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# SEQUENTIAL AND PARALLEL LETTER PROCESSING IN LETTER-BY-LETTER DYSLEXIA

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Four experiments are reported that focus on the issue of sequential vs. parallel letter processing in letter-by-letter (LBL) dyslexia; these were conducted on patient IH. Expt. 1 showed a large linear reduction of word naming times with an increase in the number of orthographic neighbours of the target (i.e., words of the same length differing by just one letter; N size). Given the large negative linear correlation existing between word length and N size, this result raises the possibility that the large word length effect diagnostic of LBL dyslexia may be, in fact, an artefact of uncontrolled N size. Expt. 2 falsified this possibility by showing that the word length effect is unaffected by whether N size is controlled for or not. This result also suggested that the facilitatory effect of increased N size in LBL dyslexia is based on the parallel processing of the constituent letters of the target. Further supporting a contribution of parallel letter processing to overt word recognition performance in the disorder, Expt. 3 showed significant but independent effects of word length and letter confusability (i.e., similarity of the constituent letters of the target word with other letters of the alphabet). The letter confusability effect therefore appears to rest on the parallel analysis of the letters in the target word. Finally, Expt. 4 showed that the facilitatory effect of N size is prevented with high letter-confusability targets. These observations suggest that LBL dyslexia rests on an impairment of letter encoding that results in an excessive level of background noise in the activation of lexical-orthographic representations when letters are processed in parallel. This prevents overt identification of the target and forces sequential letter processing in order to achieve this goal.

## INTRODUCTION

Letter-by-letter (LBL) dyslexia is an acquired reading disorder caused by left occipital lobe lesions (Damasio & Damasio, 1983; Dejerine, 1892) in previously literate adults. Its diagnostic behavioural features are laborious reading accompanied by a large linear increase in the time required for the overt recognition of a word as a function of the number of letters it comprises (e.g., Patterson & Kay, 1982; Warrington & Shallice, 1980). This latter feature has traditionally been taken as an unambiguous demonstration that overt word recognition in LBL dyslexia proceeds by the slow, sequential identification of individual letters in the stimulus. This feature clearly distinguishes LBL dyslexics

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from neurologically intact adult readers, who appear to recognise words through the spatially parallel (i.e., simultaneous) processing of all letters in the stimulus. Indeed, in normal readers, the so-called word length effect characterising LBL dyslexia is either absent or extremely weak (Forster & Chambers, 1973; Frederiksen & Kroll, 1976; Weekes, 1997). Based on this feature, LBL dyslexia should be attributed to some impairment that prevents parallel letter processing, either to occur, or at least to access internal lexical representations in a way that would allow the recognition of the stimuli.

Mounting evidence has been gathered in recent years for a residual parallel letter processing capacity in LBL dyslexia. Indeed, several reports have provided indications for a phenomenon labelled implicit reading, whereby the performance of LBL dyslexics suggests an accurate lexical access for words they cannot identify overtly, which is based on the parallel processing of the letters constituting the stimulus (Arguin, Bowers, & Bub, 1996; Arguin, Bub, & Bowers, 1998; Bowers, Arguin, & Bub, 1996a; Bowers, Bub, & Arguin, 1996b; Bub & Arguin, 1995; Bub, Black, & Howell, 1989; Coslett & Saffran, 1989; Coslett, Saffran, Greenbaum, & Schwartz, 1993; Reuter-Lorenz & Brunn, 1990; Shallice & Saffran, 1986). Perhaps the most striking demonstration of implicit reading in LBL dyslexia has been observed in tasks of lexical or semantic decisions, where patients perform well above chance without being able to identify the stimulus explicitly. In these conditions, when assessed, the word length effect is absent, thereby indicating that implicit reading is achieved through the parallel processing of the letters of the target (Bub & Arguin, 1995; Coslett & Saffran, 1989). Related evidence has been provided by Bowers et al. (1996b) and by Arguin et al. (1998), using a priming paradigm where an upper-case target word to be named was preceded by a briefly exposed (i.e., 100 ms) lower-case prime that was then backward masked. Even though the exposure duration of the prime was insufficient for the subject to identify it overtly, substantial reductions of correct response times (RTs) were observed for target words preceded by same-word primes relative to unrelated primes. Moreover, this effect of same-word primes was entirely specific to the prime displayed and it was based on the processing of all of its constituent letters. Thus, no priming effect was observed for targets that differed from the prime by just one letter, no matter what the position of that letter was in the string (Bowers et al., 1996a).

The evidence for implicit reading in LBL dyslexia (i.e., residual lexical access based on parallel letter processing) has been obtained in conditions that did not require overt identification of the stimulus. Thus, the fast semantic or lexical decisions described earlier or the priming effects observed with brief prime exposure durations were obtained although the patient failed to provide signs of reliable overt recognition of the stimulus. In fact, Coslett and Saffran (1994; Coslett et al., 1993) have argued for a fundamental opposition between the processing strategies involved for overt word recognition and implicit reading, suggesting that the latter would only be possible when the patient is not attempting to identify the stimulus explicitly. These considerations raise questions as to whether parallel letter processing in LBL dyslexia has any impact on the overt word recognition performance of LBL dyslexics.

The first indication that parallel letter processing may indeed contribute to overt word recognition performance in LBL dyslexia has been provided by Howard (1991; but see Behrmann & Shallice, 1995, for discrepant findings). In a visual word naming task, he showed that the subset of correct reading responses that are the fastest in the response time distribution of LBL dyslexics result from the parallel processing of the constituent letters in the target. He also showed that this parallel process was subject to a significant rate of error. Howard further proposed that it was when this process failed that patients had to resort to serial letter processing for the overt recognition of a word. This study thus suggests that the lexical activation process assumed to be responsible for implicit reading may in fact allow the patient to recognise a word without serial letter processing on some proportion of trials.

More recent evidence for the notion that parallel letter processing provides a measurable contribution to overt word recognition in LBL dyslexics was reported by Arguin et al. (1998). In their study of LBL dyslexic patient IH, they examined the effect of the number of orthographic neighbours (i.e., N size) of the target word on overt naming latency and accuracy. Orthographic neighbours of a target letter string are words of the same length that differ from it by just one letter (Coltheart, Davelaar, Jonasson, & Besner, 1977).

In neurologically intact readers, an increase in the N size of a target word leads to reduced naming latencies and occasionally reduced error rates (Andrews, 1989, 1992; Arguin et al., 1998; Carreiras, Perea, & Grainger, 1997; Sears, Hino, & Lupker, 1995). This facilitatory effect of increased N size is considered to index a process involved in orthographic encoding (Andrews, 1989, 1992; Arguin et al., 1998; Carreiras et al., 1997; Coltheart et al., 1977; Pugh, Rexer, Peter, & Katz, 1994; Sears et al., 1995). Specifically, it appears that a visually presented word activates not only its own internal orthographic-lexical representation, but also, albeit to a lesser degree, that of its orthographic neighbours. According to the interactive activation model of visual word recognition from McClelland and Rumelhart (1981), this lexical activation is then assumed to provide facilitatory feedback to compatible representations at a preceding processing level responsible for the identification of the constituent letters of the stimulus. With more orthographic neighbours, therefore, more intense facilitatory feedback is sent from the activated lexical representations to letter representations compatible with the target. It is this greater degree of facilitatory feedback on the letter identification process with increased N size that is considered responsible for the facilitatory effect of this factor on reading performance. Crucially, the parallel processing of the constituent letters of the target is required for this facilitatory effect of increased N size. Indeed, if parallel letter processing is prevented, the N size effect reverses and becomes inhibitory. Thus, in normal readers, orthographic neighbours inhibit rather than facilitate performance if a letter distinguishing the target from its neighbours is delayed by 100 ms relative to the other letters (Pugh et al., 1994). Similarly, Arguin and Bub (1997) have reported a patient with a visuospatial attention deficit who showed a severe inhibitory effect of the number of orthographic neighbours, which differed from the target by the letter positions she had difficulty attending.

Arguin et al. (1998) have shown that N size has a facilitatory effect on the word naming performance of their LBL dyslexic patient (IH), thereby supporting the hypothesis of a contribution of parallel letter processing to overt word recognition. This parallel letter processing did not appear normal, however, as the facilitatory N size effect in IH did not vary as a function of the lexical frequency of the target, in contrast to what is found in neurologically intact readers. The latter show substantial facilitation from increased N size with low-frequency target words but a markedly reduced or absent N size effect with high-frequency words (Andrews, 1989, 1992; Arguin et al., 1998; Sears et al., 1995). IH's results therefore suggest that, although parallel letter processing may contribute to overt word recognition in LBL dyslexia, this processing is anomalous in some unknown manner, thus leading to an activation of internal lexical representations that is too weak or imprecise to support overt word recognition. Arguin et al. proposed that it would be because of this anomaly that LBL dyslexics must resort to sequential letter analysis to recognise visually presented words explicitly. In this respect, a specification of the impairment affecting parallel letter processing in LBL dyslexia appears fundamental for a proper understanding of the functional causes of the disorder and for any prospect of developing adequate rehabilitation methods (e.g., Arguin & Bub, 1994; Behrmann & McLeod, 1995). The present paper is a contribution toward this goal.

The experiments reported in this article were conducted on LBL dyslexic patient IH. They investigate the relation of the N size effect in LBL dyslexia to the issue of serial vs. parallel letter processing and use the interactive effects of N size with other stimulus parameters as an index of the impairment that prevents parallel letter encoding from reliably supporting overt word recognition. Based on the fact that the number of letters in English words is highly correlated with N size, Expts. 1 and 2 investigate whether the word length effect in the naming task, which is a diagnostic sign of the disorder, does indeed reflect serial letter processing or whether this observation is an artefact of the uncontrolled effects of N size. Expts. 3 and 4 investigate the role of visual similarity among letters in the modulation of the reading performance in LBL dyslexia and its interactive effects with N size and word length.

## CASE REPORT

The subject who took part in all the experiments described in this article, IH, has also been described in other papers (Arguin et al., 1998; Bowers et al., 1996a, b). We will thus summarise his clinical and neurological features only briefly. IH is a right-handed English-speaking male with 15 years of formal education who suffered from a subarachnoid haemorrhage in 1983. He was 59 years old at the time of testing. No CT or MRI scan are available but the neurological report indicates that the haematoma was located in the left temporo-occipital area. Performance on the WAIS intelligence scale indicated an IQ in the low normal range (global score of 90), with no asymmetry between the verbal (score of 89) and performance scales (score of 92). IH's main behavioural symptoms were a complete right-homonymous hemianopia, anomia, surface agraphia, and reading problems. His reading latencies averaged 1200–1500 ms for four-letter words and increased linearly by about 500 ms for each additional letter in the word. This linear effect of word length on naming latency classifies IH as a letter-by-letter dyslexic. IH also presents symptoms of surface dyslexia; his reading performance is affected by the regularity of spelling-to-sound correspondences as well as by lexical frequency (see Arguin et al., 1998 for additional details). The patient thus suffers from a combination of LBL dyslexia and surface dyslexia, a disorder identified by Patterson and Kay (1982) as Type II LBL reading, and by Friedman and Hadley (1992) as letter-by-letter surface dyslexia.

A number of subtests of the Psycholinguisitc Assessment Language Processing in Aphasia (PALPA; Kay, Lesser, & Coltheart, 1992) were administered to IH. These showed normal auditory phonological processing, with 67/72 correct on same-different matching with auditory minimal nonword pairs, and 71/72 correct with minimal word pairs. Auditory lexical processing also appeared intact, with IH accepting all the auditory words presented as being lexical items. Semantic processing was relatively spared, with a performance of 38/40 correct in matching spoken words to visual pictures. IH's poor performance (6/60 correct) on the Boston naming task (Kaplan, Goodglass, & Weintraub, 1983), however, revealed a severe anomia. This deficit was also markedly apparent in the patient's sponteneous speech, which comprised very many hesitations and circumlocutions, and a frequent incapacity to find any term appropriate to formulate even relatively common statements. The studies reported in this paper have been approved by the Ethics committee of the Institut Universitaire de Gériatrie de Montréal, where this work has been conducted.

## EXPERIMENT 1

A strong linear inverse relationship exists between N size and word length in English. Specifically, the longer the word, the smaller the number of its orthographic neighbours. For words ranging from three to six letters, this negative correlation is $r = -0.98$; with an average of 9.25, 6.01, 1.68, and 0.61 orthographic neighbours for three-, four-, five-, and six-letter words, respectively (see also Weekes, 1997). As indicated ealier, increased N size has a very large facilitatory effect on word naming performance in LBL dyslexia. For instance, Arguin et al. (1998) reported a reduction of correct RTs of 222 ms as N size increased from 0–3 to 11+ neighbours. This effect is about one order of magnitude greater than that observed in normal controls (e.g., Andrews, 1989, 1992; Arguin et al., 1998; Sears et al., 1995). In addition to Arguin et al., a large facilitatory N size effect has also been obtained by Arguin and Bub (1996) and by Montant and Behrmann (2001) in other LBL dyslexics. Given the magnitude of the N size effect and the fact that the value of this parameter decreases dramatically as word length increases, one legitimate question that may be raised is whether the word length effect in LBL dyslexia actually reflects the sequential processing of the individual letters comprising the word or whether it is an artefact of N size.

On its own, a linear increase of correct RTs as a function of word length, no matter how large, remains ambiguous as to whether letter processing is serial or parallel (see Snodgrass & Townsend, 1980; Townsend, 1990; for relevant discussions). For instance, one could imagine that letter processing still occurs in parallel in LBL dyslexia, but that this parallel processing capacity has become limited in a way that makes it overly sensitive to the effect of orthographic neighbourhood size. If this were so, RTs would increase linearly with increased word length, not because of serial letter processing, but instead because longer words have fewer orthographic neighbours. At present this alternative account of the word length effect cannot be excluded given that, to our knowledge, tests examining this effect in LBL dyslexia have never controlled for the likely mismatches in N size across words of different lengths.

The tests performed in Expts. 1 and 2 examine whether the word length effect characteristic of LBL dyslexia is an artefact of N size or whether it truly reflects the sequential processing of individual letters in the word. The results of these experiments will also be relevant to the issue of whether the occurrence of a facilitatory effect of increased N size in LBL dyslexia implies that parallel letter processing provides a significant contribution to overt word recognition. If the word length effect in LBL dyslexia is indeed an artefact of the negative linear correlation of this factor with N size, one prediction that may be made is that correct RTs in the word naming task will decrease linearly with increasing N size for words that are of a constant length. Although the observation of this result would not falsify the standard interpretation of the large word length effect characterising LBL dyslexia, it would certainly question its validity.

In Expt. 1, LBL dyslexic patient IH was asked to read aloud individually presented words of a constant length that varied according to four distinct levels of N size. Items from different levels of the N size factor were precisely matched on other fundamental stimulus parameters that would be likely to affect performance if left uncontrolled.

## Methods

*Stimuli.* Stimuli were 160 four-letter English words divided equally into four conditions defined according to orthographic neighbourhood size: 0–1, 4–5, 8–9, or 12–13 neighbours. Across conditions, words were matched on lexical frequency (Kuçera & Francis, 1967), $F(3, 156) = 1.44$; n.s., and single-letter, $F(3, 156) = 2.51$; n.s. and bigram frequencies, $F(3, 156) = 1.32$; n.s. (Mayzner & Tresselt, 1965).

*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 lowercase, presented to the left of fixation (because of the patient's right hemianopia), which remained visible until 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. After each response, the experimenter registered the subject's response via the computer keyboard and then triggered the next trial by a key press.

Throughout the experiment, a total of four trials (2.5 %) were lost due to the failure of the subject's response to trigger the microphone. These trials were not considered in the data analyses.

## Results

Average correct response times (RTs) and error rates are shown in Figures 1 and 2, respectively. The correlation between RTs and error rates was of +.97 ($p < .05$), which indicates no speed-accuracy tradeoff. Two data points (1.53% of correct trials) were removed from the RT analysis because response latencies were more than 3 *SD*s away from the mean of their condition.

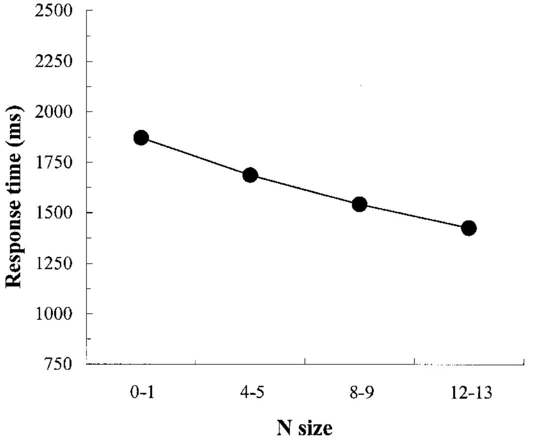

**Figure 1.** *Average correct response times (ms) in IH as a function of orthographic neighbourhood size (N size; Expt. 1).*

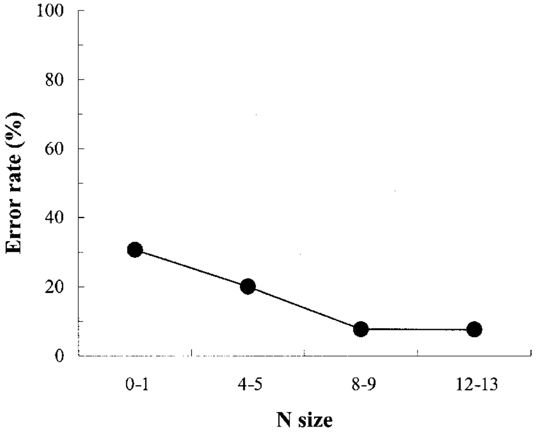

**Figure 2.** *Error rates (%) in IH as a function of orthographic neighbourhood size (N size; Expt. 1).*

An ANOVA performed on correct RTs showed a main effect of N size, $F(3, 125) = 4.56$; $p < .005$, with RTs decreasing linearly as orthographic neighbourhood size increased. A linear regression analysis of RTs as a function of N size indicated that each additional orthographic neighbour reduced response times by 37 ms and that this effect was linear ($r^2 = 0.98$).

A Chi-square analysis applied on error rates showed that the effect of orthographic neighbourhood size on error rates was significant, $\chi^2(3) = 9.21$; $p < .05$. Orthogonal comparisons revealed that IH was more accurate with words having 8–9 neighbours, $\chi^2(1) = 5.37$, $p < .025$, and 12–13 neighbours, $\chi^2(1) = 5.37$, $p < .025$, when compared to words having fewer neighbours. A linear regression analysis of error rates as a function of N size indicated that, for each additional orthographic neighbour, error rates declined linearly by 2.03% ($r^2 = 0.90$).

## Discussion

The results of Expt. 1 show a substantial linear decrease of correct RTs and of error rates as the N size of the target words is gradually increased. The facilitatory effect of increased N size replicates previous observations from IH that were reported by Arguin et al. (1998). For every additional orthographic neighbour the target word has, RTs decrease by an amount of 37 ms and error rates decrease by about 2%. The negative relation demonstrated by IH between his correct RTs and N size is congruent with the hypothesis presented earlier, that the word length effect in LBL dyslexia might not actually reflect sequential letter processing, but rather that it is an artefact of the correlation existing between word length and N size.

It may be noted, however, that given the present results, the word length effect predicted for IH by the N size artefact hypothesis is 112 ms/letter[1] for word lengths ranging between three and six letters. This is well below the relatively stable word length effect of about 500 ms/letter shown by IH. Even if this observation does not falsify the hypothesis that the word length effect in LBL dyslexia is entirely an artefact of uncontrolled N size, it certainly weakens its credibility. Nevertheless, the present results do suggest that N size may contribute significantly to the magnitude of the word length effect in the disorder. This will be examined in Expt. 2.

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[1] Prediction based on the observation of a linear reduction of correct RTs of 37 ms per additional neighbour and on the variation of the average number of orthographic neighbours across word lengths (see earlier).

## EXPERIMENT 2

If the word length effect in LBL dyslexia is an artefact of N size, either partially or completely, then it should be reduced or abolished if words of different lengths are accurately matched in terms of their numbers of orthographic neighbours. In Expt. 2, IH was required to identify overtly individually presented words comprised of a variable number of letters. In one condition, words of different lengths were matched on several important stimulus parameters, but not on N size. Consequently, in this uncontrolled list, items of increasing length had markedly decreasing numbers of orthographic neighbours. In another condition, words of different lengths were accurately matched again on several important variables, this time including N size. The key test performed in Expt. 2 was to determine whether the word length effect on the correct RTs of IH varied as a function of whether N size was controlled or not[2].

### Method

*Stimuli.* Two sets of 120 stimuli were used, including an equal number ($n = 40$ per level) of four-, five-, and six-letter words in each. In one set, words of different lengths were matched according to their number of orthographic neighbours. Thus, words of different lengths all had an average N size of 1.5, $F(2, 117) < 1$. In the other set of items, no control of neighbourhood density was performed. Consequently, there was a significant variation of N size across words of different lengths, $F(2, 117) = 46.38$, $p < .001$, with average N sizes of 4.85, 2.18, and 0.48 for four-, five-, and six-letter words respectively. Otherwise, in both stimulus sets, words of different lengths were matched according to lexical frequency, single-letter frequency, bigram frequency, and letter confusability (all tests for these matches produced, $F(2, 117) < 1$; letter confusability is an index of the shape similarity between a particular target letter and the remaining letters of the alphabet; see Expt. 3 for a more detailed description).

*Procedure.* The procedure was exactly the same as in Expt. 1, except that the stimuli were printed in capital letters[3]. Throughout the experiment, a total of three trials (1.25 %) were lost due to the failure of the subject's response to trigger the microphone. These trials were not considered in the data analyses.

### Results

Average correct RTs and error rates are shown in Figures 3 and 4, respectively. The correlation between RTs and error rates was of +.65 (n.s.), which indicates no speed-accuracy trade-off. One data point (0.56 % of trials) was removed from the RT analysis because the response latency was more than 3 *SD*s away from the mean of its condition.

A two-way ANOVA performed on correct RTs, with neighbourhood size control (N size control vs. no N size control) and word length as factors showed main effects of length, $F(2, 185) = 46.88$; $p < .001$, and of neighbourhood size control, $F(1, 185) = 3.98$; $p < .05$. These indicate that correct RTs increased as word length increased and that RTs were longer with than without N size control. The interaction between word length and N size control was not significant, $F(2, 185) = 1.50$; n.s.

Chi-square analyses of error rates as a function of word length showed a significant effect of length when N size was controlled for, $\chi^2(2) = 10.14$; $p < .01$, but no effect when it was not controlled, $\chi^2(2) = 0.13$; n.s.

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[2] A possible alternative experimental strategy would have been to construct a factorial design of word length × N size. This was attempted but it proved impossible to obtain a sufficient number of words per condition due to the very high correlation existing between word length and N size and to the limited number of words that are available in the English vocabulary.

[3] Letter confusion matrices are only available for upper-case letters and not for lower-case letters. Consequently, all experiments in which letter confusability is a factor (Expts. 3 and 4) or a control variable (Expt. 2) were conducted with stimuli printed in upper-case letters.

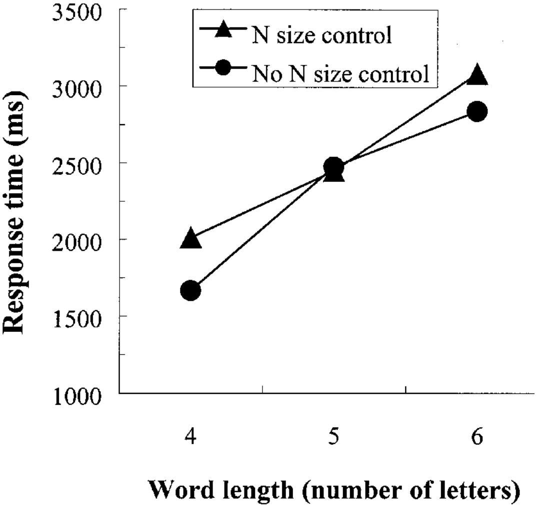

**Figure 3.** *Average correct response times (ms) in IH as a function of word length and N size control (Expt. 2).*

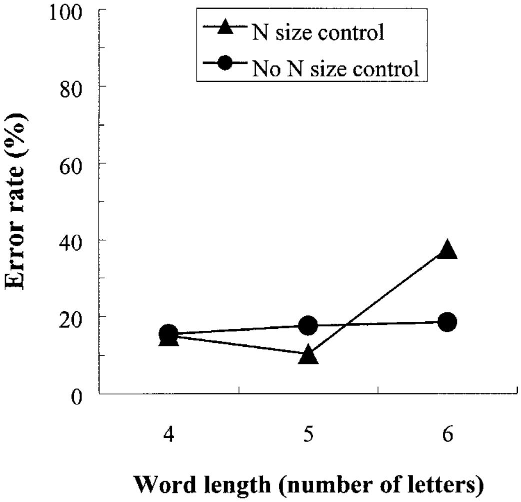

**Figure 4.** *Error rates (%) in IH as a function of word length and N size control (Expt. 2).*

## Discussion

The results of Expt. 2 indicate that the large and linear word length effect that has traditionally been taken as the diagnostic sign for LBL dyslexia is not an artefact of the correlation of this factor with N size. Thus, whether or not N size was controlled for in the examination of the word length effect on IH's RTs, the magnitude of this effect remained unchanged. One significant difference as a function of whether N size was controlled for or not is a uniform increase of correct RTs, independent of word length, in the former condition compared with the latter. This result simply reflects the fact that average N size was smaller when words of different lengths were matched for N size than when they were not. The observation, therefore, is congruent with the large facilitatory effect of increased N size in LBL dyslexia previously found in Expt. 1 as well as by Arguin et al. (1998), Arguin and Bub (1996), and Montant and Behrmann (2001). Another difference in the results as a function of whether or not N size was controlled pertains to error rates, which increased significantly with word length in the controlled list but not in the uncontrolled list. Although no obvious interpretation may be proposed for this latter observation, it should be underlined that it is the opposite of what should be predicted if the word length effect in IH was an artefact of N size.

Apart from being relevant for an interpretation of the word length effect in LBL dyslexia, the results of Expt. 2 also have implications for our understanding of the N size effect in the disorder. In the first examination of this factor in an LBL dyslexic, Arguin et al. (1998) argued that a facilitatory effect of increased N size must reflect a residual capacity for the parallel processing of the constituent letters of the stimulus. The main arguments involved in this reasoning, which are listed in the Introduction of the present paper, are indirect and concern classes of readers other than LBL dyslexics. The present results provide a direct indication that the effect of orthographic neighbourhood size may be independent from the sequential letter processing that mediates the word length effect. This therefore supports the position that the facilitatory N size effect in LBL dyslexia reflects a contribution of parallel letter processing to overt word recognition performance in the disorder. The possible reason why this residual parallel letter processing would fail to consistently support overt word recognition in the disorder (i.e., why serial letter processing is required) is the issue addressed in the following experiments.

## EXPERIMENT 3

A wide variety of markedly different hypotheses have been proposed in the literature on LBL dyslexia to account for the disorder (see, e.g., Arguin et al., 1998; Behrmann & Shallice, 1995; Bowers et al., 1996b, for reviews). Current evidence points to a low-level deficit prior to lexical access as the most likely possibility (Arguin & Bub, 1993; Arguin et al., 1998; Behrmann & Shallice, 1995). It remains unclear, however, exactly what this deficit might be. Some authors have argued that the letter encoding deficit in LBL dyslexia rests on a general impairment of the visuoperceptual function, which would affect the encoding of the shapes of letters and also of other nonlinguistic visual materials (Behrmann, Nelson, & Sekuler, 1998a; Behrmann, Plaut, & Nelson, 1998b; Farah & Wallace, 1991; Friedman & Alexander, 1984; Kinsbourne & Warrington, 1962; Levine & Calvanio, 1978; Rapp & Caramazza, 1991). However, except for the single-case study of Farah and Wallace (1991), the more or less subtle visual impairments demonstrated have never been shown directly to impact on reading performance in such a way that it could account for the disorder. Furthermore, the generality of the hypothesis is not entirely clear since LBL dyslexia may exist without concomitant evidence for a general visuoperceptual impairment, despite reasonable efforts on the part of experimenters to reveal such a problem (e.g., Arguin & Bub, 1993). Even then, however, evidence may be found that visual similarity among letters plays a key role in determining reading performance (Arguin & Bub, 1993). This kind of observation points to a possible deficit in either the encoding of letter shapes or in the function mapping letter shape information to subsequent processing stages.

In the context of previous unpublished tests of the impact of visual similarity among letters, our laboratory has developed a new stimulus parameter labelled "letter confusability." Letter confusability is defined as the shape similarity between a particular target letter and the remaining letters of the alphabet, with confusability values determined from empirical letter confusion matrices obtained in previous studies on neurologically intact observers (Gilmore, Hersh, Caramazza, & Griffin, 1979; Loomis, 1982; Townsend, 1971; Van der Heijden, Malhas, & Van den Roovaart, 1984). Specifically, the confusability value for a particular letter consists of the error probability in the identification performance of normal readers for that letter when it is displayed very briefly and then masked. For target words, letter confusability is the average of the confusability of their constituent letters. In pilot testing, increased letter confusability had no impact on the reading performance of neurologically intact observers (see also Expt. 4). Their correct word naming latency was of 485 ms for low letter-confusability target words (i.e., with confusability values of 0.42 or lower) and of 490 ms for high letter-confusability words (i.e., with confusability values of .53 or higher), $F(1, 9) = 1.03$; n.s. Error rates in the corresponding conditions were of 0.8% and of 1.1%, $F(1, 9) < 1$. By contrast, the average overt word recognition latencies of four LBL readers for four-letter words were increased by 225 ms (increase of 3.5% in error rates) by the same increase in letter confusability.

Expt. 3 examined the effect of letter confusability in patient IH in relation to the sequential letter encoding process that characterises the disorder. Specifically, the word length effect was tested in the naming task with items of either low or high letter confusability. Otherwise, items from different conditions were matched on several other stimulus parameters that may impact on performance. This test allows an examination of the effect of letter confusability (i.e., visual similarity among letters) on the processing of each individual letter in the sequential analysis required by LBL dyslexics for overt word recognition. If such a relation exists, the word length effect should vary as a function of the confusability of the letters making up the words. In particular, the magnitude of the word length effect should increase with high compared to low letter-confusability target words.

An alternative result is possible however, in light of our previous observations on the N size effect, which suggest a residual capacity for parallel letter processing in LBL dyslexics that contributes to their overt word recognition performance. This alternative is that letter confusability significantly affects overt word recognition performance in the disorder, but that this effect remains invariant across words of different lengths. The occurrence of such a result would further support the contribution of parallel letter processing in LBL dyslexia. It would also point to a possible cause as to why this parallel letter analysis cannot support overt word recognition on its own in the disorder and, hence, why sequential letter encoding is required for this performance.

## Method

*Stimuli.* Targets were 300 words divided equally into 6 conditions according to their length (4, 5, or 6 letters) and their letter confusability (low: confusability of .41 or below; high: confusability of .54 or higher). There were thus 50 words per condition. Across levels of the letter confusability factor, words of the same length were matched pairwise on lexical frequency, N size, single-letter and bigram frequencies, all *F*s (1, 98) < 1.

*Procedure.* The procedure was the same as in Expt. 2, except that the duration of the fixation point was 750 ms instead of 1500 ms. There was also a 250 ms blank interval between the fixation point and the onset of the target.

Throughout the experiment, a total of six trials (2%) were lost due to the failure of the subject's response to trigger the microphone. These trials were not considered in the data analyses.

## Results

Average correct RTs and error rates in IH are shown in Figures 5 and 6, respectively. The correlation between RTs and error rates was +.84 ($p < .05$), which indicates no speed-accuracy trade-off. Correct RTs that were more than 3 *SD*s away from the mean for their condition were discarded. Only one data point (0.45 % of correct trials) was removed from the analysis on this criterion.

A two-way ANOVA conducted on correct RTs with word length and letter confusability as factors showed main effects of word length, $F(2, 216) = 103.92$; $p < .01$, and of letter confusability, $F(1, 216) = 3.83$; $p = .05$. The interaction between these factors was not significant, $F(2, 216) < 1$. The main effects indicate increasing RTs with longer words and shorter RTs for low than high-confusability words.

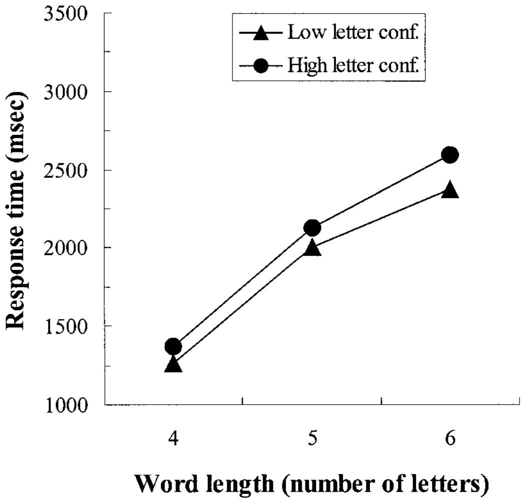

**Figure 5.** *Average correct response times (ms) in IH as a function of word length and letter confusability (Expt. 3).*

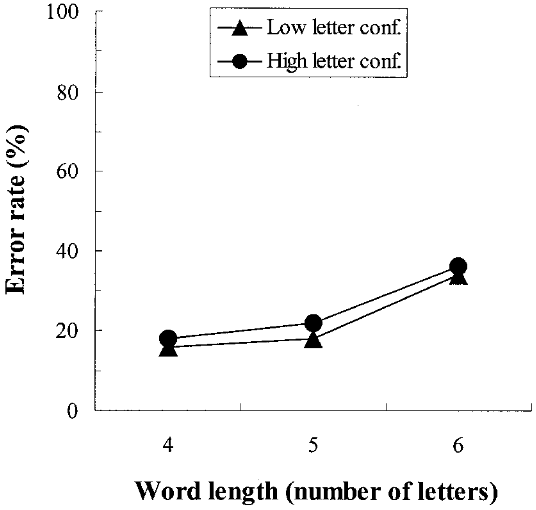

**Figure 6.** *Error rates (%) in IH as a function of word length and letter confusability (Expt. 3).*

Chi-square analyses of error rates as a function of word length indicated a significant effect of length for low-confusability words, $\chi^2(2) = 6.29$; $p < .05$, whereas this effect failed to reach significance with high letter confusability words, $\chi^2(2) = 4.72$; n.s.

## Discussion

The results of Expt. 3 show that whereas letter confusability had an impact on IH's overt word recognition performance, it failed to significantly modulate the magnitude of his word length effect. The main implication of this observation is that, although the visual similarity among letters does affect overt word recognition performance in IH, it appears to have no impact on the time required to identify individual letters in the sequential letter processing that is the hallmark of LBL dyslexia. In turn, this suggests that letter confusability mainly affects a form of processing independent of sequential letter analysis, whereby the constituent letters of the target word would be processed in parallel. In this respect, Expt. 3 provides converging evidence for one main conclusion of Expt. 2, namely that parallel letter processing appears to contribute to overt word recognition performance in LBL dyslexia, even though it seems incapable of supporting this performance on its own; i.e., without eventually resorting to sequential letter analysis.

An additional implication of the results of Expt. 3 is that they identify visual similarity among letters as a probable determinant of LBL dyslexia. Thus, the apparently abnormal susceptibility to letter confusability observed in IH (a formal test of the letter confusability effect in normal readers is provided in Expt. 4) points to an impairment affecting the discrimination between visually similar letters. In particular, it suggests that parallel letter processing in the patient cannot resolve the difference between visually similar letters completely and in a reliable manner. This problem is exacerbated with high letter-confusability target words. It is proposed that this difficulty may explain why parallel processing fails to support overt word identification in the disorder, as well as the obligation of LBL dyslexics to revert to a compensatory strategy of sequential letter identification for that purpose.

More specifically, instead of being able to identify positively each letter in the word examined, parallel letter analysis in LBL dyslexia may leave a significant degree of uncertainty about the identity of these letters. Transmitted to the level of lexical-orthographic representations, this uncertainty about letter identities should cause several candidate words to be significantly activated because of their compatibility with the degraded letter input. In terms of the decision mechanism involved in the absolute identification of the target word (i.e., "*x*, and not any other word, is the target"), this widespread activity among lexical representations translates into a high level of background noise against which the activation of the best (i.e., most highly activated) lexical candidate is assessed (e.g., Arguin & Bub, 1995; Luce, 1959, 1977). This background noise at the level of lexical orthographic representations may be excessive and may thus prevent the reliable identification of the target, except perhaps in a minority of trials leading to particularly fast overt identification responses, as shown by Howard (1991). Apart from these exceptional trials, however, LBL dyslexics would be forced to revert to sequential letter analysis for overt word recognition. One possible function of sequential processing would be to allow LBL dyslexics to focus their processing resources on single letters rather than spread them across the entire word, and thus resolve the difference between the letters that are shown and visually similar alternatives more effectively.

Expt. 4 will provide a test for the hypothesis that visual similarity among letters is a fundamental determinant of the incapacity of parallel processing of reliably supporting overt word recognition in LBL dyslexia. It will also provide a formal test of the letter confusability effect in neurologically intact readers, which is required to establish that the effect of this factor documented in LBL dyslexia is indeed abnormal.

## EXPERIMENT 4

Since LBL dyslexics may show a facilitatory N size effect on their overt word recognition performance, it must be concluded that they are capable of performing a degree of discrimination between the target word and its orthographic neighbours. Indeed, were this otherwise, the lexical-orthographic activation produced by the target would be lost in the background noise produced by the equally high activation of its orthographic neighbours. In such circumstances, there would be no reason to suppose that a larger N size should have a facilitatory effect on performance. In fact, we might assume just the opposite, as a greater degree of background noise should occur with high than low N size targets because of the larger number of activated lexical-orthographic representations (see Introduction for a relevant discussion of this issue).

Until now, the investigation of the N size effect in LBL dyslexia has only been conducted in the context of experiments that ignored any possible role of the visual similarity among the constituent letters of the target and other letters of the alphabet. The negative impact of increased letter confusability documented in Expt. 3, and the interpretation proposed earlier for this effect, suggest that words with different levels of letter confusability may differ in their potential to lead to a facilitatory effect of N size. In particular, since high letter confusability is assumed to magnify the degree of background noise in the activation of lexical-orthographic representations resulting from parallel letter processing, it should also negatively affect the capacity of an LBL dyslexic to discriminate between the target and its orthographic neighbours. Since this latter capacity is obviously essential for a facilitatory N size effect, it may be predicted that high letter confusability will either reduce or prevent a facilitatory effect of increased N size. With low letter-confusability target words, however, it should be possible to replicate the facilitatory N size effect previously found in IH (Arguin et al., 1998) and in other LBL dyslexics (Arguin & Bub, 1996; Montant & Behrmann, 2001).

Expt. 4 will assess this prediction in IH by using a word naming task where the N size and letter confusability of the target words are manipulated factorially. Distinct groups of young and age-matched neurologically intact readers will also be examined in Expt. 4 in order to determine whether their performance is affected by letter confusability and whether this factor interacts with N size. Words belonging to different conditions will be matched on other important properties to control their potential impact on the results.

### Method

*Subjects.* Subjects were IH, a group of 12 age-matched neurologically intact controls with a mean age of 55 years (range: 51–66) and a mean schooling duration of 16 years (range: 13–20), and another group of 10 neurologically intact university students aged between 20 and 26 years. All were right-handers and had normal or corrected vision.

*Stimuli.* Targets were 200 four-letter words varying orthogonally on their numbers of orthographic neighbours (N size: low, 0–4 neighbours; high, 9 or more neighbours) and on their letter confusability (low, confusability below .45; high, confusability of .53 or higher). There were 50 items in each condition. Across conditions, words were matched on lexical frequency and on single-letter and bigram frequencies, all *F*s (1, 196) < 1.

*Procedure.* For IH, the procedure was identical to that of Expt. 2. From his complete set of data, a total of seven trials (3.5%) were lost due to the failure of the subject's response to trigger the microphone. These trials were not considered in the data analyses.

The age-matched control subjects were tested on the same list and using the same procedure as for IH. Throughout their data set, a total of 27 trials (1.1%) were lost because the subject's oral response failed to trigger the microphone.

For the young normal controls, the observations for the relevant words were extracted from a large database comprising their reading performance on a total of 1285 four-letter English words. These databases were obtained for each subject in a sequence of 10 blocks of 120–130 trials within which items were distributed in a random order, with blocks also administered in a random order across subjects. Each trial began with fixation point of a 500 ms duration, followed by a 250 ms blank interval, and then by the upper-case target word centred on the location of ocular fixation. Subjects were required to name the target as rapidly as possible while avoiding errors. Across all trials on the relevant items, no trial was lost due to failure of the subject's response to trigger the voice-key.

## Results

Figures 7 and 8 show the correct RTs of the age-matched normal readers in each condition. Correct RTs that were more than 3 *SD*s away from the mean for their condition (1.1% of trials) were rejected as outliers. The correlation between correct RTs and error rates was +.54 (n.s.), thus showing no speed-accuracy trade-off. The ANOVA applied on the correct RTs observed in these age-matched readers, with factors of letter confusability and N size, showed a highly significant effect of N size, $F(1, 11) = 28.1$; $p < .001$, no effect of letter confusability, $F(1, 11) < 1$, and no interaction between those two factors, $F(1, 11) = 1.8$; n.s. The significant neighbourhood size effect indicates shorter RTs with targets that have many orthographic neighbours than with targets that have few. The analysis applied on error rates showed no main effect of either N size, $F(1, 11) < 1$, or of letter confusability, $F(1, 11) < 1$, but a significant cross-over interaction of N size x confusability, $F(1, 11) = 4.7$; $p = .05$. However, simple effect analyses of this interaction revealed no significant effect of orthographic neighbourhood size for either low, $F(1, 11) = 1.3$; n.s., or high letter confusability targets, $F(1, 11) = 2.1$; n.s.

Figures 9 and 10 show the correct RTs obtained in the young neurologically intact readers in each condition. Correct RTs that were more than 3 *SD*s away from the mean for their condition (0.6% of trials) were rejected as outliers. The correlation between correct RTs and error rates was +.82 (n.s.), thus showing no speed-accuracy trade-off. The analysis of correct RTs in the young normal readers showed a significant effect of N size, $F(1, 9) = 57.8$; $p < .001$, but no effect of letter confusability, $F(1, 9) = 2.1$; n.s., and no interaction, $F(1, 9) < 1$. The N size effect indicated shorter RTs for target words that have a large number of orthographic neighbours than for words that have few. The outcome of the data analyses on error rates largely paralleled that for RTs. Thus, the results showed a marginally significant facilitatory effect of increased N size, $F(1, 9) = 4.8$; $p = .05$, but no effect of letter

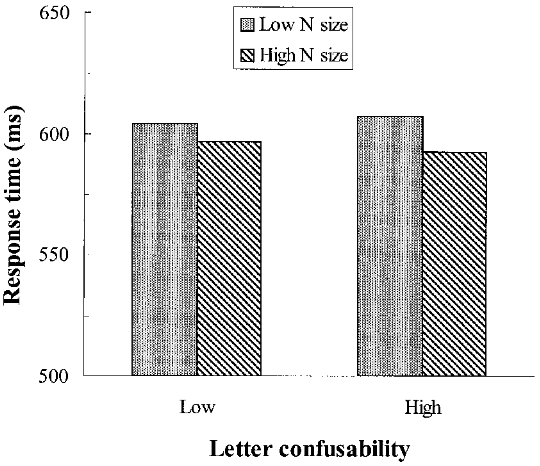

**Figure 7.** *Average correct response times (ms) in neurologically intact readers age matched to IH as a function of letter confusability and N size (Expt. 4).*

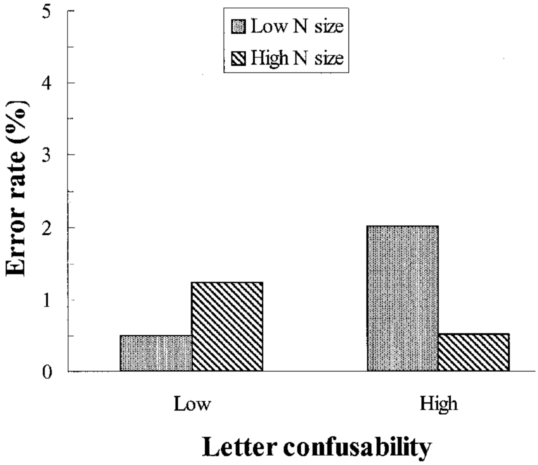

**Figure 8.** *Error rates (%) in neurologically intact readers age-matched to IH as a function of letter confusability and N size (Expt. 4).*

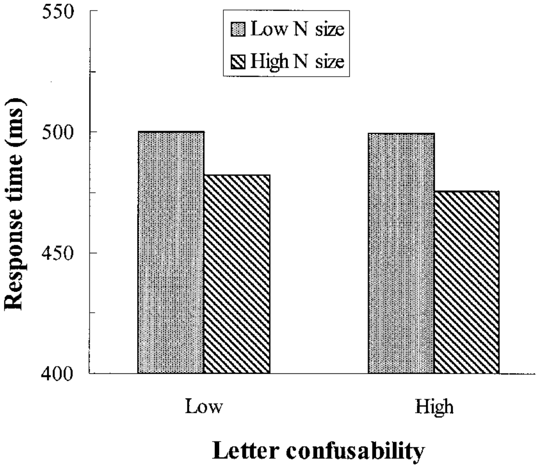

**Figure 9.** *Average correct response times (ms) in young neurologically intact readers as a function of letter confusability and N size (Expt. 4).*

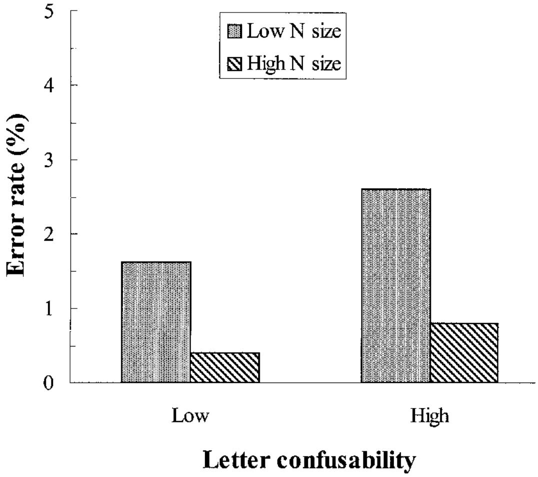

**Figure 10.** *Error rates (%) in young neurologically intact readers as a function of letter confusability and N size (Expt. 4).*

confusability, $F(1, 9) = 1.7$; n.s., and no interaction between N size and letter confusability, $F(1, 9) < 1$. Again, the N size effect indicates improved performance with the increased neighbourhood size of the target.

Average correct RTs and error rates for IH are presented in Figures 11 and 12, respectively. The correlation between RTs and error rates was +.98 ($p = .02$), which indicates no speed-accuracy tradeoff. Correct RTs that were more than 3 *SD*s away from the mean for their condition were discarded. A total of two data points (1.36% of correct trials) were removed from the analysis on this criterion. A two-way ANOVA conducted on correct RTs with orthographic neighbourhood size and letter confusability as factors showed a main effect of neighbourhood size, $F(1, 141) = 14.50$; $p < .001$, but no main effect of letter confusability, $F(1, 141) = 2.90$; n.s. However, the interaction of N size and letter-confusability was significant, $F(1, 141) = 8.18$; $p < .01$. Simple effects analyses indicated that increased N size had a facilitatory effect with low letter-confusability words, $F(1, 141) = 22.90$, $p < .001$. In contrast, N size had no effect with high letter-confusability targets, $F(1, 141) < 1$. A chi-square analysis showed there was no significant difference in error rates across conditions, $\chi^2(1) = 1.70$; n.s.

## Discussion

The present results indicate that the word naming performance of neurologically intact normal readers (in age-matched subjects and younger university students) is resistant to the effect of letter confusability. Thus, this factor had no impact on their performance and it did not prevent the facilitatory N size effect. In contrast, the results of LBL dyslexic IH show that the facilitatory effect of increased N size on his overt word recognition performance is prevented with high letter-confusability target words.

This result is accounted for by a degradation of the letter identity information that is passed by parallel processing to the lexical-orthographic representation system with high letter confusability. This degradation prevents the effective discrimination between the target and its neighbours (required for increased N size to facilitate overt word recognition performance) and thus blurs the contrast between their activations. However, this discrimination between the target and its orthographic neighbours appears possible with low letter-confusability target words, as a facilitatory effect of increased N size is observed with these items.

This residual discrimination capacity for low letter-confusability words observed in IH cannot be

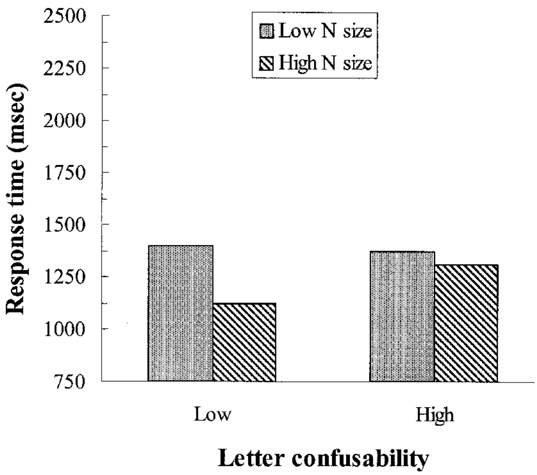

**Figure 11.** *Average correct response times (ms) in IH as a function of letter confusability and N size (Expt. 4).*

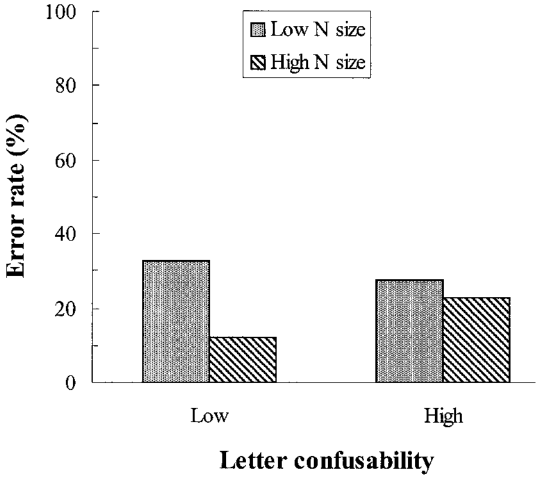

**Figure 12.** *Error rates (%) in IH as a function of letter confusability and N size (Expt. 4).*

conceived as normal by any means, however. Indeed, even with low letter-confusability words, the patient remains incapable of overtly recognising items based on parallel letter processing in a consistent manner (cf., Expt. 3), in contrast to neurologically intact readers (Forster & Chambers, 1973; Frederiksen & Kroll, 1976; Weekes, 1997). Furthermore, the magnitude of the N size effect with low letter-confusability is many times greater in IH (277 ms) than in either group of normal controls (age-matched; 8 ms; young; 18 ms). Again, this points to a severe anomaly of orthographic encoding in IH.

The account that is proposed, therefore, is that parallel letter processing in IH provides an impoverished input to the lexical-orthographic system with respect to the discrimination between visually similar letters and that an increase in letter confusability only worsens the problem. Because of this impoverished input, parallel letter processing cannot support overt word recognition and the patient is forced to examine the constituent letters of the target in sequence. With low letter-confusability targets, it is assumed that the activation contrast between the lexical representations of the target and its neighbours, although not sufficient to permit definite identification of the target, is large enough to allow a facilitatory effect of increased N size. With high letter confusability, however, it is proposed that the patient is no longer capable of reliably discriminating the target from its neighbours. In other words, it is hypothesised that the activation contrast between the target and its neighbours is either null or too weak to support the neighbourhood size effect.

## GENERAL DISCUSSION

The research reported in the present paper has focused on the issues of sequential and parallel letter processing in the acquired reading disorder of LBL dyslexia. Expt. 1 demonstrated that a parametric increase in the number of orthographic neighbours of the target causes a continuous, linear decrease of word naming times in LBL patient IH. The results of Expt. 2, however, showed that the magnitude of the word length effect in IH is not modified significantly by whether words of different lengths are matched or not on N size. These findings suggest that the word length effect in LBL dyslexia is not an artefact of N size, but rather that it truly reflects sequential letter processing. In turn, this also suggests that the facilitatory effect of increased N size in the disorder rests on parallel letter processing. The results of Expt. 3 demonstrated a cost of increased letter confusability on overt word identification performance in IH. They also suggest that the patient's rate of sequential letter identification is not affected by letter confusability, and thus that the latter effect only impacts on parallel letter processing. Congruently, Expt. 4 showed that the facilitatory effect of increased N size in the word naming performance of LBL patient IH is abolished if the words used are made of high confusability letters. In sharp contrast, no effect of letter confusability was observed in the performance of neurologically intact readers, who only showed a facilitatory effect of increased N size in Expt. 4. Taken together, the effects of N size and of letter confusability as well as the form of the interactive effect of these factors in IH provide key indications regarding the nature of his functional impairment and of the mechanisms involved in his residual reading capacity. These are discussed next.

## Parallel letter processing in LBL dyslexia

The notion that a residual capacity for parallel letter processing exists and that it may contribute to overt word recognition performance in LBL dyslexia is not widespread among investigators of the disorder. In fact, the only authors to argue for such a possibility thus far are Howard (1991) and Arguin et al. (1998). A residual contribution of parallel letter processing to overt word recognition in LBL dyslexics may be more widespread than previously thought, however. Indeed, in a separate investigation of three other LBL dyslexics, Arguin and Bub (1996) have found a facilitatory effect of increased N size on word naming performance in all of them (see also Montant & Behrmann, 2001). From the theoretical and empirical arguments discussed in this paper, the occurrence of such a facilitatory N size effect suggests that parallel letter processing contributes to overt word recognition performance in these patients as well. Clearly, however, parallel letter processing is incapable of supporting overt word recognition on its own in the disorder, hence the necessity of sequential letter identification. A likely reason for this incapacity is indicated by the letter confusability effect and the interaction of this factor with orthographic neighbourhood size, which were demonstrated in Expts. 3 and 4.

The results of Expt. 3 demonstrate a cost of high letter-confusability that does not vary significantly across different word lengths. This shows that orthographic encoding is constrained by visual similarity, which is congruent with previous observations pointing to an early impairment of letter encoding in LBL dyslexia (see, e.g., Arguin et al., 1998; Behrmann & Shallice, 1995, for reviews). In Expt. 4, the interaction of letter confusability × N size indicates that the facilitatory effect of increased orthographic neighbourhood size, although present for low letter-confusability words, is prevented by high letter confusability. We argue that this observation provides a fundamental insight with respect to the processes involved in visual word recognition in IH.

The occurrence of a facilitatory effect of increased N size implies that the activation of lexical-orthographic representations resulting from parallel letter processing can discriminate between the target and its orthographic neighbours. This discrimination is achieved by IH with low letter-confusability targets since his performance does benefit from increased N size in this condition. However, this discrimination between the target and its neighbours appears impossible with high letter-confusability items. In terms of lexical activations, this suggests that the background noise created by a high level of activation of the orthographic neighbours of the target has become too severe (compared to low letter-confusability targets) to permit the resolution of the target that is required for increased N size to facilitate reading performance. Given that this elimination of the N size effect occurs through a manipulation at the letter-level of the stimulus (i.e., letter confusability), it is proposed that the mechanisms involved in parallel letter processing in IH are impaired, such that they fail to provide a definite discrimination between the constituent letters of the target and other, visually similar, letters.

With low letter-confusability targets, the difference in the activation of the lexical representation of the target and those of its orthographic neighbours that results from parallel letter processing seems larger (i.e., reduced background noise relative to target activation) than with high letter-confusability words, thus allowing the N size effect to occur. Even then, however, the activation contrast between the target and other words appears insufficient to support overt identification performance. Thus, even with low letter-confusability targets, overt word recognition requires serial letter processing (cf. large word length effect in Expt. 3 with low letter-confusability words). It is argued that this situation is caused by the fact that a substantial degree of background noise still occurs in the activation of lexical-orthographic representations with low letter-confusability words, which prevents the reliable absolute identification of the target (i.e., that the item presented is *x* and not any other word; e.g., Arguin & Bub, 1995; Luce, 1959, 1977) based on parallel letter processing.

It may be speculated that the residual parallel processing capacity of LBL dyslexics suggested by the present findings is also responsible for the implicit reading phenomena previously described in a number of patients (see Introduction). Indeed, it appears that the key difference between tasks of absolute identification (as in the word naming task) and classification (as in the lexical or semantic decision tasks) concerns the decision criteria that are applied over the relevant set of internal representations (here, lexical-orthographic representations). Thus, Arguin and Bub (1995; see also Luce, 1959, 1977) have shown, on the basis of both empirical evidence and computational simulations, that absolute identification decisions rest on a signal-to-noise ratio criterion. Specifically, this type of decision appears to require the ratio of the activation of the target representation over that of all other representations within the relevant representation domain to reach a particular level before an identification response can be made. If this ratio is too low, because of an excessive level of background noise produced by the activation of alternative representations, no absolute identification response may be emitted. In contrast, Arguin and Bub (1995) proposed that classification decisions only require a sufficient overall level of activation to be reached within the relevant representation system, and that the degree of background noise existing in that system is irrelevant. This more lenient decision criterion, therefore, would allow correct classification responses even though the background noise produced by the activation of words other than the target would be so high as to prevent its absolute identification. Given these assumptions about decision criteria, the observation of implicit reading in LBL dyslexia is entirely congruent with the hypothesis, discussed earlier, of "noisy" lexical-orthographic activation resulting from a residual but impaired parallel letter analysis.

The neural basis of implicit reading in LBL dyslexia is currently an unresolved issue (see e.g., Behrmann et al., 1998b; Saffran & Coslett, 1998). The proposal that the residual parallel letter processing capacity of LBL dyslexics that contributes to overt word recognition is the functional basis for implicit reading relates to this issue. Saffran and Coslett (1998; see also Coslett & Saffran, 1994) have argued that particular right-hemisphere mechanisms, which are otherwise not involved in overt word recognition, would be responsible for implicit reading in LBL dyslexics. Clearly, most LBL dyslexics must encode visual stimuli via their right hemisphere because of a right hemianopia caused by the left occipital damage. Saffran and Coslett have presented arguments suggesting that the right-hemispheric contribution may extend well beyond perceptual encoding and that it may entirely support implicit reading. Possibly the most direct support for an extended contribution of the right hemisphere in LBL dyslexia comes from the study of Coslett and Monsul (1994). They have shown that transcranial magnetic stimulation (TMS) applied to the right temporo-parietal area of an LBL dyslexic had a dramatic impact on his reading accuracy (71% correct without TMS; 21% correct with TMS). TMS had no impact when applied to the homologous area of the left hemisphere. In contrast, Behrmann et al. (1998b) have argued that there is no need to invoke special right-hemispheric mechanisms to explain phenomena such as implicit reading. They proposed that these observations can be well accounted for on the basis of a single integrated reading system involving the left and right hemispheres, which would subserve both implicit and overt word recognition. By identifying the mechanisms involved in implicit reading with the residual parallel letter processing capacity modulating overt word recognition performance in LBL dyslexia, the hypothesis proposed earlier sides with the view proposed by Behrmann et al. It should be emphasised, however, that this position does not rule out the possibility of an advanced right-hemispheric contribution to the residual parallel letter processing capacity of LBL dyslexics. This remains an open issue that will require direct empirical testing to be resolved.

## Sequential letter processing in LBL dyslexia

Since residual parallel letter processing fails to support overt word recognition in LBL dyslexia consistently, it may appear unsurprising that sequential letter identification is required for this type of performance. At a deeper level of analysis, however, a fundamental issue concerns the reasons why the impasse reached by parallel letter processing with respect to word identification can be solved by patients reverting to sequential letter identification.

The independent effects of word length and of letter confusability observed in Expt. 3 suggest that sequential letter analysis in LBL dyslexic patient IH is relatively impervious to the negative impact of visual similarity among letters, which only appears to affect parallel processing significantly. This implies that whereas parallel processing may provide ambiguous information to lexical-orthographic representations about the constituent letters of the target word, sequential letter processing appears to provide clearer and more decisive information in this regard.

The difference between sequential and parallel letter processing may be characterised in terms of the way selective visual attention is allocated to target words. Specifically, parallel processing is associated with attention being spread over the entire surface area of the word. In contrast, sequential processing is associated with the narrowing down of the focus of attention on individual letters, which are scanned one after the other. One assumed function of focused attention is to increase the signal-to-noise ratio in the processing of the stimulus (Bashinski & Bacharach, 1980; Hawkins et al., 1990; Henderson, 1991; Hummel & Stankiewicz, 1998). Consequently, the focused attention to individual letters that is involved in sequential letter processing may be conceived as improving the capacity of the letter identification system to resolve the difference between visually similar letters and, therefore, of passing a more definite signal to the lexical-orthographic representation system about the identities of the letters constituting the target than parallel processing. This, of course, would be fundamental in LBL dyslexia since parallel letter analysis on its own is incapable of supporting overt word recognition due to unresolved uncertainty at the letter level. It is conceivable that focused attention at the letter level may also contribute to reading performance in neurologically intact observers when stimulation conditions, for instance, are particularly unfavourable (see, e.g., Behrmann et al., 1998b; Plaut, 1999; for relevant discussions). Similarly to LBL dyslexia, sequential letter processing in these circumstances would serve to improve the low signal-to-noise ratio at the lexical-orthographic level, which is itself caused by uncertainty regarding the identity of the constituent letters of the target word.

## Conclusions

The findings here suggest a view of LBL dyslexia whereby parallel letter processing still occurs and may contribute to overt word recognition performance. However, lexical activation resulting from this parallel letter analysis suffers from a level of background noise that is too high to permit the absolute identification of the target. Based on the letter confusability effect, it is argued that the background noise at the lexical level is a consequence of a problem preventing the letter identification stage in fully resolving the differences between visually similar letters. This implies, congruently with a number of previous observations, that the disorder of LBL dyslexia may be assigned to an impaired letter encoding stage (Arguin & Bub, 1993; Behrmann & Shallice, 1995; Kay & Hanley, 1991; Reuter-Lorenz & Brunn, 1990). It is proposed that these difficulties associated with parallel letter processing render sequential letter analysis mandatory for overt word recognition. Further, it is proposed that this sequential processing involves focused attention at the level of individual letters, which serves to reduce noise at the letter identification stage. Although the present study was conducted in a single LBL dyslexic, IH, observations congruent with the present view of the disorder have been obtained from distinct series of experiments in three other cases (patients DM, JL, and JT), which will be the object of a separate report.

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