff and Behrmann (2004).
[d] PD has participated in several previous studies (Hanley & Kay, 1992, 1996; Kay & Hanley, 1991).

the diagnosis of LBL reading. All individuals are right-handed, with the exception of JC, have normal or corrected-to normal (20/40) visual acuity, and all provided informed consent. An additional patient, OL, who suffered a focal lesion to right parietal cortex but who has no reading impairment, served as a further control subject; revealing an impairment in the performance of the LBL readers, but not in OL, will indicate that brain damage per se is not responsible for the particular pattern of disorder observed in the LBL readers and that the altered behavioural profile is therefore specific to the LBL patients. Images of the lesion site in two LBL patients, DK and EL, and in the brain-damaged control, OL, are shown in Fig. 1.

2.2. General methodology

All experiments with the LBL readers were carried out on a laptop computer using the DMASTR software (DMDX; K.I. Forster and J.C. Forster). Stimuli were presented following a central fixation point, to the left of centre in order to circumvent the right visual field defect shown by most patients. Each stimulus remained on the screen until response, or until the timeout limit was reached. The brain-damaged control subject, OL, completed the experiments on a Dell laptop running ePrime experimental software.

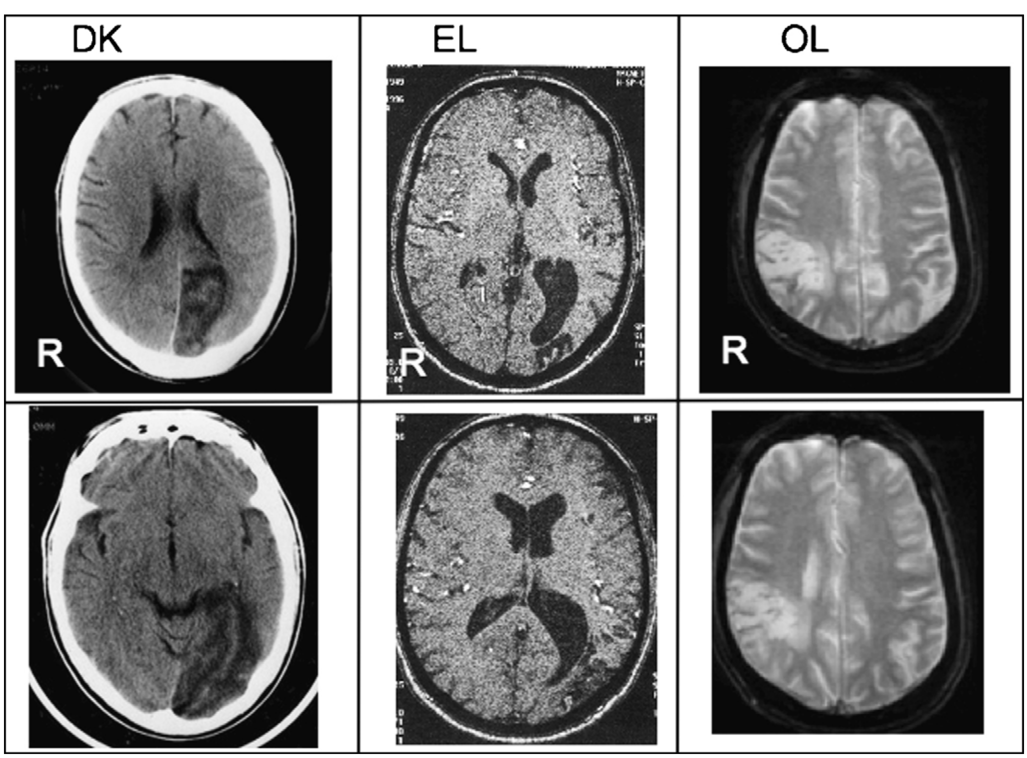

Fig. 1. MRI scan for patients DK, EL and OL revealing the left posterior occipitotemporal lesion in the first two cases and the right parietal lesion in OL.

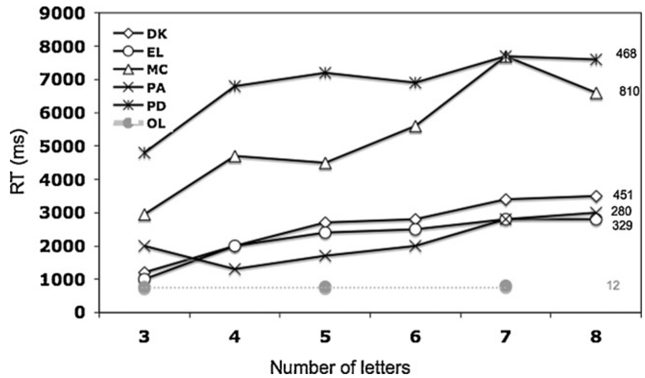

Fig. 2. Reading latencies as a function of word length (and slope in ms) for LBL readers and brain-damaged control subject, OL.

2.3. Reading performance

2.3.1. Method

A list of 120 words was used, ranging from 3 to 8 letters in length and controlled for frequency and imageability (Chialant & Caramazza, 1998). There were high and low frequency (HF mean = 200; LF mean = 30 per million) and high and low imageability (HI mean = 575; LI mean = 406) words, with these variables being orthogonally crossed. Frequency and imageability values in this and subsequent experiments were obtained from the MRC database (Coltheart, 1981), with frequencies taken from Kucera and Francis (1967). Words were presented one at a time in capital letters[2] and participants read each word aloud as accurately and as quickly as possible. Stimuli remained on the screen for 20 s, after which the next trial was presented. Only first responses were scored for accuracy and trials where the patient self-corrected or spelled letters aloud before naming the word were excluded from analysis. Only the correct 'first time' responses were used in the reaction time analyses. Trials on which there were microphone errors were also eliminated. The word list was presented in 5 blocks of 24 words each, distributed over 2 testing sessions. A practice block of 12 trials was run before each testing session. OL read words of 3, 5 and 7 letters in length in a single session, and accuracy and RT were recorded.

2.3.2. Results

2.3.2.1. LBL readers. Accuracy and latency data were obtained for DK, EL, MC, PA, and PD. Information about PL's reading accuracy is also included, but not latency, as she spelled the majority of words out loud before naming them. JC could not read enough words accurately to be able to complete this task and so, below, we characterize the nature and severity of his reading disorder using other data.

ANOVA was conducted on the RT data for five LBL patients from correct trials with length (3, 4, 5, 6, 7 or 8 letters), frequency (high or low) and imageability (high or low) as within-subject factors. Linear regression was used to determine the slope of the length effect. The reading latencies as a function of word length for each patient are plotted in Fig. 2, along with the slope of the word length function, and summary data are presented in Table 2.

Errors across all LBL patients tended to be mainly of the visual kind (e.g. patient PL: INSTINCT—'instance', AUDIENCE—'advance') and predominantly involved letters at the end of words (e.g. DK: LUNG—'lunge', REMOVAL—'remove'; and MC: AUDIENCE—'audition', TRUTH—'truce'; DOUBT—'double', MOUTH—'mouse'). Some transpositions within a word were also produced (e.g. PA: BEARD—'bread', MATURITY—'maternity'). Occasional letter misidentifications (e.g. MC: DEGREE—'decree', BIT—'pit') were observed as were regularisation or mispronunciation of irregular words (e.g. PA: PRESTIGE—'prestig', CENT—'kent'; PL: LOGIC and LEGEND pronounced with a hard 'g').

As evident from Fig. 2 and Table 2, the extent of the reading impairment varies in accuracy, latency and regression slope from patient to patient although the qualitative profile is similar. Such a range of quantitative difference in performance in LBL readers is not unusual; Behrmann, Plaut, et al. (1998) report data from seven LBL readers, with reading latencies varying between about 1000 and 8000 ms for 3, 5, and 7 letter words, and a regression slope of between 97 and 1409 ms. In the current study, as seen in Fig. 2, DK, EL, MC, PA and PD all have RT slopes that fall in this range.

JC failed to read most words and, as such, his reading could not be measured using the word list adopted here. Thus, a second word list was used, consisting of 48 words, between 3 and 8 letters in length and of both high and low frequency and imageability. In addition, half the words had regular spellings, and the other half had irregular spellings. The list was divided into three groups, with equal numbers of words from each condition in each group. These groups were presented in all three modalities (reading, writing and identifying words spelled aloud) on three separate occasions, so that the same word was not used more than once on a single testing occasion. The order in which the tasks were performed was varied systematically across the three testing sessions, to allow for possible order effects. JC read only 14/48 words correctly. Albeit still impaired, his writing and oral spelling were more accurate than his reading (28/48 and 27/48, respectively; two-tailed Fisher exact test: writing versus reading [$z = 2.66$, $p < 0.01$]; oral spelling versus reading [$z = 2.46$, $p = 0.01$]). Writing and spelling problems do not always accompany LBL reading, but they are not unusual either and have been reported in many previous case studies (Behrmann, Plaut, et al., 1998; Ingles & Eskes, 2008; Patterson & Kay, 1982; Rapp & Caramazza, 1991).

Table 2
Accuracy, RT and results of ANOVAs for LBL readers.

Patient	Accuracy	Frequency	Imageability	Interactions
DK				
Accuracy	99%			
RT	451[a]	$p < 0.001$	$p < 0.01$	n.s.
EL				
Accuracy	94%			
RT	329[a]	n.s.	n.s.	$p < 0.006$
MC				
Accuracy	71%			
RT	810[a]	n.s.	n.s.	n.s.
PA				
Accuracy	83%			
RT	280[a]	n.s.	$p < 0.05$	n.s.
PD				
Accuracy	63%			
RT	468[a]	$p < 0.001$	$p < 0.05$	$p < 0.005$
PL[b]				
Accuracy	46%	n.s.	$p = 0.07$	n.s.
RT n/a				
JC	Unable to read many words; see below for profile			

[a] RT presented here is the slope in ms obtained from regressing word length against reaction time. It is significant in all 5 cases.

[b] Latency data could not be obtained from PL as he read the letters aloud individually, precluding the measurement of RT. Analyses are done on his error data.

2.3.2.2. Brain-damaged control. OL made 5 errors, 3 on 3 letter words and 1 each on the 5 and 7 letter words. His intercept across word length is 720 ms and the slope is 12 ms/letter (see Fig. 2). The minimal slope in RT, calculated across word length, and the small number of errors, especially on longer words, confirms that he is not a LBL reader.

2.3.3. Discussion

All five patients for whom reading latency data could be obtained showed abnormally long latencies, taking around 3 s or more for the longest words. In contrast, young college students take roughly 500–600 ms (Weekes, 1997). Also in contrast with normal subjects who show minimal, if any, increase in RT with word length for high frequency words and very small effects with low frequency words (e.g. Weekes, 1997), the patients also all show an increase in RT with each additional letter that is strikingly large and statistically significant. Although all the patients except PA had right visual field deficits, the stimuli were presented into the intact left field for all participants and the length effects are still much greater than the 51–162 ms per letter reported by Leff, Crewes, Plant, Scott, and Wise (2001) for patients with right hemianopia, confirming the LBL profile for the patients included here. The patients' RTs for 7-letter words are also considerably longer than the 2.5-s guideline suggested by these authors as a minimum for LBL reading. These findings provide conclusive evidence that all five of these patients are LBL readers. Although we do not have latency information for the remaining two patients, their reading profiles, manifest in accuracy, are consistent with LBL reading, with more errors towards the end than beginning of words, especially for longer words.

In contrast with the LBL pattern, OL, the patient with right parietal damage, read only somewhat more slowly (intercept 720 ms) than the rates cited for college students (500–600 ms) and shows minimal increase in RT or accuracy with additional letters, testifying to the absence of LBL reading.

We note the considerable heterogeneity among the LBL patients, not only in terms of severity of the alexia but also in terms of the lesion site and other, accompanying neuropsychological deficits. While such heterogeneity may seem problematic, this is not the case here—the presence of the length effect is the defining variable

[2] Although normal text is nearly always displayed in lower case, upper case block script is often used for testing the LBL patients to provide the clearest script for these readers. As the script becomes more complex visually, reading is even more impaired—if the patients are impaired even on upper case block script, this is particularly revealing.

for inclusion and the issue at stake is what gives rise to this length effect. We take up the issue of lesion site and its relevance in the final discussion and also consider some other aspects of the patient sample at that time. A final note about the patients is that, with some exceptions, they have not finished 12 years of school. We do not, however, think that this is critical to the observed pattern as this is not true of all patients and, also, the brain-damaged patient OL is matched to the patients on education level and, as will be evident below, shows a very different pattern of behavior. Having established that the LBL patients, but not OL, fit the requisite criteria for LBL reading, the three following experiments were carried out with the aim of investigating the visual processing abilities of the LBL readers.

3. Experiment 1: the role of visual complexity—checkerboards

To determine whether the LBL readers were more affected by the visual complexity of the stimulus than matched control participants and the brain-damaged control, Experiment 1 used a non-linguistic stimulus in which visual complexity could be easily manipulated. The stimulus of choice consisted of grids of black and white squares, in a same/different matching task, where the size of the grid could be manipulated. Note that same/different matching studies have proved useful in past studies of LBL reading (Behrmann & Shallice, 1995; Kay & Hanley, 1991) in which participants compared pairs of words, pseudowords or letter strings.

3.1. Method

3.1.1. Participants

All seven patients and the brain-damaged control subject participated in this study. In this and all subsequent experiments, two matched control participants were tested for each LBL patient. These participants were matched with their respective patient as closely as possible for age, gender, handedness and years of education. The same controls participated in all experiments, except that a different (but equally matched) participant served as a second control for EL in Experiment 2.

3.1.2. Stimuli

A set of 48 checkerboards was designed, comprising grids of black and white squares (Fig. 3). The grid sizes were 3 × 3, 4 × 4, 5 × 5 and 6 × 6 squares so that the total number of squares in the grid varied from 9 to 36. The size of the small squares was kept constant (subtending 0.5° of visual angle at a distance of 50 cm) so that the overall size of the checkerboard increased as more squares were added. Grids were constructed so that many blocks of the same colour did not appear together and obvious patterns (e.g. black, white, black, white) were avoided. Each checkerboard was paired once with itself, and once with a checkerboard differing only by a single square to yield one 'same' and one 'different' stimulus pair for a total of 96 stimuli. The grids were presented above one another and to the left of screen centre.

3.1.3. Procedure

Each trial comprised a fixation point presented for 1000 ms, followed by the pair of checkerboards. Subjects were asked to determine whether the members of the pair were the same or different, and to respond as quickly and accurately as possible using a key press. Stimuli remained on the screen until a response was given, at which point a blank screen was presented for 1000 ms prior to the beginning of the

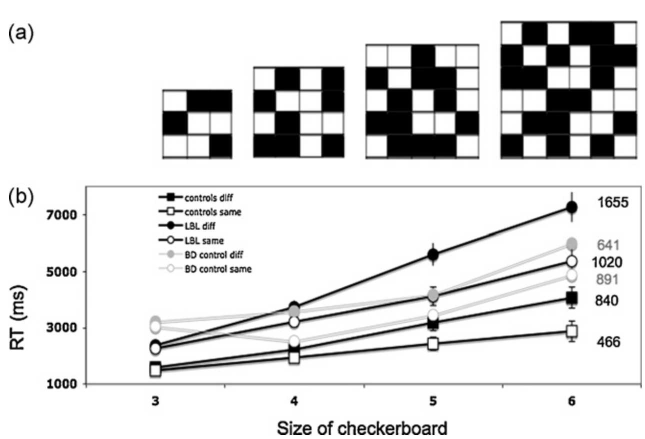

Fig. 3. (a) Examples of the 3 × 3, 4 × 4, 5 × 5 and 6 × 6 checkerboards. (b) Mean RT (and mean SE) for the LBL readers, controls and brain-damaged control on same and different trials as a function of matrix size.

next trial. A block of 12 practice trials preceded two blocks of 48 trials each (stimulus size randomized within block).

In this and all subsequent experiments, a repeated measures ANOVA is conducted with the factors of interest as within-subjects and group as a between-subjects factor. Given that the two groups are of unequal size and variance, reducing the reliability of the ANOVA (Mycroft, Mitchell, & Kay, 2002), the results are interpreted conservatively. Note, however, that the group differences are robust, on the order of seconds, and are highly significant. In the ANOVAs, because our interest concerns group differences, we report only those interactions in which group is a factor (and also consider whether there is a main effect of group). For the sake of completeness, we also examine the data from the individual patients and report these patterns. The data from the brain-damaged control, OL, are also reported individually as a further benchmark for comparison of the LBL data.

3.1.4. Results

An ANOVA with response type (same or different) and level of visual complexity (3 × 3, 4 × 4, 5 × 5, and 6 × 6 grids) as the repeated measures factors and group (patients, matched controls) as a between-subjects factor revealed a three-way interaction of these factors ($F(3,57) = 3.7$, $p < 0.02$). As evident from Fig. 3b, and confirmed using Tukey post hoc tests (at $p < 0.05$), this interaction arises because of a disproportionate increase in RT as visual complexity increases for the LBL patients but not for the controls, especially for the different trials and especially at the two matrix sizes that were largest. LBL patients performed particularly poorly, relative to controls on different versus same trials (group × response type: $F(1,19) = 7.1$, $p < 0.02$), and on larger matrix sizes (group × size: $F(3,19) = 13.6$, $p < 0.0001$).

As a summary measure, we also calculated the slope of RT against matrix size for each individual for both same and different trials, separately (given the interaction with response type reported above). The average RT slopes for same and different trials for the controls was 466 and 840 ms, respectively, whereas the comparable average values for the patients is 1020 and 1655 ms, clearly reflecting the difference between the groups across the matrix sizes. An ANOVA performed on the slope as the dependent measure revealed a main effect of group ($F(1,19) = 15.4$, $p < 0.001$), as well as an interaction of group × response type ($F(1,19) = 6.09$, $p = 0.02$), confirming the steeper slopes for different than same trials for the LBL group. To examine the data on a case-by-case data and explore the individual findings, we calculated the 95% confidence intervals (CI) around the slope of the control subjects and then evaluated which, if any, individual patients fell outside these CIs. For the different trials, every LBL reader fell outside of the control CI and, for the same trials, all LBL readers, with the exception of EL, fell outside the control CI. In contrast with the LBL readers and as a benchmark for comparison, OL shows RT slopes that are closer to those of the normal controls and well within the CI (see Fig. 3b).

Finally, we calculated the intercepts for the two groups, for same and different trials and subjected these to an ANOVA. Not surprisingly, there is a significant difference in intercept between the two groups ($F(1,19) = 44.1$, $p < 0.000$), but this was modulated by the trial type with a larger difference between the groups for the different than for same trials ($F(1,19) = 6.25$, $p < 0.03$). We note that the intercept for OL for both trial types is even higher than that observed for the LBLs and controls—of relevance here is that his slope (for same and for different trials) is not as steep as those of the LBL readers, again confirming the difference in performance between him and the LBL readers.

3.1.5. Discussion

Despite the wide variation in reading performance, there are nevertheless striking similarities across the seven LBL patients on this purely visual task. First, the average group slope is significantly steeper than the average control slope and, in absolute RT, the LBL readers are significantly slower, relative to the controls, in deciding whether the checkerboards are the same or different. The slowing in RT for the LBL readers is most apparent at matrix size 5 and 6 and to a greater extent for the different than same trials. Second, in individual analyses, six of the seven patients have significant difficulty in dealing with stimuli of increasing visual complexity, with their slopes falling outside the control CI for both same and different trials, and the additional LBL patient shows this same pattern but only for different trials. The pattern of performance on both slope and intercept is quite different for the brain-damaged control subject, who has a higher intercept, reflecting overall slowing of performance, and a flatter slope.

These findings indicate that the LBL readers perform more poorly than the controls and the BD control as a function of visual complexity on this checkerboard matching task and we attribute this to a more general visual impairment in the LBL readers. It is the case, however, that the LBL patients showed intercepts that were significantly different from their controls, suggesting that some of this 'visual complexity' effect might be a result of more generalized slowing. Closer scrutiny of the data indicates that this latter interpretation is unlikely to be the case. For example, DK, PA and PD had intercepts for the effect of visual complexity that were lower than their matched controls but slopes that were far steeper. As further evidence that the difference in intercept cannot fully account for the steeper slopes in the LBL readers, we took two LBL readers, JC and MC, whose intercepts were 1492 and 1719, respectively, and found two controls with intercepts of 1493 and 1769, respectively (not necessarily their own controls but matched on intercept now), and then compared their slopes. In both cases, the slopes of the LBL readers were much steeper than their matched intercept controls (JC slope: 1138, control 926; MC slope 1447,

Fig. 4. Symbols used in Experiment 2.

control 1263). Finally, the control patient, OL, has a higher intercept than the controls and LBL readers but a flatter slope. It is not the case, therefore, that a simple explanation of overall slowing, as reflected by different intercepts, can explain the disproportionate increment in RT across matrix size in the LBL readers.

A further, alternative explanation for the group difference might be in terms of impaired feature analysis, a hypothesis previously proposed to explain LBL reading (Humphreys & Price, 1994); however, this too can be discounted as the stimuli do not contain any obvious letter-like features (Massaro, 1998; McClelland & Rumelhart, 1981; Rumelhart & Zipser, 1985). Instead, a more fundamental impaired visual processing deficit, which becomes increasingly apparent with increased complexity of the input, seems to be the most likely explanation of the slowed RTs with visual complexity in LBL reading.

That six patients show effects of visual complexity that are significantly greater than the controls is consistent with previous data suggesting that a subtle visual processing impairment might be the source of LBL reading. It is somewhat surprising that the seventh patient, EL, differs from her controls only on ‘different’ trials, since a previous study showed that visual complexity of line drawings influenced her time to name the pictures more than it did controls (Behrmann, Nelson, et al., 1998). Note, however, that EL is one of the fastest LBL readers and so her deficit might be too subtle to be detected on this task on the ‘same’ trials. We explore this further below.

Importantly, even for those patients for whom a visual processing difficulty seems certain, it is not yet appropriate to draw any obvious relationships between the perceptual impairment and LBL reading. Experiments 2 and 3 address this issue more directly by showing that the profile of performance on linguistic and non-linguistic material is similar in LBL readers, suggesting a close association between the visuoperceptual and reading difficulties.

4. Experiment 2: matching words and symbols

The previous experiment revealed a significant difference in the processing of visually complex, non-alphanumeric stimuli between the two groups and a difference between the LBL readers and OL. Here, we turn to examine the processing of linguistic and non-linguistic stimuli when visual complexity is controlled. Specifically, in addition to comparing performance on linguistic and non-linguistic stimuli, we explore effects of length and the location of the difference on ‘different’ trials, two hallmarks of LBL reading. Participants performed same-different matching of pairs of words or pairs of symbol strings: when the words or strings differ, the difference could arise at the beginning, middle or end of words. If the impairment giving rise to LBL reading is a more fundamental perceptual difficulty, we might expect to find similar deficits for words and for symbols.

4.1. Method

4.1.1. Stimuli

A list of word pairs was compiled (see Appendix A) in which the two items differed only by a single letter, and the position of this difference was either at the beginning, middle or end of the word. There were equal numbers of 5, 6 and 7 letter words. For 6 letter words, the middle of the word was defined as either the third or the fourth letter. The pairs were matched as closely as possible for frequency and imageability. ‘Same’ word pairs were compiled by pairing one word with itself. For half the trials, the first word was repeated and, for the other half, it was the second word. Visual complexity of letters and symbols in both this and the subsequent experiment was measured in the way described in Section 1. The number of strokes to form each letter (printed in upper case *sans serif* Arial font) was counted. Upper case letters were used because their strokes are better defined—lower case letters are often joined together and there is more variation in their form.

A set of 24 symbols was created (Fig. 4), corresponding to 24 letters of the alphabet (Q and Z were not used). For each letter, its corresponding symbol contained the same number of strokes. Symmetry was also matched so that if the letter was symmetrical about the vertical axis then so was the symbol, and vice versa. From the lists of word pairs, each letter was substituted by its corresponding symbol. This meant that the visual complexity of the symbol strings was exactly equivalent to that of the word strings.[3]

4.1.2. Procedure

Participants familiarized themselves with the symbols before beginning the experiment. During the experiment, following a fixation point, the pairs were presented on a computer screen for an unlimited duration, and participants made same/different judgements as quickly and accurately as possible with a key press. The experiment was run over two testing sessions, with symbols and words blocked and 12 practice trials before each block, consisting of 108 trials each and containing 2 breaks. Symbols were always presented first so that subjects would be less likely to generalise a letter-processing strategy to the symbols.

4.1.3. Results

The first analysis, using only correct trials, examined effects of response type (same or different), stimulus type (word or symbol strings) and length (5, 6, or 7 characters). The second analysis takes ‘different’ responses only and includes position of difference (beginning, middle or end of the strings), stimulus type and length as factors.

The LBL readers responded more slowly overall than the controls [$F(1,19) = 59.94$, $p < 0.001$] and their performance was more affected by response type [$F(1,19) = 62.78$, $p < 0.001$; different slower than same] and by length (linear [$F(1,19) = 34.89$, $p < 0.001$]) (Fig. 5a and b) than the controls. There was less difference between responses to words and symbol strings for the patients than for the controls [$F(1,19) = 34.37$, $p < 0.001$]. Importantly, the four-way interaction between response type, stimulus type, length and group was not significant and neither was the three-way interaction of stimulus type, length and group [both $F < 1$]. To assess the individual profiles, we constructed 95% confidence intervals around the slopes for the words and symbol strings, separately for same and different trials. All LBL patients' slopes fell outside of the CIs of the controls for same trials for words and symbols whereas for different trials, six of the seven LBL readers fell outside the CIs for words and only 3 fell outside the CIs for symbol strings. For the effect of length, the intercept for the LBL patients was significantly higher than the controls for words [$F(1,19) = 8.60$, $p < 0.01$] but did not differ significantly across groups for symbols [$F < 1$]. Patient OL appeared to find this task very difficult; he performed even more slowly than the LBL patients for both words and symbols, and his slopes fell outside the CIs of the controls for symbols, but not for words.

In the second analysis, the patients were significantly more affected by the position of the difference than were the controls ($F(1,19) = 65.06$, $p < 0.001$) (Fig. 6a and b). The only interaction that reached significance was the linear position of difference × length × group interaction ($F(1,19) = 28.45$, $p < 0.001$) because the LBL readers showed increasing effects of position of difference with longer strings, while the controls did not show this effect. Importantly, this held true for words and symbol strings and to an equal extent. OL was also affected by the position of difference and this did not differ for words and symbols. It appears that OL found this task particularly difficult—his performance is particularly slow and shows a large slope for the position of difference analysis. As we will see from the next experiment, this pattern does not hold for him in Experiment 3 and so we conclude that the matching task proved particularly taxing for him.

4.1.4. Discussion

Not surprisingly, the LBL patients were slower than their matched control subjects in judging pairs of words. More interesting is that they were also slower than the controls to process the non-linguistic stimuli and that their slopes, calculated by regressing RT against string length, were not statistically different across the two display types. Thus, the LBL patients showed stronger length effects than controls with both word and symbol strings and to a similar degree. It is the case that the patients showed less overall RT difference between words and symbols than did the controls, who performed more quickly for words than symbols. One possible explanation for this is given that the bottom up perceptual processing is slow in the LBL readers, they are unable to activate any top-down existing lexical representations, thereby eliminating any word superiority/advantage (Behrmann, Plaut, et al., 1998; Johnson & Rayner, 2007). Indeed the performance of the LBL readers on both words and symbols is slower than the controls' performance on symbols, suggesting that both display types may be equivalently problematic to the LBL readers (the same holds in the position of difference analysis, see below). OL was very slow in matching both words and symbol strings but has a flatter slope than the LBL readers on word matching.

For the position of difference analysis, the effect of position of difference did not interact with stimulus type so that the LBL patients were equivalently slow at detecting the difference as a function of position for both words and symbol strings.

[3] One aspect of the letter and symbol stimuli that was not controlled for was their confusability. Although confusion matrices exist for both upper and lower case letters, it is difficult to envisage mapping a confusion matrix for the symbol stimuli, which are unknown and cannot easily be referred to by name.

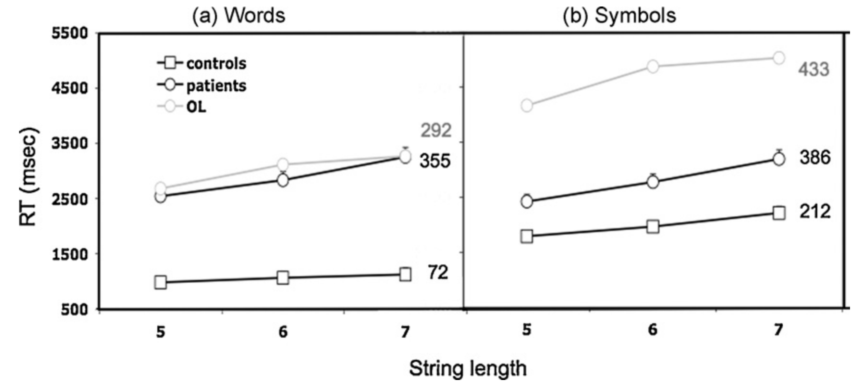

Fig. 5. Mean (and 1 SE) for LBL patients, BD patient, OL, and controls on matching of (a) words and (b) symbols, with the slope for each line included (in ms). At this scale it is difficult to see the standard error bars for the controls well.

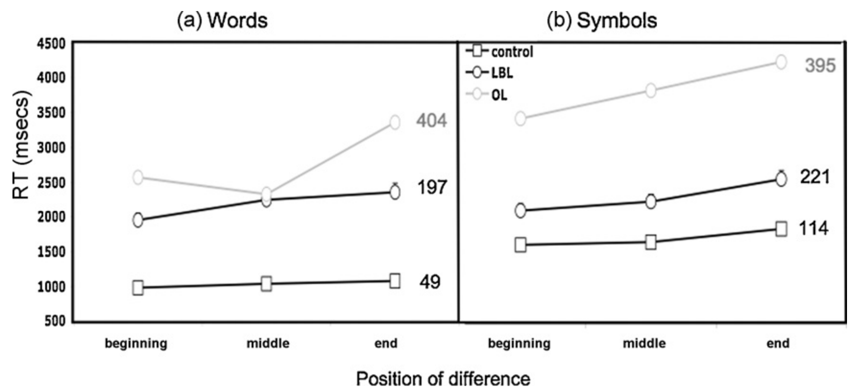

Fig. 6. Mean (and 1 SE) matching performance for LBL patients, BD patient, OL, and controls on matching of (a) words and (b) symbols as a function of position of difference (and slope in ms). At this scale it is difficult to see the standard error bars for the controls well.

Again, matching pairs on both stimulus types was slower than the controls' matching time on symbols, as in the above analysis. OL who was extremely slow on words and symbol strings, took inordinately long on words and symbols especially when the difference was at the end of the string, likely reflecting his overall perceptual difficulty.

In summary, not only are the LBL patients impaired, relative to the matched controls, in processing both words and symbol stimuli, but they also show qualitatively similar effects of length and left-to-right processing (reflected in the position of difference) with both stimulus types. These data therefore provide further evidence in support of the idea that the patients have a visual processing impairment, which affects their processing of symbol strings in the same way it impacts upon the processing of letters in words. Patient OL does not show an effect of length to the same extent as the controls but he is very variable in his RT to detect the difference in the pair when the difference arises at the end of the string. This steep slope for detecting the difference is not mirrored in the subsequent experiment, however, and so may need to be interpreted cautiously.

5. Experiment 3: visual search with strings of random letters and symbols

To confirm further that the LBL readers have an impairment extending beyond words and that this impairment impacts linguistic and non-linguistic material equivalently, in this final experiment, participants searched for a target letter or symbol embedded within a letter or symbol string, respectively. This task is perceptually more similar to reading, since it involves the processing of a single string rather than the comparison of two strings presented simultaneously. It is also possible, in this task, to examine the processing of stimuli containing very small numbers of characters (from one upwards) and hence might give a better indication of visual processing capacity across a larger stimulus range, allowing closer comparisons to the patients' reading latencies. If the reading impairment is indeed related to faulty visual processing, then these two measures might also be correlated.

All trials are 'target-present' trials and search can be self-terminated once the target is acquired. This too is akin to terminating reading when one discerns the presence of the orthographic uniqueness point, the letter position in a word where that letter pattern uniquely identifies the word. To obtain a measure of search for the entire string, trials where the target appears at the end are also used. We recognize, of course, that a linguistic task such as reading requires access to lexical, semantic and phonological information whereas perceptual search does not but nevertheless, there may be sufficient similarities across the task that a direct comparison of these two tasks might be revealing.

5.1. Method

5.1.1. Stimuli

Stimuli were strings of either letters or symbols (taken from Experiment 2). Two letters were chosen as letter targets in the letter strings (D and V) and two symbols were chosen as symbol targets (∠ and ʘ). Targets are matched on visual complexity, defined by the number strokes (all targets are drawn with two strokes).

Strings ranged between one and six characters in length. A target was always present and its position varied between the beginning, middle and end of the strings for three- to six-character strings. For four-character strings, the middle was defined as positions 2 and 3; for six-character strings, it was positions 3 and 4. Targets appeared an equal number of times at each of these two locations. For one-character strings there was evidently only one possible location for the target. For two-character strings the targets appeared equally often at the beginning and end of the string (positions one and two, respectively). Targets measured 0.5 cm × 0.6 cm, subtending 0.57° × 0.69° of visual angle when viewed from a distance of 50 cm. The longest stimuli were 4.4 cm long, subtending 5.03° of visual angle. The left end of the string was always positioned 50 mm from the fixation point.

5.1.2. Procedure

Letter and symbol strings were blocked (two blocks of letters and two of symbol strings) for a total of 720 stimuli. Blocks were presented in counterbalanced order in an ABBA design and two blocks were run in each of two sessions. Stimuli were presented for unlimited exposure duration following a fixation point lasting 1000 ms.

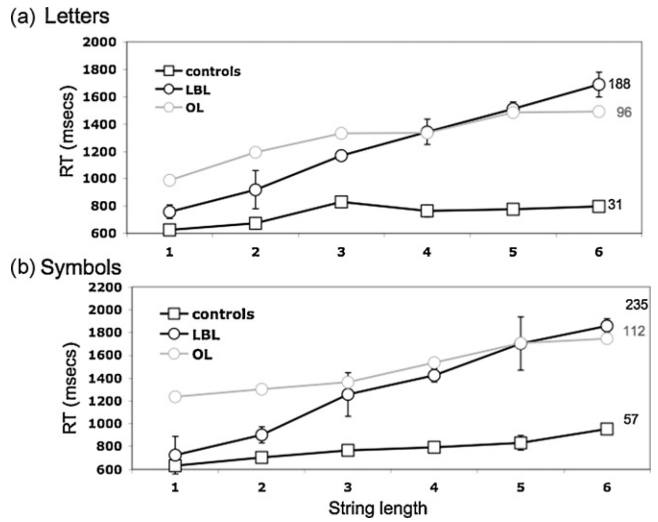

Fig. 7. Mean RT (and 1 SE) as a function of string length to detect target in (a) letter or (b) symbol strings for the LBL readers, brain-damaged patient OL, and matched controls (and slope in ms).

Subjects were asked to identify which of the two targets (either letters or symbols) was present, and to respond with a key press as quickly and accurately as possible. Stimuli remained on the screen until response, at which point a blank screen was shown for 1000 ms before the next trial commenced.

5.1.3. Results

The first ANOVA used all correct responses to explore effects of stimulus type (letter or symbol string) and length (1, 2, 3, 4, 5 or 6 characters). The second ANOVA took responses to 3, 4, 5 and 6 character strings only, to examine the effect of target location (beginning, middle or end of the string) along with stimulus type and length.

The LBL readers responded more slowly than the controls [$F(1,13) = 142.53$, $p < 0.001$] and showed a stronger effect of length [$F(1,13) = 232.81$, $p < 0.001$] (Fig. 7a and b). The length × stimulus type × group interaction was not significant [$F(1,13) = 1.31$, $p = 0.27$]. To assess the individual profiles, we constructed 95% confidence intervals around the slopes for the letters and symbol strings. All LBL patients' slopes fell outside of the CIs of the controls for both letters and symbols, with the exception of patient PA. Importantly, there was no effect of stimulus type nor did it interact with group [$F < 1$]. For the patients, the intercept for the effect of length did not differ significantly from that of the controls, either for letters or for symbols (both [$F < 1$]). Of importance, for both letters and symbols, patient OL has a higher intercept and a flatter slope than the LBL readers, highlighting that the linear effect of length (for both linguistic and non-linguistic stimuli) is specific to the LBL readers.

In the analysis of detection time as a function of position of the target in the string (Fig. 8a and b), the LBL readers were also increasingly different from controls in the effect of target location as string length increased [$F(1,13) = 30.90$, $p < 0.001$]. Finally, the four way target location × linear length × stimulus type × group interaction was reliable [$F(1,13) = 8.10$, $p = 0.01$]; this arises both because the LBL readers have a marginally greater effect of target location for symbols than for words and that the controls show a marginal flattening of the target location function for symbols over words. The effect of target location increased both with increasing length of the stimuli and for symbol strings relative to letters, for patients more than for the control participants. All LBL readers fell outside of the 95% CI established around the control mean for both letters and symbols although, again, PA was an exception falling close to but not outside the normal CI boundaries. As in the previous analysis, patient OL has a higher intercept but a slightly flatter slope than the LBL readers for both stimulus types (Fig. 8).

5.1.4. Discussion

The patients all performed similarly on this target detection task; relative to the controls, they are slower to process both the letter and symbol strings, show stronger effects of length and target location for both stimulus types and detecting targets at the beginning faster than those in the middle and at the end, reflecting processing of the strings from left to right. There is also an interaction of the effect of target location with the length of the string, showing even greater position effects for longer strings. PA shows roughly the same pattern as the other patients but did not fall outside the normal boundaries for the length effect nor for the position of target effect. We note that she is the mildest LBL reader (and also has no hemianopia, likely reflecting a more circumscribed lesion) and so the absence of strong effects despite the same general profile is perhaps not surprising.

Although we only have RT data from both reading latency and this task for 3 individuals, PA, MC and PD, it is of interest that the slope of the length effect in reading (Table 2) correlated significantly with the similar slope measure obtained

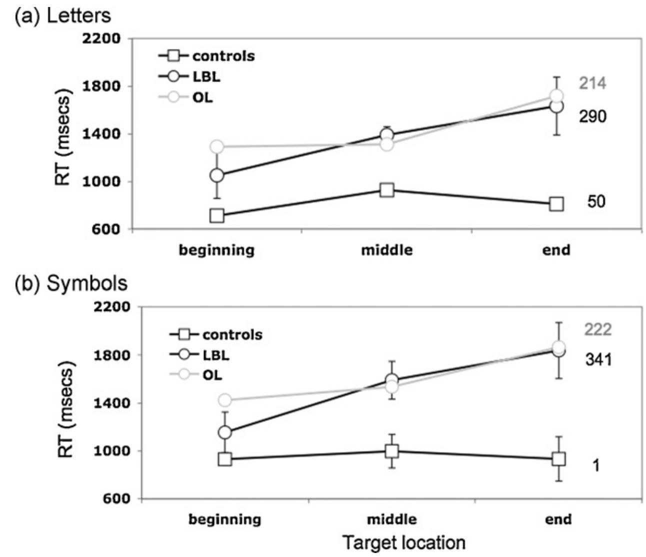

Fig. 8. Mean RT (and 1 SE) to detect target in (a) letter or (b) symbol strings for the LBL readers, brain-damaged patient OL, and matched controls (and slope in ms) as a target location.

for the target detection as a function of position (Pearson's $R = 30.20$, $p < 0.05$). As expected, reading gives rise to a somewhat steeper reaction time slope with word length, presumably because of the extra lexical, semantic and phonological processing involved, and the fact that responses are spoken rather than made with a key press. Nevertheless, the association between reading and perceptual search suggests a strong relationship between visual processing difficulties and LBL reading.

6. General discussion

This research investigates the visual processing abilities of seven LBL readers in a series of matching and search tasks, using both linguistic and non-linguistic stimuli in which visual complexity and/or length is systematically manipulated. Many explanations of the functional underpinnings of LBL reading have been postulated, spanning almost every level of cognitive processing from a prelexical disorder in visual processing (Behrmann, Nelson, et al., 1998; Farah & Wallace, 1991), to a problem in letter identification (Kay & Hanley, 1991; Reuter-Lorenz & Brunn, 1990) or in parallel access to a visual input lexicon (Patterson & Kay, 1982) or in the visual input lexicon itself (Warrington & Shallice, 1980), and/or in accessing phonology (Bowers et al., 1996). In their proposal that LBL is a consequence of a visual disorder, Farah and Wallace (1991) stated that it is critical to test the visual processing of all LBL readers and assess their visual capabilities in relation to their slow reading performance. We do so in this study and examine the theoretical implications of our findings.

At the outset of this paper, we presented evidence that all seven patients are impaired in reading, with some affected more mildly and others more profoundly. Accuracy and length effects varied across the group, with one individual unable to complete the reading task (JC) and one achieving 99% correct (DK), and with length ranging from 280 (PA) to 810 ms (MC) per letter across the patients. Despite the quantitative variability across the patients, they all show the hallmark qualitative features of LBL readers. Also, all LBL readers read more poorly than OL, a brain-damaged individual with a circumscribed lesion affecting right parietal cortex.

We then reported data from the LBL readers, OL and matched controls obtained from three experiments, using checkerboard stimuli as well as letters/words and matched non-alphanumeric symbols. The patients responded significantly more slowly than their matched controls even on the non-linguistic tasks, although not as slowly as the brain-damaged patient, OL. Generalised cognitive and motor slowing were both ruled out as explanations for the group differences: motor slowing per se is unlikely to vary with visual properties of the display such as visual complexity (Experiment 1) or string length (Experiments 2 and 3), and cognitive slowing was considered unlikely since the patients did not have always have a higher intercept than the controls (for the effect of visual complexity and for effects of length). We also show that when the intercept is equated for patients and controls, the effects of visual complexity and length still remain. As these tasks did not require access to any lexical or semantic information, or even to letter identities, the most likely explanation of the difficulties was considered to be a more fundamental visual processing impairment.

Of great interest is that the linear increase in RT in the LBL readers in all three experiments, reflected as the slope of the function calculated over visual complexity or length of input strings, was significantly steeper than that of the matched controls or of OL. Also, processing proceeded from left to right, with fastest responses to differences between pairs of strings when the difference was nearer the beginning. The patients also showed an interaction between the effects of target location and length, with target location affecting performance more with longer strings, as predicted with sequential left-to-right processing. These effects of length and position of difference/target location held similarly across linguistic and non-linguistic stimuli, suggesting that the same impairment underlies both types of input. Finally, in almost all experiments and all conditions of these experiments, with few exceptions, individual LBL readers showed a steeper slope than the controls (falling outside confidence intervals established around the mean slope of the controls). Taken together, these findings reveal an impairment in the LBL readers that extends beyond their processing of linguistic material.

6.1. Relationship between LBL reading and visual processing problems

As evident from the data, the impairment evinced by the LBL readers appears to have equivalent impact, both qualitatively and quantitatively, on the processing of linguistic and non-linguistic material. Additionally, in a subset of the LBL readers we report a correlation between the increase in RT to detect targets as a function of location and the magnitude of the length effect. These findings all suggest a relationship between the general processing of visual material and reading. Whether this relationship is purely correlational or whether there is a causal component is, of course, difficult to establish definitively.

Although clearly not conclusive, we would propose that the co-occurrence of specific patterns in both linguistic and non-linguistic material are suggestive of a single underlying cause. We do this firstly because it is parsimonious, avoiding the need to hypothesise an additional language-level problem given that visual difficulties are demonstrated for all patients. Secondly, and more importantly, we observe similar effects of length and patterns of left-to-right processing with both linguistic and non-linguistic stimuli. The logic here (and adopted ubiquitously in psychology experiments) is that when an independent measure impacts performance on two different inputs in the same way, it is likely that the inputs are processed by the same underlying mechanism. For the symbol strings, with no basis in language apart from their letter-like features, it seems this must be a consequence of a general visual deficit. Data from Experiment 3 also support a close relationship between visual processing capacity and reading speed with the significant positive correlation between these measures.

The qualitatively similar patterns of performance with linguistic and non-linguistic stimuli and the association between visual processing and reading difficulty is probably the strongest evidence to date that a visual impairment may play a causal role in LBL reading. One other study that claimed a causal link was based on additive factors methodology (Farah & Wallace, 1991), which requires extreme care in its application (McClelland, 1979). The only other similar work is by Rapp and Caramazza (1991) who showed a left-to-right processing gradient in *accuracy* in both a bar detection and a letter detection task in an individual with LBL reading. Consistent with this, the work presented here demonstrates left-to-right processing in a group of seven LBL readers with both linguistic and non-linguistic stimuli. This is of significance because RTs are the measure commonly used to diagnose LBL reading. We do note, again, that our proposal of causality remains to be verified and that the data we present are suggestive rather than conclusive of a single underlying cause.

6.2. At what level the visuoperceptual impairment?

We have postulated that the LBL reading likely arises from a general visual processing deficit. The question though is at what stage of visual processing does this disorder manifest? One immediate explanation for the findings might be the presence of a hemianopia given that, for normal participants, naming latencies are slower and effects of length are greater for words presented in the left visual field (Bub & Lewine, 1988; Ellis, Young & Anderson, 1988). The appeal to a hemianopic deficit, however, does not hold for several reasons: stimuli were presented to the left of fixation in all studies for both patients and controls and there is still a marked group difference. Also, the stimuli were presented for an unlimited exposure duration, allowing participants enough time to process the information, and there is still a large difference in performance across the two groups.

A second possibility is that the problem arises not so much in the early sensory aspects of vision but at stages where spatial frequency is computed. More specifically, Arguin and Fiset and colleagues (Arguin, Fiset, & Bub, 2002) have proposed that the problem in LBL readers concerns their susceptibility to visual confusability. They suggest that LBL readers rely on lower spatial frequencies for parallel processing than do controls, that these lower spatial frequencies produce confusions between visually similar letters, and that the LBL compensatory strategy allows them to extract higher spatial frequencies (Fiset et al., 2006). The LBL strategy would thus increase the spatial resolution of the visual system, effectively resolving the issue pertaining to between-letter similarity (Plaut, 1999). To substantiate their claim, they replicated the main features of LBL dyslexia with normal individuals who were required to read low-contrast, high-pass-filtered words. Additionally, they showed that when the visual input is not confusable, LBL patients perform like their controls (Fiset et al., 2005).

In contrast with the hypothesis of a more general alteration in perceptual processing as above, other explanations have suggested that the deficit is more domain-specific, arising at higher levels of the visual processing system that exclusively mediate orthographic processing. Support for this claim is garnered from many recent functional imaging studies that have delineated a region of ventral occipito-temporal cortex that is differentially responsive to specific forms of visual input. For example, there is considerable evidence indicating that a particular area of the left hemisphere, namely the mid-portion of the left fusiform gyrus, also known as the 'visual word form area' (VWFA), centred on Talairach coordinates ($x = -43$, $y = -54$, $z = -12$), is preferentially involved in letter and word recognition (Cohen et al., 2000). This cortical region is more strongly activated by real words than by consonant strings (Cohen et al., 2000, 2002, 2003; Dehaene, Cohen, Sigman, & Vinckier, 2005), indicating sensitivity to orthographic regularity. More recent work indicates a gradient of selectivity through the entire span of the occipitotemporal cortex, especially in the left hemisphere, with activation becoming more selective for higher level orthographic stimuli from letters through bigrams and then morphemes progressively towards the anterior fusiform region (Vinckier et al., 2007). Interestingly, the study by Cohen et al. (2002) examined brain activation to checkerboard stimuli, similar to those used in Experiment 1. Their finding that the VWFA shows more activation to letter strings than to checkerboards (and also to visual objects such as faces and houses), indicates a difference in neural circuitry underlying the processing of these stimulus types and leads the authors to favour an interpretation of activation by alphabetic stimuli.

In a similar vein, Polk and Farah (2002) provide evidence that alternating case words and pseudowords activate left ventral visual cortex in a similar way to normal words and pseudowords. This led them to conclude that it is not perceptual familiarity of the stimuli per se that is important, but some more abstract feature such as orthographic regularity. Hasson, Levy, Behrmann, Hendler, and Malach (2002) also observed left lateralised activation in the anterior occipito-temporal region for participants viewing unpronounceable Hebrew letter strings. Finally, Tarkiainen et al. (1999) report a study using magnetoencephalography to examine activation patterns associated with looking at single letters, two-letter syllable strings, words and symbol strings (of particular interest in relation to Experiments 2 and 3, which also use strings of symbols). The stimulus types all gave rise to initial activation (~100 ms after stimulus onset) in the visual areas V1 through to V4v, consistent with visual processing common to all stimuli. A second pattern occurred ~150 ms after stimulus onset, located in inferior occipito-temporal cortex, and with left hemisphere dominance. This pattern of activation, most marked for the letter strings, especially for words, and less pronounced for the geometric symbols, is consistent with the claim of a visual word form area whose specificity is to linguistic stimuli. Taken together, these findings suggest that there is a neural substrate that is largely dedicated to or indispensable for processing written language and these data provide support for the idea that there is a region of cortex that is orthography-specific.

The consensus from these neuroimaging studies is that there exists a region of left ventral cortex that is optimised for orthographic input and an obvious prediction is that damage to this region would result in an orthography-selective disorder. As laid out below, several of the patients in our sample have a lesion to this specific cortical region. However, as we have shown the disorder extends beyond orthography. Our claim then is that LBL results from a more general perceptual impairment and, as we discuss below, these data have further implications for the proposal of domain-specificity of pure alexia.

6.3. LBL reading and its relation to pure alexia

Our claim thus far is that there is a general visuoperceptual impairment that underlies LBL reading and the primary evidence is the finding that visual processing of both orthographic and non-orthographic material is impacted in the patients and that the impairment affects these two types of material in similar ways. One immediate question is whether these findings challenge the claim of cortical specificity of the VWFA alluded to above and we argue that they do. The clear prediction from a domain-specific account is that a lesion to the VWFA should result in pure alexia; an impairment only for letters and words would be consistent with this orthographic hypothesis. An impairment that affects all forms of visual input, alphanumeric as well as non-linguistic like the symbols used here, would be consistent with a more domain-general underlying mechanism.

While all patients in the current study evince LBL reading, only a small subset of them have lesions to this critical ventral occipitotemporal area and the findings from this subset only are considered to be pertinent here. Patients DK and EL, whose lesions are depicted in Fig. 1, and also JC and MC (although MC also has some frontal involvement) do have such lesions and their data allow us to address the cortical specificity of this orthographic cortical region.

Given that the performance of this subset of patients, like the others in the group, is similarly impacted by linguistic and non-linguistic stimuli, their data are compatible the latter, domain-general view. These findings suggest, then, that there may well be a region of cortex fine-tuned or even optimised for letter/word processing but that this cortical region is not dedicated or exclusively responsive to orthographic input.

Consistent with the claim of a more general perceptual function, Hasson et al. (2002), in their imaging study observe that “even in the most word-selective regions there was significant activation to other object categories” (p. 487) and similar findings have been presented by others (Devlin, Jamison, Gonnerman, & Matthews, 2006; Price & Devlin, 2003) in which multiple visual stimulus types give rise to activation in this cortical region. Also, Starrfelt and Gerlach (2007) propose that the mid-fusiform region may be responsible for complex visual analysis, which applies across multiple types of visual stimuli.

It is the case, however, that even if the qualitative pattern of results is equivalent across linguistic and non-linguistic visual input among the LBL (and pure alexia) patients, it is almost always the case that performance is somewhat worse for letter stimuli than for other symbols, even digits (Ingles & Eskes, 2008). This inferiority for letters does not fundamentally undermine our hypothesis and need not compel a claim for domain-specificity—rather, we suggest, like others, that letters and words may be particularly susceptible to impairment (e.g. Farah, 1997). Thus, this ventral cortical region may be more fine-tuned for stimuli that occur frequently and are supported by feedback from language areas. Damage, then, affects verbal material more markedly but other non-linguistic material that requires complex visual analysis is also affected.

One immediate question is how such an area of cortex might emerge given the evolutionary recency of orthographic input? Recent evidence has suggested that by virtue of an individual's experience and growing familiarity with orthographic input, activation in this area becomes stronger (Baker et al., 2007). The idea, then, is that the statistics of the visual environment, rather than genetics alone (Polk, Park, Smith, & Park, 2007), gives rise to representations that might be most useful and adaptive for the observer who reads. Given that reading is a relatively recent cultural phenomenon and it is untenable that a predetermined hard-wired system is in place to handle these visual inputs, a system that recycles a region of cortex and is sensitized to the peculiarities of the visual input seems plausible (Dehaene & Cohen, 2007). Also, given that letters and words require fine-grained visual acuity and discriminability, it is adaptive that this region occupies higher level visual cortex outside of extrastriate regions, occupying the region that would be the anterior extrapolation of the fovea (Levy, Hasson, Hendler, & Malach, 2001).

In summary, there are several studies showing that posterior regions of visual cortex in the left hemisphere are fine-tuned for words although responsive to other stimuli as well. Damage to these visual areas would therefore affect the processing of words more than other stimuli and, as such, provides one potential explanation of pure alexia. LBL reading is one manifestation of the impairment to this region of cortex. The reading deficit, however, likely results from a more general visual processing impairment.

6.4. Generalizability of the findings across cases

We have suggested that a visuoperceptual impairment may lie at the root of LBL reading. If this is indeed so, we would expect all LBL readers to evince such an impairment and the question is whether this is the case. Some researchers have argued for qualitatively different forms of the disorder (Rosazza, Appollonio, Isella, & Shallice, 2007) while others have suggested that there may not be a single basic deficit in LBL but that LBL may be a compensatory strategy adopted by all these different patients (Price & Humphreys, 1992). Ruling out a visuoperceptual impairment in all cases will require a stringent analysis of the patient's visual abilities, an approach not taken thus far in all studies. We repeat the appeal by Farah and Wallace (1991) to undertake detailed examination of these abilities in all individuals and we suggest that a fine-grained test should compare the processing of matched linguistic and non-linguistic stimuli. By using carefully designed stimuli (checkerboards where the level of visual complexity can be tightly controlled and symbols with features similar to letters and of a similar level of visual complexity but with no linguistic meaning), and comparing RT measures with those of control participants, the methodology provides a clear way of establishing whether LBL readers have any visual difficulties that might be expected to impact upon their reading.

We do not expect that every LBL reader will be identical—indeed, we see considerable variability even among our own cases. For example, although patient PA showed strong effects of position of difference and target location on her performance, she did not show substantial effects of length. Also, some, but not all, of our patients have co-occurring deficits such as in spelling or writing, as has been reported for other cases too (Friedman & Alexander, 1984). It remains a possibility then that there is some heterogeneity in the manifestation of the disorder and this variability requires further examination and explanation.

7. Conclusions

The aim of the studies reported in this article was to address the role of a visual-processing impairment as a possible causal factor in LBL reading, and to elucidate the mechanisms by which this occurs. All the patients tested showed impaired visual processing across a range of different visual materials and exhibited similar patterns of performance, with effects of length and left-to-right sequential processing. This occurred with both linguistic and non-linguistic stimuli, consistent with the notion of a close relationship and possibly even a causal role for visual difficulties in giving rise to LBL reading. We have also demonstrated that it is possible to design well-balanced materials to address the issue of visual processing in LBL reading in detail. These materials allow us to make direct comparisons of the processing of linguistic and non-linguistic stimulus strings for the first time, and to uncover how visual processing may potentially be responsible for LBL reading patterns. Finally, the data of a subset of the patient enable us to consider the claims of cortical specificity of a domain-specific orthographic region of cortex and we suggest that a domain-general impairment may underlie both the LBL reading and the more classic profile of pure alexia.

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Appendix A. Word list for Experiment 2: word and symbol matching

CANAL	BANAL	COARSE	HOARSE	PLATTER	CHATTER
NIECE	PIECE	HOLLOW	FOLLOW	BEQUEST	REQUEST
FABLE	TABLE	FASTER	MASTER	WISHING	FISHING
TRIBE	BRIBE	AERIAL	SERIAL	SLIPPER	CLIPPER
ALIVE	OLIVE	MIDDLE	FIDDLE	CULTURE	VULTURE
TENSE	SENSE	RATION	NATION	ROYALTY	LOYALTY
ROAST	TOAST	FICKLE	PICKLE	FAILING	RAILING
HASTY	NASTY	MORBID	FORBID	BADNESS	MADNESS
AURAL	MURAL	MUDDLE	PUDDLE	FIGMENT	PIGMENT
CAUSE	PAUSE	EFFECT	AFFECT	WITNESS	FITNESS
BUILT	GUILT	MOTION	NOTION	MILLION	BILLION
BRICK	TRICK	PORTAL	MORTAL	LOBSTER	MOBSTER
SEVER	SEWER	JUNGLE	JUGGLE	HARVEST	HARDEST
BLAND	BLIND	SIMILE	SIMPLE	PRIVATE	PRIMATE
NASAL	NAVAL	DECREE	DEGREE	TRACTOR	TRAITOR
BADGE	BARGE	HURDLE	HUDDLE	CROOKED	CROAKED
GRAND	GRIND	REPORT	RESORT	PLATTER	PLASTER
WRING	WRONG	HEARTH	HEALTH	REARING	READING
CRASH	CRUSH	GROVEL	GRAVEL	STUMBLE	STUBBLE
ABODE	ABIDE	CLENCH	CLINCH	TORRENT	TORMENT
GROPE	GRAPE	FRIEZE	FREEZE	WHISPER	WHIMPER
STYLE	STALE	EXCUSE	EXCISE	WORKING	WORDING
WHILE	WHOLE	BECOME	BECAME	FEELING	FEEDING
PURSE	PULSE	FILTER	FALTER	FENCING	FENDING
SCOUT	SCOUR	SQUIRT	SQUIRE	CONVENT	CONVENE
STARE	START	PATRON	PATROL	CONTENT	CONTEND
HEAVE	HEAVY	PRAYED	PRAYER	CLOTHES	CLOTHED
STEAM	STEAL	POSTER	POSTED	CRUISER	CRUISED
PEACE	PEACH	LOCKED	LOCKER	SLIPPER	SLIPPED
LEASE	LEAST	MATTED	MATTER	CHARTED	CHARTER
CHARM	CHART	ROBBED	ROBBER	THICKET	THICKEN
ADORN	ADORE	DISMAY	DISMAL	FIELDED	FIELDER
TRAIT	TRAIL	SHOVED	SHOVEL	TOURIST	TOURISM
CHEAP	CHEAT	BROKEN	BROKER	VICTORY	VICTORS
CLEAN	CLEAR	APPEAL	APPEAR	PRODUCE	PRODUCT
TOWER	TOWED	WALLET	WALLED	STEAMER	STEAMED

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