COGNITIVE NEUROPSYCHOLOGY, 2005, 22 (5), 589–602

Psychology Press
Taylor & Francis Group

PARALLEL PROCESSING BLOCKED BY LETTER SIMILARITY IN LETTER-BY-LETTER DYSLEXIA: A REPLICATION

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An investigation of the joint effects of orthographic neighbourhood size (N size) and of letter confusability in three letter-by-letter (LBL) dyslexics is reported. All three patients showed a facilitatory effect of increased N size with low letter-confusability words, but no N size effect with high confusability words. This exactly replicates previous observations by Arguin, Fiset, and Bub (2002) in another LBL dyslexic. A facilitatory N size effect requires parallel letter processing and the word recognition performance of normal readers is unaffected by letter confusability. The present findings therefore signal that the residual capacity for parallel letter processing in LBL dyslexia is blocked by letter similarity. This implies a deficit of letter encoding or identification, which appears to be a general feature of LBL dyslexia since it is exhibited by all of the four patients so tested.

INTRODUCTION

Letter-by-letter (LBL) reading is a type of acquired dyslexia associated with damage to the prestriate cortex of the dominant occipital lobe (Black & Behrmann, 1994; Damasio & Damasio, 1983). In a variety of tasks such as naming written words aloud or recognising words under limited viewing conditions, the performance of LBL readers is slow and laborious, and is markedly affected by the number of letters in the word. The impact of word length on reading speed is very large; word recognition times typically increase by half a second or more for every additional letter.

Based on these surface characteristics of the disorder—including the very slow performance and a linear influence of word length on reading speed—the traditional view has been that LBL readers identify written words by attending sequentially to their individual letters. Indeed, the choice of the term LBL reading to label the disorder is itself a theoretical claim about the nature of the process these patients must be using to identify a written word. To make explicit a strong version of this claim: The encoding of orthographic elements in normal readers yields an integrated perceptual representation, such that each individual component of the word is synthesised into a representation

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We are grateful to DM, JL, and JT for their generous collaboration. This study was supported by a grant from the Canadian Institutes of Health Research. Martin Arguin is chercheur-boursier of the Fonds de la Recherche en Santé du Québec.

http://www.tandf.co.uk/journals/pp/02643294.html
DOI:10.1080/02643290442000202

of the pattern as a whole (cf. Johnson & Pugh, 1994). This kind of orthographic representation is completely lacking in LBL readers, who decode words by sequentially attending to their constituent letters. LBL reading may benefit from some kind of feedback due to the patient's knowledge of word-level information, but individual letters are the elements that contact this information, and no form of integrated structure derived from the perception of orthographic units larger than single letters is directly available to the patient (Patterson & Kay, 1982; Warrington & Shallice, 1980). LBL reading is therefore qualitatively different from the perceptual process available to normal readers.

The view of LBL reading as a strict sequential process operating on individual letters has led to a number of theoretical interpretations of the disorder. These accounts either assume a general perceptual deficit that prevents normal parallel activation of words from constituent letters (e.g., Behrmann, Plaut, & Nelson, 1998), or they assume a more specific deficit affecting the mechanism that determines relational encoding of letters constituting the orthographic form of the word (e.g., Warrington & Shallice, 1980). Unfortunately, all such interpretations of the disorder are based on what appears to be an overly simplistic view of LBL reading, because evidence has increasingly called into question the assumption that patients have no direct access to an integrated structural representation when viewing printed words. The evidence in support of a residual parallel letter processing capacity in LBL dyslexia is discussed next.

Residual parallel letter processing

One kind of evidence indicates that LBL readers gain rapid but unconscious access to the orthographic form and meaning of words even though the display is quite rapid, too brief for explicit identification via a laborious LBL strategy. Thus, some patients can perform word classification tasks well above chance (e.g., discriminating between words and pronounceable nonwords) even before they have had sufficient time to explicitly identify the letters (Bub & Arguin, 1995; Coslett & Saffran, 1989; Lambon Ralph, Hesketh, & Sage, 2004). When assessed, this tacit form of word–nonword decision, occurring without the patient having conscious access to the specific identity of the target, shows no effect of array length on speeded responding, thereby demonstrating that this performance is supported by parallel letter processing (Bub & Arguin, 1995). In a related demonstration, a LBL reader's ability to identify upper-case words was reliably facilitated by a masked same-word prime in lower-case letters displayed for 100 ms (Bowers, Arguin, & Bub, 1996). The priming was clearly based on perceptual elements that transcended the particular form of a letter, given that primes and targets were presented in different case. In addition, the effect depended on processing all the constituent letters of the prime since no priming was observed for targets that differed from the prime by just one letter, regardless of the position of the letter in the string.

The evidence that LBL dyslexia does not completely abolish unconscious activation of written words implies that it is too strong a claim to argue that no higher-order perceptual units are directly available from print. But it remains possible that reading for the purposes of explicitly identifying words is indeed letter-by-letter, and that the tacit activation of words via parallel encoding of letters either involves entirely different processing mechanisms (Saffran & Coslett, 1998; but see Lambon Ralph et al., 2004, for evidence against this view) or is too weak to significantly affect the strategy that LBL readers must generally use to decipher written words (Behrmann et al., 1998).

There is enough preliminary evidence, however, to suggest that parallel letter processing contributes directly to the processes that determine explicit word recognition in LBL readers. In previous work, we have examined the effect of orthographic neighbourhood size (N size) on the reading performance of a LBL reader (IH). An orthographic neighbour of a target letter string is a word of the same length that differs from it by just one letter (Coltheart, Davelaar, Jonasson, & Besner, 1977). Normal readers identify written words with many neighbours more quickly than words with fewer neighbours in naming and lexical decision tasks (see Andrews, 1997, for a detailed review). IH shows a similar pattern; we have repeatedly demonstrated that the speed with which he identifies written words, though exhibiting all the typical features of LBL reading, nevertheless is strongly modulated by N size. Thus, IH showed a large linear reduction of word naming times as a function of a systematic increase in the number of orthographic neighbours of the target (Arguin et al., 2002).

In general, the fact that dense orthographic neighbourhoods can facilitate word recognition in certain reading tasks implies that the simultaneous activation of many words contributes positively to the identification of a target. Theoretical accounts of the facilitating role of a large number of orthographic neighbours, such as the interactive-activation model of Rumelhart and McClelland (1986), include the assumption that a word with many neighbours generates high levels of concurrent activation over candidates that share letters with the target. Because of this increased activity, the letter clusters in a word from a dense neighbourhood receive more excitatory feedback from the partially activated set of words that resembles it. Words with many orthographic neighbours are therefore more readily encoded than words with fewer neighbours (see Sears, Hino, & Lupker, 1999, for a discussion of recent theoretical interpretations of the N size effect).

A basic assumption shared by current models of normal reading is that for the facilitating effect of a large orthographic neighbourhood to occur, a number of letters in the printed word must be mapped at the same time onto stored representations of words. For example, Mozer (1987) developed a connectionist net with a layer of perceptual units that encodes letter clusters as triplets in four consecutive slots. Seidenberg and McClelland (1989) implemented a similar coding schema in their parallel, distributed model of written word naming and lexical decision. A recent statistical analysis by Sears et al. (1999) of the error scores derived from the performance of this latter computational model shows the expected N size effect. In general, error scores for words from large orthographic neighbourhoods were lower than the scores for matched words from smaller neighbourhoods.

We assume that the facilitatory effect of large neighbourhoods on reading performance could not occur in a LBL reader like IH if he was exclusively relying on a slow, sequential analysis of individual letter identities, without any access to larger units of orthographic structure. In keeping with this assumption, normal readers fail to show a facilitatory N size effect under conditions that disrupt their ability to perceptually integrate the letters in words. Snodgrass and Mintzer (1993) presented words in a series of increasing fragments and subjects were asked either to make successive attempts at identifying the word or to produce a single response. In neither case was there a beneficial influence of increased N size on performance. The successive guessing procedure yielded insubstantial effects of orthographic neighbourhood, and when subjects made a single identification response to perceptually fragmented words their accuracy was actually lower for words from large neighbourhoods than words from small neighbourhoods. The impairment for words from larger neighbourhoods occurred when word fragments were presented either quickly (167 ms/fragment) or slowly (1 s/fragment). Carreiras, Perea, and Grainger (1997) reported similar costs for large N size words under restricted viewing conditions (interleaved presentations of the target word and a mask). Pugh et al. (1994) found, in normal readers, that more orthographic neighbours hinder rather than enhance word identification if a letter distinguishing the target from its neighbours is delayed by 100 ms relative to the other letters. Arguin and Bub (1997) have reported a patient with a visuospatial attention deficit whose ability to identify written words was adversely affected by an increase in the number of orthographic neighbours differing from the target in letter positions she had difficulty attending. Perhaps demonstrating even more directly that parallel letter processing is required for a facilitatory N size effect is recent evidence from our laboratory showing that the orthographic neighbourhood size effect is entirely abolished in LBL dyslexia and normal readers as well if the letters making up the target word are presented sequentially (rate of 550 ms/letter; approximating the magnitude of the word length effect observed in several LBL dyslexics studied in our laboratory) in an incremental fasion from left to right (Fiset & Arguin, 2004; Fiset, Arguin, & McCabe, 2004).

In summary, reading words presented as a sequence of letters or of perceptually degraded fragments, or under other limited viewing conditions, either yields a cost associated with large N size or no effect thereof. By contrast, the evidence thus far indicates that the effect of a large orthographic neighbourhood on so-called LBL reading is facilitatory. We conclude that word identification, in at least some LBL readers, cannot simply be viewed as a piecemeal analysis of individual letters, but rather that it must involve parallel letter encoding as well. It should be underlined that this proposal implies a joint contribution of parallel and serial letter processing to overt word recognition performance in LBL dyslexia and that the residual parallel letter processing capacity is incapable of reliably supporting this performance on its own.

The N size effect as a second-order probe

Given the above, what, then, is the nature of the core deficit responsible for LBL reading? Further examination of the pattern of the N size effect in a LBL reader (IH) disclosed interesting deviations from the normal profile that afford some potentially important clues on the nature of his impairment. In normal readers, the facilitation due to large neighbourhoods is modulated by word frequency; there is little or no beneficial N size effect on the identification of high frequency words, in contrast to the substantial influence of this variable on the identification of lower frequency words (e.g., Sears, Hino, & Lupker, 1995). According to Andrews (1989), high frequency words have greater levels of resting activation than lower frequency words, and therefore reach the threshold needed for identification without the additional support of excitatory feedback from a large orthographic neighbourhood. Sears et al. (1999) obtained theoretical support for the observation that the N size effect is modulated by word frequency in their analysis of the orthographic error scores computed from Seidenberg and McClelland's (1989) parallel distributed model of word reading.

In previous research, we replicated the finding that normal readers show greatly reduced effects of N size with high relative to low frequency words in a naming task (Arguin, Bub, & Bowers, 1998). For IH, by contrast, the facilitation generated by a large orthographic neighbourhood was unaffected by word frequency. This result suggests that the activation of high frequency words from direct letter input is sufficiently altered in IH to benefit just as much as low frequency words from the feedback due to orthographic neighbours.

Further investigation disclosed an additional difference between IH and normal readers that provides an important clue on the nature of the deficit affecting the perception of orthographic units in LBL reading. Arguin et al. (2002) considered whether IH's reading efficiency depends on the degree to which each of the letters making up a word is visually confusable with other letters. These authors devised a confusability score for target words, based on the visual confusability of their constituent letters. The confusability value for a particular letter is defined as the probability of misidentifying the letter when it is displayed very briefly and masked. These values were obtained from published, empirically derived confusion matrices that were averaged (Gilmore, Hersh, Caramazza, & Griffin, 1979; Loomis, 1982; Townsend, 1971; Van der Heijden, Malhas, & Van den Roovaart, 1984). For each target word, confusability is defined as the average of the confusability scores of its constituent letters. Remarkably, normal readers under conventional viewing conditions identify words with high average confusability scores as quickly and accurately as they identify words with low confusability scores (Cosky, 1976). These findings were replicated separately in young (20–26 years) and older (51–66 years) normal readers by Arguin et al. (2002). By contrast, letter confusability had a substantial impact on IH; his reading performance was slower and less accurate for words that yielded higher average visual confusability scores.

Of considerable interest, letter confusability did not modulate the very substantial influence of word length that remains a hallmark of IH's reading performance. Thus, the perceptual difficulty occasioned by words with more visually confusable letters could not be affecting a sequential letter-by-letter process in IH. Indeed, if the locus of increased perceptual difficulty were indeed a process that operated sequentially on individual letters, then longer words should have produced bigger effects of high average letter confusability than shorter words. Instead, the impact of letter confusability was constant across different word lengths (four-, five- and six-letter words matched for word frequency, number of orthographic neighbours, and single-letter and bigram frequencies). This result provides converging evidence for the claim that LBL reading is not simply based on a sequential analysis of individual letters, but rather that parallel letter encoding also contributes to overt word recognition performance.

What impact, if any, does letter confusability have on the degree to which IH's reading is facilitated by the increased N size? The answer is clear: Normal readers show benefits of high N size on the speed with which they name words, regardless of whether the letters constituting the words yield high or low average confusability scores (Arguin et al., 2002). For IH, however, the facilitatory N size effect is markedly dependent on letter confusability. Larger neighbourhoods lead to better reading performance if words are made up of letters with low average visual confusability, but there is no advantage for high N size words if their letters are high in visual confusability. The fact that IH does not show facilitation if words with a large number of orthographic neighbours also contain letters of high visual confusability suggests that enough imprecision has developed around the activation of letter inputs to interfere with the supportive effect generated by the activation of many orthographic neighbours.

Relatedly, we note that a moderate degree of visual masking in normal readers can yield a small cost (instead of a benefit) for words associated with a large orthographic neighbourhood (Sears et al., 1999). Sears et al. suggest that if words are still reasonably visible under conditions of visual masking, readers may delimit a set of possibilities from partial letter information. If these possibilities include the orthographic neighbours of the target, a large neighbourhood would lead to a disadvantage because it becomes less likely that the word itself would be generated as the correct response. If one were to assume that some of IH's reading responses are driven by an inferential process based on partially specified letter information, then it should be expected that his performance would get worse with high N size words. Since IH actually shows no cost associated with high N size words even when the letters are high in visual confusability, it may be suggested that guessing based on partial letter information does not play a significant role in his performance.

The current study

We wish to test the generality of the findings obtained with IH, given their theoretical importance. In the present article, we assess three LBL readers in order to establish the validity of the evidence indicating that a large orthographic neighbourhood has a facilitating rather than an interfering effect on LBL reading. Furthermore, we wish to determine whether the performance of these additional cases replicates our finding that the facilitation is prevented by an increase in letter confusability. Confirmation of these results would provide a strong case against the view that LBL readers identify words by analysing individual letters without any access to an integrated orthographic structure. Assuming this evidence holds up under scrutiny, the very term that we now use to refer to the disorder is misleading, and the possibility emerges that LBL reading, despite the misconception associated with its name, holds important clues about the normal mechanisms of orthographic encoding.

EXPERIMENT 1

The purpose of Experiment 1 is to document the fact that the three patients investigated here do suffer from LBL dyslexia. In addition to examining the word length effect, we also investigated whether this effect is modulated by word frequency, as previously reported by Behrmann et al. (1998). Thus, patients were shown words one at a time for overt naming and the words varied orthogonally according to their length and their lexical frequency.

Methods

Participants

DM sufferred a left parieto-occipital haemorrhage resulting from the rupturing of an arterio-venous malformation at the age of 24. He was a university engineering student at the time. He has been the subject of a number of previous articles regarding his reading disorder and additional details on his condition can be found in these publications (Arguin & Bub, 1993, 1994; Bub & Arguin, 1995). His main behavioural symptoms were of a complete right-homonymous hemianopia, episodic memory difficulties, and reading problems. DM showed no evidence for any linguistic impairment in addition to his dyslexia.

JL was a retired engineer when he suffered a stroke with loss of consciousness in 1986, which led to his hospitalisation. Apart from his reading deficit, he had a dense right hemianopia and a mild anomia. Otherwise, his language was entirely normal and his spelling abilities were excellent.

At the age of 25, JT sufferred a massive intraventricular haemorrhage secondary to an arteriovenous malformation in the medial left occipital horn. He had a college education and he worked as an electronics technician before his haemorrhage. In addition to his dyslexia, he also exhibited a right hemianopia, a mild visual object agnosia, and a deficit of colour cognition (with normal colour discrimination), which was the object of a published report (Woodward, Dixon, Mullen, Christensen, & Bub, 1999).

Stimuli

Stimuli were 160 words divided equally among four lengths and two lexical frequency ranges, for 20 items per condition. Word lengths were of 3, 4, 5, and 6 letters. Low frequency words had a lexical frequency lower than 30 per million (average of 25; Francis & Kucera, 1982) and high frequency words had a frequency greater than 100 per million (average of 288).

Procedure

Each trial began with a 1500 ms fixation point, displayed at the centre of a computer screen. This was followed by the target printed in upper case, presented 1 cm to the left of fixation. The target remained visible until the subject's response. The task was to name the target as rapidly as possible while avoiding errors. All stimuli appeared in black over a white background and were printed in Geneva 24-point bold font. Responses were registered by a voice-key connected to the computer controlling the experiment. Each response was registered by the experimenter via the computer keyboard, who then triggered the next trial by a key press. Throughout the experiment, a total of 10 trials (2.1%) were lost due to the failure of the subject's response to trigger the microphone or from the triggering of the microphone by an anticipatory utterance or an incomplete response. These trials were not considered in the data analyses.

Results

The average correct RTs for each patient in each condition are illustrated in Figures 1–3. Correct RTs that were more than 3*SD*s away from the mean of their condition were rejected from data analyses (0.5%, 1.0%, and 3.5% of trials for DM, JL, and JT, respectively). For each patient the correlation between correct RTs and error rates was positive, thus indicating no speed–accuracy trade-off: $r(6)$ of +.68, +.37, and +.09 for DM, JL, and JT, respectively. The overall error rates were of 1.9%, 5.0%, and 5.3% for DM, JL, and JT, respectively. No patient showed a significant variation of his error rates across conditions, $\chi^2(3)$ of 0.0, 3.0, and 4.0 for DM, JL, and JT, respectively; $p > .25$ for all statistics.

All patients showed a significant linear effect of word length, with slopes ranging from 217 ms/item

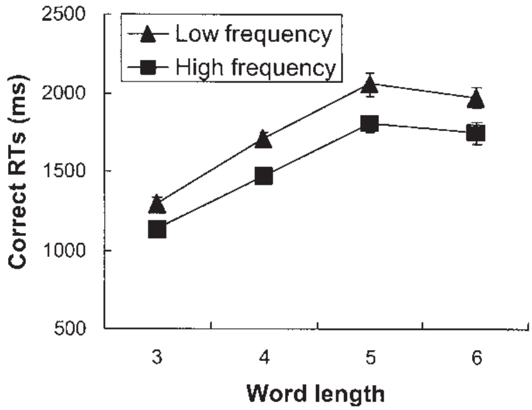

Figure 1. *Correct RTs and corresponding standard errors of DM in Exp. 1 as a function of word length (number of letters) and word frequency.*

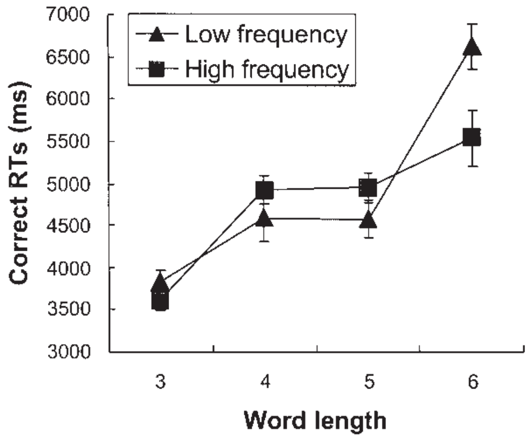

Figure 3. *Correct RTs and corresponding standard errors of JT in Exp. 1 as a function of word length (number of letters) and word frequency.*

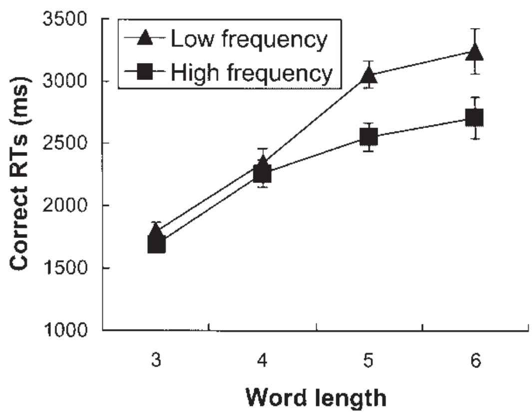

Figure 2. *Correct RTs and corresponding standard errors of JL in Exp. 1 as a function of word length (number of letters) and word frequency.*

to 835 ms/item, depending on the patient and on word frequency. The relevant statistics as well as the slopes of correct RTs as a function of word length are reported separately for each patient and each word frequency in Table 1. In addition to the effect of word length, DM also showed a significant main effect of word frequency, with shorter RTs for high frequency than low frequency words. No effect of frequency was found for JL and JT and no subject showed a significant interaction of length × frequency. It may be noted, however, that the linear regression analyses suggest a trend for weaker slopes with high than low frequency words, especially for JL and JT.

Discussion

Experiment 1 confirms that DM, JL, and JT suffer from LBL dyslexia. Each shows a substantial word length effect that is well outside the 10-15 ms/letter range documented in normal, neurologically intact readers (Forster & Chambers, 1973). None of the patients shows a significant modulation of his word length effect by lexical frequency. However, each of them shows some tendency for a magnified effect of word length with low frequency words, as opposed to those of high frequency, congruently with the observations of Behrmann et al. (1998).

EXPERIMENT 2

As indicated in the Introduction, previous investigations of LBL dyslexic IH have provided evidence that a residual capacity for parallel letter processing provides a significant contribution to overt word recognition performance in the disorder, but that this contribution is prevented when words are made

Table 1. *Statistics of the ANOVAs applied on the correct RTs of each patient in Exp. 1 as well as those pertaining to the regression analyses of RTs as a function of word length, which were conducted separately for low and high frequency words*

	DM	*JL*	*JT*
Frequency	$F(1, 148) = 8.5$	$F(1, 142) = 3.1$	$F(1, 137) < 1$
	$p < .005$	*ns*	*ns*
Length	$F(3, 148) = 18.5$	$F(3, 142) = 10.4$	$F(3, 137) = 9.1$
	$p < .001$	$p < .001$	$p < .001$
F × L	$F(1, 148) < 1$	$F(3, 142) < 1$	$F(3, 137) = 1.1$
	ns	*ns*	*ns*
Slope—Low F	239.5 ms/item	504 ms/item	835 ms/item
R^2	.80	.96	.81
Slope—High F	217.2 ms/item	335 ms/item	580 ms/item
R^2	.84	.93	.85

of high-confusability letters (Arguin et al., 1998, 2002). The goal of Experiment 2 is to investigate whether this is true of other LBL dyslexics. The present experiment therefore replicates the conditions of the crucial Experiment 4 of Arguin et al. (2002), which examined the joint effects of letter confusability and of orthographic neighbourhood size (i.e., N size). The latter factor is used as an index of the contribution of parallel letter processing to the word naming performance of patients.

In the previous investigation of Arguin et al. (2002), IH's word naming performance was greatly enhanced by increased N size with low letter confusability words. However, this facilitatory N size effect was abolished with words made of highly confusable letters. In contrast to the patient, normal readers (either young, 20–26 years, or age-matched to IH, 51–66 years) showed a moderate performance improvement with high N size words that did not vary according to letter confusability.

Methods

Participants

Participants were the same as in Experiment 1.

Stimuli

Subjects were administered a total of 870 stimuli, which were 4-letter upper-case words. These were distributed equally across 10 blocks of trials that were administered over a period of several days. Out of the total set of stimuli, 200 words were retained for analysis in the present experiment. These were precisely the same words as those used in Experiment 4 of Arguin et al. (2002). These words varied according to their numbers of orthographic neighbours (N size: low, 0–4 neighbours; high, 9 or more neighbours) and on the confusability of their constituent letters (low, confusability below .45; high, confusability of .53 or higher).[1] There was an equal number of words for each of these four conditions. Across conditions, words were matched on lexical frequency and on single-letter and bigram frequencies, all $Fs(1, 196) < 1$. The complete stimulus list used in Experiment 2 is reported in Appendix A.

Procedure

The progress of each trial and the procedure to register the responses from subjects were the same as in Experiment 1. For the entire set of trials

[1] The letter confusability scores were obtained by averaging the letter confusion matrices published in Gilmore et al. (1979), Loomis (1982), Townsend (1971), and Van der Heijden et al. (1984). They correspond to the total error rates for each individual letter of the alphabet. These values range between .24 (for the letter L) and .71 (for the letter B), with an average of .47 and a standard deviation of .13.

retained for the present experiment, a total of 10 trials (1.7%) were lost due to the failure of the subject's response to trigger the microphone or from the triggering of the microphone by an anticipatory utterance or an incomplete response. These trials were not considered in the data analyses.

Results

The average correct RTs for each patient in each condition are illustrated in Figures 4–6. Correct RTs that were more than 3 *SD*s away from the mean of their condition were rejected from data analyses (1.5%, 1.1%, and 2.5% of trials for DM, JL, and JT, respectively). For each patient the correlation between correct RTs and error rates was null or positive, thus indicating no speed–accuracy trade-off: $r(6)$ of .0, +.36, and +.57 for DM, JL, and JT, respectively. The overall error rates were of 0%, 8.0%, and 5.0% for DM, JL, and JT, respectively. No patient showed a significant variation of his error rates across conditions, $\chi^2(3)$ of .0, .04, and .04 for DM, JL, and JT, respectively; $p > .25$ for all statistics.

The outcome of the analyses of correct RTs for each patient are reported in Table 2. The main effect of N size, which was significant in JL and JT, reflected the fact that RTs were shorter with high than low N size words. The main effect of letter confusability, significant in DM and JL, indicated shorter RTs with low than high letter confusability words. The data of all three patients indicated that the occurrence of the N size effect was determined by the letter confusability level of words. Thus, with low letter confusability items, all patients showed a significant performance

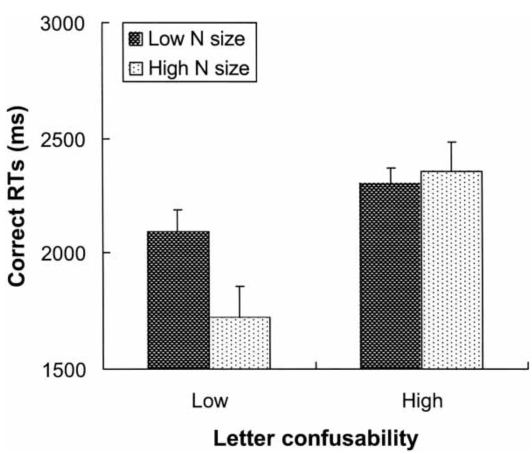

Figure 4. *Correct RTs and corresponding standard errors of DM in Exp. 2 as a function of N size and letter confusability.*

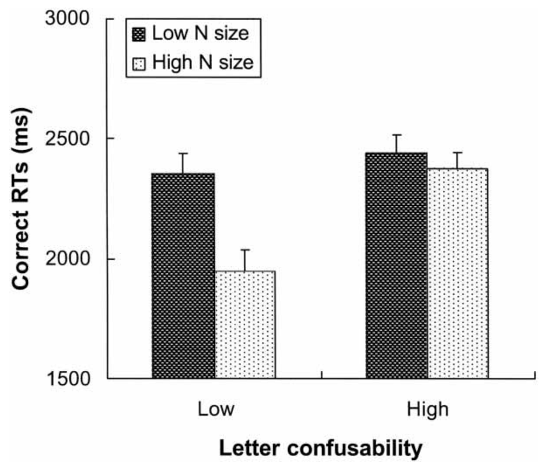

Figure 5. *Correct RTs and corresponding standard errors of JL in Exp. 2 as a function of N size and letter confusability.*

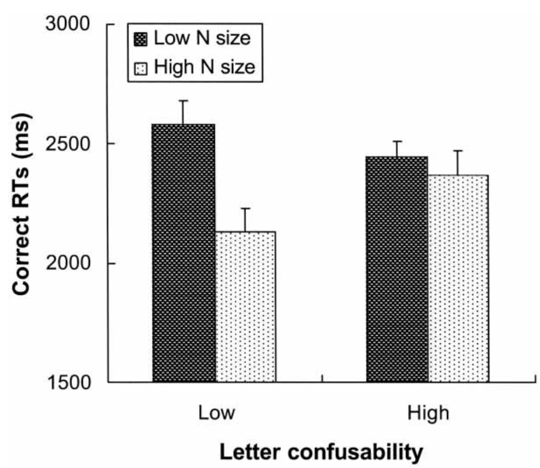

Figure 6. *Correct RTs and corresponding standard errors of JT in Exp. 2 as a function of N size and letter confusability.*

Table 2. *Statistics of the ANOVAs applied on the correct RTs of each patient in Exp. 2, as well as those pertaining to the analysis of the simple effects of the N size × Letter confusability interaction*

	DM	*JL*	*JT*
N size	$F(1, 193) = 2.1$ *ns*	$F(1, 174) = 8.8$ $p < .001$	$F(1, 182) = 7.6$ $p < .001$
Letter confusability	$F(1, 193) = 15.2$ $p < .001$	$F(1, 174) = 10.5$ $p < .001$	$F(1, 182) < 1$ *ns*
N × confusability	$F(1, 193) = 3.9$ $p = .05$	$F(1, 174) = 4.5$ $p < .05$	$F(1, 182) = 3.8$ $p = .05$
N size with low confusability	$F(1, 193) = 5.8$ $p < .05$	$F(1, 174) = 12.9$ $p < .001$	$F(1, 182) = 11.2$ $p < .001$
N size with high confusability	$F(1, 193) < 1$ *ns*	$F(1, 174) < 1$ *ns*	$F(1, 182) < 1$ *ns*

facilitation with high N size words relative to low N size (effect magnitude of 367, 410, and 453 ms, for DM, JL, and JT, respectively). However, this effect was entirely eliminated with high letter confusability words.

Discussion

The observations of Experiment 2 provide a complete replication of the previous findings of Arguin et al. (2002) with IH regarding the joint effects of N size and letter confusability. Thus, all three patients, DM, JL, and JT, showed a very substantial benefit of increased N size with low letter confusability words. The evidence regarding the N size effect is markedly different with high letter confusability words. In this case, all three patients investigated here failed to show an N size effect (all Fs < 1). As discussed below, the particular form of the N size × Letter confusability interaction reported here and in Arguin et al. (2002) as well as the fact that it is now precisely replicated in four LBL dyslexics have important implications for our understanding of the functional cause for the disorder.

GENERAL DISCUSSION

The goal of the present investigation was to determine whether the interaction of N size and letter confusability that was first documented in LBL dyslexic IH replicates in other patients with the same disorder, but who may vary according to superficial aspects of their behavioural symptoms. LBL dyslexia is characterised by the failure of parallel letter processing to support overt word recognition on its own, thereby forcing patients to decode words in an apparently serial, letter-by-letter manner. This defining feature of the disorder has long been interpreted as an indication that parallel letter processing is completely inactive in LBL dyslexia and that their residual reading performance is entirely mediated by sequential letter processing.

The occurrence of the facilitatory effect of N size in the disorder, however (Arguin et al., 1998, 2002; Montant & Behrmann, 2001), argues against this position. Indeed, as explained in the Introduction, the facilitatory N size effect on the overt reading performance of LBL dyslexics indicates a significant contribution of parallel letter processing to overt word recognition performance. Thus, a theoretical analysis of the facilitatory N size effect (see Arguin et al., 1998, 2002) indicates that it requires the parallel processing of the constituent letters of a word to occur. More importantly, when the simultaneous processing of all the letters in the word is effectively prevented, either by experimental manipulation (Carreiras et al., 1997; Fiset & Arguin, 2004; Fiset et al., 2004; Pugh, Rexer, Peter, & Katz, 1994; Snodgrass &

Mintzer, 1993) or by brain damage (Arguin & Bub, 1997), an increased orthographic neighbourhood size either has no effect or results in a performance decrement; i.e., an inhibitory effect. The most direct evidence that a facilitatory N size effect implies parallel letter processing has been obtained in normal readers and in LBL dyslexia with words displayed incrementally, one letter at a time. Indeed, with this form of presentation, which forces an exclusive sequential letter processing, the N size effect is completely abolished (Fiset & Arguin, 2004; Fiset et al., 2004). Most significantly as well, Arguin et al. (2002) have demonstrated the independence of the effects of N size and of word length on reading performance in LBL dyslexia. The direct implication of this finding is that the N size effect is not based upon the serial letter processing indexed by the word length effect, but instead that it originates from a parallel analysis of the letters within the word.

The observations reported here, as well as those of Experiment 4 of Arguin et al. (2002), show that the parallel letter processing capacity of LBL dyslexics that is indexed by the facilitatory N size effect is blocked by high letter confusability. This is a major observation inasmuch as it points to the functional impairment that appears to be the root cause of the parallel processing deficit in LBL dyslexia.

The factor of letter confusability refers to the visual similarity between a given letter and the remaining letters of the alphabet. Normal readers are entirely insensitive to this factor under standard stimulus exposure conditions (Arguin et al., 2002; Cosky, 1976). As shown here and in Arguin et al., however, the reading performance of LBL dyslexics is significantly degraded by increased letter confusability. This points to a low-level impairment affecting letter identification that concerns either the perceptual discrimination of letters or the mapping of their perceptual representations onto letter identities. With high letter confusability words, this letter encoding impairment entirely prevents parallel processing from contributing to overt word recognition performance in LBL dyslexia, as demonstrated by the form of the N size × Letter confusability interaction exhibited by patients. In the case of low letter confusability words, we argue that while the letter encoding impairment does not entirely block the contribution of parallel letter processing to reading performance, as demonstrated by the facilitatory N size effect, it nevertheless prevents it from reliably supporting overt word recognition on its own.

Indeed, the poor perceptual discrimination of letters or a deficient mapping of the shape representations of letters onto their identities means that there is an abnormal degree of noise, or uncertainty, at the letter identification process. Although higher-order processing pertaining to the recognition of the letter string may help resolve some of the ambiguity present at the letter level, it must also be realised that the magnitude of the noise problem that is present at this level can only be greatly amplified when it comes to identifying an item made of a combination of several letters, thereby preventing a decision as to the particular identity of the target word. This, we argue, is the fundamental reason why parallel letter processing fails to reliably support overt word recognition in patients, who must therefore rely on sequential letter encoding to perform this task.

Conclusion

The present report replicates, in three LBL dyslexics, the previous findings of Arguin et al. (2002) in patient IH, that high letter confusability prevents the facilitatory effect of increased N size that is evident with low confusability words. This result indicates that the residual capacity of LBL dyslexics for such processing is blocked by the increased letter discrimination difficulty imposed by high letter confusability words, which implies a deficit of letter discrimination or identification. The fact that residual parallel processing is blocked by high letter similarity in each of the four LBL dyslexics examined argues for the generality of the phenomenon.

Manuscript received 15 August 2003
Revised manuscript received 13 May 2004
Revised manuscript accepted 9 June 2004
PrEview proof published online 15 December 2004

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APPENDIX A

Stimulus list used in Experiment 2

Target	*Letter confusability*	*N size*
ALTO	Low	Low
AUNT	Low	Low
AUTO	Low	Low
CALM	Low	Low
CITY	Low	Low
CYST	Low	Low
DUCT	Low	Low
FACT	Low	Low
FAIR	Low	Low
FILM	Low	Low
FOLK	Low	Low
GAIT	Low	Low
GALA	Low	Low
GOUT	Low	Low
GULF	Low	Low
HAIR	Low	Low
HALO	Low	Low
HAUL	Low	Low
HAZY	Low	Low
HOLY	Low	Low
INCH	Low	Low
INTO	Low	Low
ITCH	Low	Low
KELP	Low	Low
KITE	Low	Low
KNIT	Low	Low
LAZY	Low	Low
LIAR	Low	Low
LIED	Low	Low
LILY	Low	Low
LION	Low	Low
LISP	Low	Low
LOAF	Low	Low
LOUD	Low	Low
NAVY	Low	Low
OILY	Low	Low
ONLY	Low	Low
PALM	Low	Low
PITY	Low	Low
PLAN	Low	Low
RICH	Low	Low
SALT	Low	Low
SOUL	Low	Low
THUD	Low	Low
TIED	Low	Low
TINY	Low	Low
TOAD	Low	Low
VARY	Low	Low
WATT	Low	Low
YELP	Low	Low
BAIL	Low	High
BULL	Low	High
CALL	Low	High
CART	Low	High
COLD	Low	High
COLE	Low	High
DALE	Low	High
DEAL	Low	High
DELL	Low	High
DICE	Low	High
DICK	Low	High
DILL	Low	High
DULL	Low	High

(Continued over leaf)

Target	*Letter confusability*	*N size*
FOIL	Low	High
GALE	Low	High
GOLD	Low	High
GULL	Low	High
LACE	Low	High
LAND	Low	High
LARD	Low	High
LAST	Low	High
LATE	Low	High
LEAD	Low	High
LENT	Low	High
LICE	Low	High
LIKE	Low	High
LOCK	Low	High
LOOT	Low	High
LUST	Low	High
NAIL	Low	High
PAIL	Low	High
PAIN	Low	High
PEAL	Low	High
PICK	Low	High
POLL	Low	High
PULL	Low	High
RAIL	Low	High
SILL	Low	High
TAIL	Low	High
TALE	Low	High
TELL	Low	High
TICK	Low	High
TIDE	Low	High
TILE	Low	High
TILL	Low	High
TOLD	Low	High
TOLL	Low	High
VAIL	Low	High
VALE	Low	High
YELL	Low	High
AMEN	High	Low
BABY	High	Low
BOAR	High	Low
BOMB	High	Low
BONY	High	Low
BRAN	High	Low
BRED	High	Low
BURN	High	Low
COMB	High	Low
DESK	High	Low
DOES	High	Low
DOOM	High	Low
DOOR	High	Low
DOWN	High	Low
EDEN	High	Low
EVEN	High	Low
FERN	High	Low
FREE	High	Low
GARB	High	Low
GERM	High	Low
GOES	High	Low
GOWN	High	Low
HAWK	High	Low
KNEE	High	Low
KNOB	High	Low
MARS	High	Low
MONK	High	Low
NORM	High	Low
OBEY	High	Low
OMEN	High	Low
OVER	High	Low
OXEN	High	Low
POEM	High	Low
ROAM	High	Low
ROMP	High	Low
ROOF	High	Low
SEWN	High	Low
SHAW	High	Low
SHED	High	Low
SNOW	High	Low
SOAK	High	Low
SPED	High	Low
STEM	High	Low
TERM	High	Low
TOMB	High	Low
USER	High	Low
VERB	High	Low
WEAK	High	Low
WHOM	High	Low
WOMB	High	Low
BAKE	High	High
BANK	High	High
BARD	High	High
BARN	High	High
BASE	High	High
BASK	High	High
BEAR	High	High
BLOW	High	High
BONE	High	High
BUNK	High	High
DONE	High	High
DOSE	High	High
FORK	High	High
FORM	High	High
GAME	High	High
GONE	High	High
HEED	High	High
HONE	High	High
HOSE	High	High
MADE	High	High
MANE	High	High
MARK	High	High
MEND	High	High
MOSS	High	High
MOST	High	High
PEEK	High	High
POSE	High	High
RAKE	High	High
REED	High	High
RODE	High	High
ROPE	High	High
ROSE	High	High
ROVE	High	High
RUSE	High	High
RUSH	High	High
SAGE	High	High
SAKE	High	High
SANK	High	High
SEAR	High	High
SEED	High	High
SENT	High	High
SORE	High	High
WADE	High	High
WAGE	High	High
WANE	High	High
WARD	High	High
WARM	High	High
WARN	High	High
WORN	High	High
WOVE	High	High