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The breakdown of parallel letter processing in letter-by-letter dyslexia

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Two critical issues were examined regarding letter-by-letter (LBL) dyslexia: (1) What is the nature of the functional impairment responsible for the incapacity of LBL patients to overtly recognise words on the sole basis of parallel letter processing? (2) What is the purpose of sequential letter processing? Four experiments focusing on these issues were conducted in LH, an LBL dyslexic. Expt 1 showed facilitatory effects of increased phonographic neighbourhood size, lexical frequency, and imageability on the word naming performance of LH. These high-order effects reflect a modulation of parallel letter processing in LH and demonstrate that he is able to rapidly access phonological, lexical, and semantic knowledge during reading. Congruently, Expt 2 demonstrated that all three high-order effects are eliminated when words are presented one letter at a time, from left to right. Expt 3 showed that these high-level effects are also abolished if target words are made of letters that are highly confusable (i.e., visually similar) to other letters of the alphabet. These observations suggest that LBL dyslexia may rest on an impairment at the letter encoding level that causes an excessive level of background noise in the activation of higher-order representations (i.e., letter combinations) when letters are processed in parallel. An additional experiment (Expt 4) shows that the letter confusability effect is also eliminated when words are presented one letter at a time, from left to right. This latter finding suggests that compensatory sequential processing invoked by LBL dyslexics serves to avoid the confusion between visually similar letters, which is present with parallel letter processing, and to amplify the signal-to-noise ratio required to achieve overt word identification.

INTRODUCTION

Letter-by-letter (LBL) dyslexia is an acquired reading disorder caused by a left occipital lobe lesion (Binder & Mohr, 1992; Cohen et al., 2003; Damasio & Damasio, 1983; Dejerine, 1892). It is characterised by very slow reading rate and a large linear word length effect. Increases of word reading latencies in the order of 500−3000 ms per additional letter have been measured (Hanley & Kay, 1996; see, however, Sekuler & Behrmann, 1996, for milder cases). This performance pattern suggests a letter-by-letter strategy that contrasts with normal reading, where the number of letters has no significant impact on reaction times, at least with relatively short (six letters or less) high-frequency words or when the number of orthographic neighbours (N size; words of the same length that differ from the target by just one letter; Coltheart,

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Davelaar, Jonasson, & Besner, 1977) is matched across word lengths (Weekes, 1997).[1] This latter pattern of results indicates that normal subjects process letters in parallel for word recognition.

The view that LBL patients are completely unable to perform visual word recognition by a parallel processing of letters has been questioned over the last 20 years. A comprehensive investigation of a phenomenon referred to as implicit reading was first reported by Shallice and Saffran (1986). They showed that patient ML was capable of indicating the lexical status (i.e., if the stimulus is a word or not), despite being incapable of reading aloud the target word within the time allotted. Subsequent investigations performed in other patients found similar discrepancies, that is, above-chance lexical or semantic classification (e.g., whether the stimulus represent an animal or not) performance under brief presentation duration (between 100–250 ms, depending on the study) with little or no explicit word recognition (Coslett & Saffran, 1989; Coslett, Saffran, Greenbaum, & Schwartz, 1993; see Saffran & Coslett, 1998, for an overview). Such findings suggest that some LBL patients are capable of processing orthographic stimuli in parallel and of rapidly accessing lexical and semantic information. The ability to make lexical or semantic decisions on words without overtly recognising them is one of the most spectacular demonstrations that LBL dyslexics can rapidly access lexical/semantic knowledge through parallel letter processing.

There is a range of other findings that also suggests rapid activation of high-level representations in LBL dyslexics. For example, some patients show a word-superiority effect (Bowers, Bub, & Arguin, 1996b; Bub, Black, & Howell, 1989; Reuter-Lorenz & Brunn, 1990; see, however, Behrmann, Black, & Bub, 1990; Kay & Hanley, 1991). Semantic and orthographic repetition priming (Bowers, Arguin, & Bub, 1996a; Bub & Arguin, 1995) and the presence of a Stroop effect (McKeeff & Behrmann, 2004, in press) also provide support for the hypothesis that parallel letter processing is capable of activating high-level representations in LBL dyslexia.

Such evidence for preserved implicit reading in LBL dyslexics is only observed in a small fraction of patients (see Behrmann, Plaut, & Nelson, 1998). Coslett et al. (1993) have suggested that differences between patients for the presence/absence of implicit effects could be explained by the reading strategy used. These authors suggested that, in order to obtain implicit reading effects, dyslexic patients should abandon their typical letter-by-letter strategy and instead use a parallel strategy of reading. In our experience, many LBL patients are reluctant to do so, which limits the applicability of implicit reading tasks for the study of parallel letter processing and its breakdown in LBL dyslexia. Here, we use a word naming task that induces more consistent high-level effects.

Some researchers have provided evidence for the implication of high-level orthographic (i.e., lexical frequency and orthographic neighbourhood size) as well as semantic (i.e., imageability) variables in word naming (Arguin & Bub, 1993, 1996; Arguin, Bub, & Bowers, 1998; Arguin, Fiset, & Bub, 2002; Bowers et al., 1996a, 1996b; Howard, 1991; Kay & Hanley, 1991; Price & Humphreys, 1992; Sekuler & Behrmann, 1996; see Behrmann et al., 1998, for a review). These effects are qualitatively comparable to those found in normal readers: Increasing lexical frequency, imageability, or N size all lead to a reduction of reading latencies in most LBL subjects. Therefore, most dyslexics seem able to rapidly access their lexical and semantic knowledge, which contribute to their overt reading performance. Clearly, however, the achieved lexical/semantic activation remains partial since the threshold for explicit identification is rarely

[1] The fact that the word length effect in normal subjects is modulated by high-level effects such as lexical frequency and number of orthographic neighbours (Weekes, 1997) suggests that, without high-level feedback, the capacity of normal readers for parallel letter processing is limited. The rapid access to high-level knowledge thus appears necessary for the parallel processing of letters. However, difficulties in the rapid access to this knowledge could strongly alter the probability of efficient parallel processing.

reached, as demonstrated by the need of LBL patients to use a compensatory sequential reading strategy for overt word recognition. The discovery of a factor that modulates the activation of high-level knowledge would constitute an important lever in attempts to identify the cause of LBL dyslexia and why patients have to use letter-by-letter reading.

Recently, Arguin et al. (2002) have proposed that the disorder of LBL dyslexia may be caused by an impairment at the letter encoding stage (see also Arguin & Bub, 1993; Behrmann & Shallice, 1995; Kay & Hanley, 1991; Reuter-Lorenz & Brunn, 1990). For instance, Arguin et al. (2002) showed that the facilitatory effect of N size disappears when patient IH had to read words composed of high-confusability letters (letter confusability is defined by the visual similarity between a target letter and all other letter of the alphabet).[2] From this, they argued for a difficulty of letter encoding that prevents parallel processing from reliably supporting overt word recognition, thereby forcing the sequential letter processing that is characteristic of the disorder. This result suggests that whereas parallel letter processing provides ambiguous information to the lexical system about the letters of the target word, sequential letter processing can provide clear and decisive information in this regard (see also Arguin & Bub, in press). The specific cause of the N size effect observed in IH (and in all other patients tested) remains uncertain, however. One subobjective of the first experiment will be a better understanding of the N size effect.

The aim of this paper is to examine two critical issues regarding LBL dyslexia: (1) What is the nature of the functional impairment responsible for the incapacity of patients to reliably identify words through parallel letter processing? (2) What is the function of sequential letter processing in the disorder? The first set of experiments (Expts 1a–1c) was designed to verify if LH, a LBL dyslexic, shows high-level variable effects (orthographic neighbourhood size, lexical frequency, and imageability) in word naming latency. In the second set of experiments, we verified the effect of sequential presentation on the three high-level effects (Expts 2a–2c). The third set of experiments (Expts 3a–3c) was designed to investigate possible interactions between the effects of high-order variables and letter confusability. To address the second question, a final experiment was designed to verify the effect of sequential letter presentation on the confusability effect (Expt 4). In the General Discussion, we discuss the implications of our results for the modelling of letter-by-letter dyslexia.

CASE REPORT

The patient who took part in the present experiments is LH, a right-handed French-speaking male who was between 42 and 44 years of age at the time of testing. At the age of 39, in 1998, LH suffered a cerebral vascular accident in the context of a dissection of the left vertebral artery. An MRI scan revealed a region of loss of brain parenchyma with CSF density in the territory of the left posterior cerebral artery (Figure 1). The image is consistent with remote left posterior cerebral artery ischaemic stroke involving the medial occipital lobe and medial temporal lobe. LH's behavioural complaints are a complete right-homonymous hemianopia, reading problems, and a complete quadriplegia. A very mild memory problem and some word-finding difficulties are also reported by LH but these were not prominent in the neuropsychological examination.

In conversation, LH shows a very good vocabulary and impressive general knowledge. In order to verify our clinical impression, we evaluated LH on the Wechsler Adult Intelligence Scale III (WAIS III). This evaluation showed that LH

[2] This metric is based on published letter confusion matrices, which were averaged (Gilmore, Hersh, Caramazza, & Griffin, 1979; Loomis, 1982; Townsend, 1971; Van Der Heijden, Malhas, & Van Den Roovaart, 1984). Letter confusion matrices are only available for upper-case letters and not for lower-case letters. Consequently, all the experiments in this article were conducted with stimuli printed in upper-case letters.

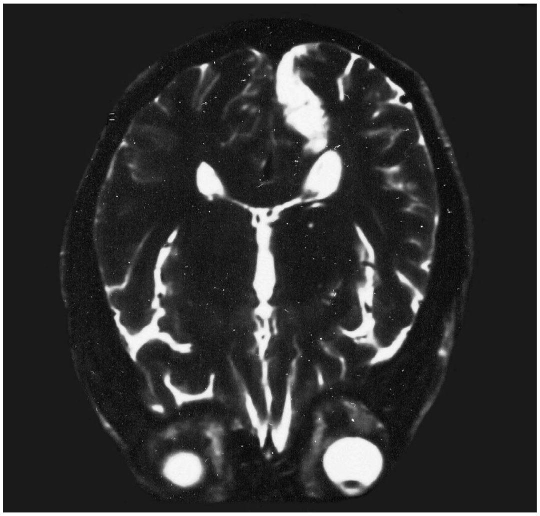

Figure 1. *MRI scan of LH.*

has a verbal IQ highly above average (144), with no significant difference between subtests. The performance IQ has not been evaluated because most tasks required the use of the hands. However, the few tasks used demonstrated very good nonverbal capacities in LH, as measured by the matrix reasoning (scaled score of 16) and the picture completion tasks (scaled score of 14). The intellectual capacities of this patient are thus preserved.

A number of subtests of the Birmingham Object Recognition Battery (BORB; Riddoch & Humphreys, 1993) were also administered to LH. He performed well within the normal range in tasks involving the discrimination of length (29/30), height (29/30), orientation (29/30), or of the spatial position of a blank space with a circle (29/30). LH identifies capital letters with ease when they are presented individually (26/26) or in superposition (54/54). Performance is also normal in the object decision (33/36) and object naming subtasks (73/76). These findings suggest that LH does not exhibit any obvious visual agnosia under these testing conditions.

We also administered reading and spelling tasks in order to verify the co-occurrence of other forms of dyslexia or dysorthographia. Naming of visually presented regular (56/56) and irregular (55/56) words as well as pseudowords (36/36) was accurate, with no significant difference across stimulus type. LH thereby does not suffer from either surface or phonological dyslexia. In a spelling task using regular and irregular words, LH showed a normal performance with no significant regularity effect (regular = 35/36, irregular = 34/36), thereby indicating no surface dysgraphia.

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.

WORD LENGTH EFFECT

This section investigates the word length effect in the reading performance of LH. We compared his performance with that of seven young neurologically intact subjects aged between 20 and 29. All were right-handers and had normal or corrected vision. They also took part in Expt 3, reported below, as controls. LH was administered a word naming task comprising 200 stimuli that ranged in length between four to seven letters (50 words of each length), matched across lengths on lexical and bigram frequencies, number of orthographic neighbours (N size), and letter confusability.

Table 1 shows the correct RTs obtained by LH in each condition. No trial was more than three standard deviations away from the mean of their condition in this task. An ANOVA conducted on the correct RTs with word length as factor showed a highly significant effect of length, $F(3, 149) = 26.8$, $p > .001$. Indeed, the patient's

Table 1. *Response times (in ms) for LH and the normal control subjects in the naming task as a function of word length*

String length	*LH*	*Control subjects*
4 letters	3456	470
5 letters	3728	465
6 letters	4314	470
7 letters	5013	488

average naming latency was of 3456 ms for 4-letter words and it increased linearly ($r^2 = .97$) by 526 ms for each additional letter in the word. A chi-square analysis of error rates as a function of word length showed no significant effect, $\chi^2(3) = 5.78$, *ns*.

Table 1 shows the correct RTs obtained in the neurologically intact readers for each condition. Correct RTs that were more than three standard deviations away from the mean of their condition (1.0% of trials) in the data of individual subjects were rejected as outliers. The correlation between correct RTs and error rates was of +.02 (*ns*), thus showing no speed–accuracy trade-off. The ANOVA applied on the correct RTs observed in these subjects with word length as factor showed a tendency for an effect of word length, $F(3, 6) = 3.4$, $p = .07$. Indeed, the naming latencies of young normal subjects increased by 6 ms ($r^2 = .57$) for each additional letter in the word. The analysis applied on error rates showed no effect of word length, $F(1, 6) = 1.1$, *ns*.

In order to rule out the possibility that output processing deficits may be contributing to LH's overt reading difficulties, the patient was asked to perform a lexical decision task. In this task, LH was shown words and pseudowords on a computer screen. He was instructed to say "yes" when he thought the stimulus was a word and "no" when he thought the stimulus was not a word (we could not use a button box due to LH's quadriplegia). A new list of 200 words, ranging in length from four to seven letters, was used for this lexical decision task. Across lengths, words were matched for lexical and bigram frequencies, N size, and letter confusability. The 200 pseudowords were constructed by changing one or two letters in a real word. All pseudowords were orthographically legal.

Table 2 shows the correct RT's obtained by LH in each condition. Five data points (1.8% of correct trials) were removed from the RT analysis because the response latency was more than three standard deviations away from the mean of its condition. A two-way ANOVA conducted on correct RTs with length and lexicality as factors showed main effects of length, $F(3, 272) = 35.7$, $p < .001$, and of lexicality, $F(1, 272) = 26.6$, $p < .001$. The interaction between these factors was not significant, $F(3, 272) < 1$. The main effects indicate increasing RTs with length and shorter RTs for words than for pseudowords. LH showed a linear length effect of 567 ms/letter ($r^2 = .96$) and 633 ms/letter ($r^2 = .99$) for words and pseudowords, respectively. Chi-square analysis of error rates as a function of word length showed a significant effect of length for words, $\chi^2(3) = 7.70$, $p < .05$, but no such effect for pseudowords, $\chi^2(3) = 1.17$, *ns*.

Table 2. *Response times (in ms) for LH and the normal control subjects in the lexical decision task as a function of word length*

	LH		*Control subjects*	
String length	*Words*	*Pseudowords*	*Words*	*Pseudowords*
4 letters	3800	4799	524	583
5 letters	4356	5239	543	616
6 letters	5206	6131	548	645
7 letters	5625	6391	542	628

Seven normal subjects served as controls in the lexical decision task. In contrast to LH, they responded by a keypress on a button box; they pressed the right button (with their right hand) to signal a word and the left button (with their left hand) to signal a pseudoword.

Table 2 shows the correct RTs obtained in the neurologically intact readers in each condition. Correct RTs that were more than three standard deviations away from the mean of their condition (1.8% of trials) were rejected as outliers. The correlation between correct RTs and error rates was of +.33 ($p < .05$), thus showing no speed–accuracy trade-off. A two-way ANOVA conducted on correct RTs with length and lexicality as factors showed main effects of length, $F(3, 6) = 9.8$, $p < .01$, and of lexicality, $F(3, 6) = 8.1$, $p < .05$. The interaction between these factors was not significant, $F(3, 6) = 1.2$, *ns*. The main effects indicate increasing RTs with length and shorter RTs for words than for pseudowords. The normal subjects show a linear length effect of 5.9 ms/letter ($r^2 = .53$) and 16.4 ms/letter ($r^2 = .65$) for words and pseudowords, respectively. The analysis applied on error rates showed no main effect of either length, $F(1, 6) = 1.9$, *ns*, or of lexicality, $F(1, 6) < 1$, and no interaction between these variables, $F(1, 6) < 1$.

To summarise, LH shows a significant word length effect in naming as well as in lexical decision and his performance is clearly distinct from that obtained by normal subjects. The fact that LH's anomalous performance occurs in a task that only requires visual recognition (lexical decision task) without spoken output indicates that his abnormal reading latencies are most likely due to an input processing deficit. Therefore, LH shows the characteristic clinical symptoms of LBL dyslexia.

EXPERIMENTAL STUDY

Experiment 1: High-level effects

In a literature review, Behrmann et al. (1998) showed that most dyslexic patients are faster when reading high (vs. low) lexical frequency words and high (vs. low) imageability words. Previous studies by Arguin and collaborators (Arguin & Bub, 1996; Arguin, Bub, & Bowers, 1998; Arguin et al., 2002; see also Montant & Behrmann, 2001) also showed a significant facilitatory effect of the number of orthographic neighbours. Expt 1 examined whether these variables modulate reading speed in LH.

Method

Procedure. Each trial began with a 500 ms fixation point displayed at the centre of a computer screen. This was followed by the target printed in upper case and presented to the left of the fixation point (because of the patient's right hemianopia), which 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 on a white background and were printed in Courier-New 24-point bold font. Stimuli subtended 2.20, 2.80, 3.45, and 4.05 degrees of visual angle for four-, five-, six- and seven-letter words respectively (height of 0.6 degree of visual angle). 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.

Experiment 1a: Orthographic neighbourhood size effect

As Montant and Behrmann (2001) have suggested, a facilitatory neighbourhood size effect may arise at various processing stages. In normal subjects, two hypotheses have been proposed to account for this effect. One, proposed by Andrews (1989, 1992, 1997), is based on the interactive-activation model of McClelland and Rumelhart (1981). This model proposed that the presentation of a written word activates not only the specific node associated with that word, but also the nodes of its orthographic neighbours. Through top-down activation, the activated lexical nodes facilitate letter recognition and this facilitation is greater for targets with a large N size given the greater number of activated lexical nodes. This hypothesis, exclusively lexical, offers an intuitive explanation for the facilitatory effect of orthographic neighbours found in dyslexics who frequently show difficulty in recognising letters (Behrmann & Shallice, 1995; Patterson & Kay, 1982; Perri, Bartolomeo, & Silveri, 1996). An alternative account of N size effect has been proposed, however, which rests on the fact that words with many neighbours have more body/rime neighbours that may disambiguate the pronunciation of the vowel in the target word (Treiman, Mullennix, Bijeljac-Babic, & Richmond-Welty, 1995). Congruently, Peereman and Content (1997) have shown that increasing N size has a facilitatory effect only if the orthographic neighbours are also phonological neighbours (phonological neighbours of a letter string are words of the same number of phonemes that differ from it by just one phoneme). It should be noted, however, that this demonstration has so far been conducted only using nonwords. One aim of Experiment 1a is to assess the above theories in order to understand the origin of the orthographic neighbourhood size effect in dyslexics.

The reading performance of LH was examined as a function of numbers of orthographic neighbours from either of two classes: phonographic neighbours and pure orthographic neighbours. Phonographic neighbours (PhN) are words that are both orthographic neighbours (same letter length, differ by one letter) and phonological neighbours (same phoneme length, differ by one phoneme) of the target. Pure orthographic neighbours (PON) are words that are orthographic but not phonological neighbours of the target. For example, the French word "TAIE" (/tε/) has "BAIE", "PAIE", "RAIE" (/bε/,/pε/,/rε/) as PhN but "TAPE" and "TAXE" (/tap/and/taks/) as PON. The logic is as follows: If the N size effect can be explained by a word-to-letter feedback mechanism, then increasing the number of orthographic neighbours (of whichever type) would help reading the target. If, on the contrary, the facilitatory N size results from the fact that lexical phonology is more readily accessible for large N size targets, then only phonographic neighbours will contribute to reading performance.

In Experiment 1a, LH was asked to read aloud individually presented words. The effects of PhN and PON were measured by comparing performances on words with few PhN and PON (baseline) to those with high PhN or high PON sizes, respectively. Given that the French language offers relatively few words with many pure orthographic neighbours, it was not possible to match the sets of PhN, PON, and control words triplet-wise on all fundamental stimulus parameters that would be likely to affect performance if left uncontrolled (lexical frequency, bigram frequency, letter confusability). In order to avoid this problem, the experiment was divided in two subtasks: (1) PhN task; (2) PON task. In each subtask, the words from the baseline condition were matched pairwise to those with either many PhN (task 1) or many PON (task 2).

Stimuli

1. PhN size task: Stimuli were 130 four- and five-letter French words divided equally into two conditions defined according to PhN (low: no PhN; high: more than four PhN). Across conditions, words were matched pairwise on the number of letters, lexical frequency (Content, Mousty, & Radeau, 1990), $F(1, 128) < 1$, bigram frequency, $F(1, 128) = 2.0$, *ns*, number of pure orthographic neighbours, $F(1, 128) < 1$, and letter confusability, $F(1, 128) < 1$.
2. PON size task: Stimuli were 76 four- and five-letter French words divided equally into two conditions defined according to pure orthographic neighbourhood size (low: no PON; high: more than four PON). Across conditions, words were matched pairwise on the number of letters, lexical frequency (Content et al., 1990), bigram frequency, number of PhN, and letter confusability, all Fs $(1, 74) < 1$.

Results

Four data points (3.4% of correct trials) were removed from the RT analysis of the PhN task because response latencies were more than three standard deviations away from the mean of their condition. No such outlier was removed from the RT analysis of the pure orthographic neighbourhood task.

PhN task. LH named high PhN size words significantly faster than low PhN words (4478 ms and 5383 ms respectively), $t(113) = 4.28$, $p < .001$. A chi-square analysis of error rates showed no significant effect of PhN size, $\chi^2(3) = 3.81$, *ns*.

PON task. The naming latencies for the low and high PON items did not differ significantly (4438 ms and 4319 ms respectively), $t(69) < 1$. A chi-square analysis of error rates as a function of PON size showed no significant effect of this factor, $\chi^2(3) = 0.21$, *ns*.

Discussion
Experiment 1a has demonstrated a PhN size effect on LH's naming latency. This replicates and extends the findings of Arguin et al. (Arguin & Bub, 1996; Arguin et al., 1998, 2002) showing that LBL dyslexics are sensitive to N size. Furthermore, our results support the conclusions of Peereman and Content (1997), who suggested that the facilitatory effect of the number of orthographic neighbours in naming comes from the fast activation of the neighbours that have a similar pronunciation to that of the target. Furthermore, the present results demonstrate that the phonographic neighbourhood size effect applies to words, rather than being restricted to nonwords (Peereman & Content, 1997). Although our interpretation of the orthographic neighbourhood size effect is quite different from that proposed by Arguin et al. (1998, 2002; Arguin & Bub, 1996), we maintain that it reflects the implication of parallel letter processing in letter-by-letter dyslexia (see Experiment 2 for direct empirical support). The results obtained here thus suggest an important role of phonological information in the probability of an efficient parallel letter processing in dyslexics patients (see also Montant, 1998).

Experiment 1b: Lexical frequency effect

N size is not the only high-level variable known to influence reading latency in LBL dyslexia. Thus, Behrmann et al. (1998) have reported evidence for lexical frequency and imageability effects in some LBL dyslexics. Experiments 1b and 1c are designed to assess these effects in LH.

Stimuli
The targets were 110 four- and five- letter words divided equally in two conditions defined according to lexical frequency (low: less than 2000/100 million; high: more than 5000/100 million in the Brulex database; Content et al., 1990). There were 55 targets in each condition. Across conditions, words were matched pairwise according to their number of letters, bigram frequency, PhN size, and letter confusability (all Fs < 1).

Results
One data point (0.9% of correct trials) was removed from the RT analysis because the response latency was more than three standard deviations away from the mean of its condition. High-frequency words (3845 ms) resulted in shorter response latencies than low-frequency words (4928 ms), $t(100) = 5.37$, $p < .001$. This replicates the frequency effects reported in a number of investigators in LBL dyslexics (see Behrmann et al., 1998). The number of errors in LH's data was not sufficient (only 1% of trials) to allow a chi-square analysis.

Experiment 1c: Imageability effect

Experiment 1c was designed to assess the imageability effect with LH. Norms for imageability were obtained in our laboratory in 12 normal subjects. Subjects had to judge the imageability of written words on a 7-point scale, where 1 meant a very low imageability and 7 a very high imageability level.

Stimuli
The targets were 120 five- and six-letter words divided equally in two conditions defined according to imageability (low: less than 2; high: more than 5). There were 60 targets in each condition. Across conditions, words were matched pairwise according to their number of letters, lexical frequency, bigram frequency, PhN size, and letter confusability (all Fs < 1).

Results
One data point (0.8% of trials) was removed from the RT analysis because the response latency was more than three standard deviations away from the mean of its condition. High-imageability words (5237 ms) resulted in shorter response latencies than low-imageability words (6322 ms), $t(111) = 3.0$, $p < .005$. This replicates the imageability effects reported previously by Behrmann et al. (1998) in LBL dyslexics. The number of errors in LH's data (two) was not sufficient to allow a chi-square analysis, but it may be noted

that both errors were made in the low imageability condition.

Experiment 2: High-level effects with serial letter presentation

In Experiment 1, we showed that the reading performance of LH is modulated by three high-level variables, namely PhN size, lexical frequency, and imageability. We suggest that these effects reflect the implication of parallel letter processing in LH's reading. If this suggestion is correct, it should be possible to eliminate these high-level effects by sequential letter presentation, a procedure that effectively prevents any possibility of parallel letter processing. The aim of Experiment 2 is to assess this working hypothesis. In order to ascertain that the words chosen for these tasks had the capacity of provoking high-level effects, the results obtained with this sequential paradigm were compared with those obtained 2 months later with the same words but using a procedure identical to that of Experiment 1.

Method

Procedure. Each trial began with a fixation point that was presented at the centre of the computer screen for 500 ms. The first letter of the word followed immediately thereafter. Each subsequent letter appeared incrementally at a rate of one additional letter every 550 ms, proceeding from left to right. Letters were printed in upper case and they remained visible until the subject's response. LH was instructed to name the word as quickly as possible while avoiding errors. Response times were measured from the onset of the last letter in the word. As in the preceding experiments conducted with LH, all letters were presented to the left of the fixation point. All words used in this experiment were chosen to have an orthographic uniqueness point (the position of the first letter, reading from left to right, that distinguishes a word from all other printed words, Kwantes & Mewhort, 1999) on the last letter in order to prevent LH from guessing the word before the end of the sequential presentation. The procedure for the control experiment (i.e., classical word naming paradigm) was the same as for Experiment 1.

Experiment 2a: Phonographic neighbourhood size effect

Stimuli

The targets were 80 five-letter words divided equally into two conditions defined according to the number of PhN (low: 0; high: 5 or higher). There were 40 targets in each condition. Across conditions, words were matched pairwise according to their number of letters, lexical frequency, bigram frequency, and letter confusability (all Fs < 1).

Results

The observations with sequential and simultaneous presentations were treated jointly for data analysis. Correct RTs that were more than three standard deviations away from the mean of their condition (2.1% of correct trials) were rejected as outliers. The correlation between correct RTs and error rates was of $+.24$ (*ns*), thus showing no speed–accuracy trade-off. A two-way ANOVA performed on correct RTs with the type of presentation (sequential vs. simultaneous) and PhN size (low vs. high) as factors showed a significant interaction between these factors, $F(1,\ 144) = 12.5$, $p = .01$, a significant effect of type of presentation, $F(1,\ 144) = 136.6$, $p < .001$, and a significant effect of PhN, $F(1,\ 144) = 10.8$, $p = .001$. Simple effects analysis indicated that the modulation of LH's performance by PhN was significant when the letters were presented simultaneously (mean RTs of 3331 ms and 2565 ms for low and high PhN words respectively), $F(1,\ 144) = 4.7$, $p < .001$, but not when letters were presented sequentially (mean RTs of 1578 ms and 1595 ms for low and high PhN words respectively), $F(1,\ 144) < 1$. This result suggests that distinct mechanisms are implied in our two different presentation types. A chi-square analysis of error rates showed no significant difference between conditions, $\chi^2(3) = 2.54$, *ns*.

Experiment 2b: Lexical frequency effect

Stimuli

The targets were 80 five- to seven-letters low-confusability words (less than 0.45) divided equally into two conditions defined according to lexical frequency (low: less than 2000/100 million; high: more than 5000/100 million in the Brulex database; Content et al., 1990). There were 40 targets in each condition. Across conditions, words were matched pairwise according to their number of letters, bigram frequency, PhN size, and letter confusability (all Fs < 1).

Results

The data obtained with sequential and simultaneous presentations were treated jointly for statistical analysis. Correct RTs that were more than three standard deviations away from the mean of their condition (0.7% of correct trials) were rejected as outliers. The correlation between correct RTs and error rates was of +.19 (*ns*), thus showing no speed–accuracy trade-off. A two-way ANOVA performed on correct RTs with the type of presentation (sequential vs. simultaneous) and lexical frequency (high vs. low) as factors showed a significant interaction between these factors, $F(1, 139) = 5.5$, $p < .05$, a significant effect of type of presentation, $F(1, 139) = 175.1$, $p < .001$, but no effect of lexical frequency, $F(1, 139) = 2.486$, *ns*. Simple effect analysis indicated that the modulation of LH's performance by lexical frequency was significant when letters in a word were presented simultaneously (mean RTs of 4210 ms and 3530 ms for low- and high-frequency words, respectively), $F(1, 139) = 2.5$, $p < .05$, but not when letters were presented sequentially (mean RTs of 1510 ms and 1695 ms for low- and high-frequency words, respectively), $F(1, 139) < 1$. A chi-square analysis of error rates showed no significant difference between conditions, $\chi^2(3) = 0.68$, *ns*.

Experiment 2c: Imageability effect

Stimuli

The targets were 80 five- to seven-letter low-confusability words divided equally into two conditions defined according to imageability (low: below 2.5; high: 5 or higher). There were 40 targets in each condition. Across conditions, words were matched pairwise according to their number of letters, lexical frequency, bigram frequency, PhN size, and letter confusability (all Fs < 1).

Results

The data from sequential and simultaneous presentations were considered jointly for statistical analysis. Correct RTs that were more than three standard deviations away from the mean of their condition (0.6% of correct trials) were rejected as outliers. The correlation between correct RTs and error rates was of −.86 (*ns*)[3], thus showing no speed–accuracy trade-off. A two-way ANOVA performed on correct RTs with the type of presentation (sequential vs. simultaneous) and imageability (high vs. low) as factors showed a significant interaction between these factors, $F(1, 141) = 4.4$, $p < .05$, a significant effect of type of presentation, $F(1, 141) = 86.5$, $p < .001$, and a significant effect of imageability, $F(1, 141) = 5.1$, $p < .05$. Simple effect analysis indicated that the modulation of LH's performance by imageability was significant when letters in a word were presented simultaneously (mean RTs of 4256 ms and 3464 ms for low- and high-imageability words, respectively), $F(1, 141) = 3.3$, $p = .001$, but not when letters were presented sequentially (mean RTs of 2252 ms and 2106 ms for low- and high-imageability words, respectively), $F(1, 141) < 1$. A chi-square analysis of error rates showed no significant difference between conditions, $\chi^2(3) = 2.29$, *ns*.

[3] Although very high, this correlation was not significant given the small number of conditions (and thus the low number of degrees of freedom) involved.

Discussion

The aim of Experiment 2 was to assess the hypothesis that the high-level effects observed on the reading performances of LH resulted from the patient's residual parallel processing capacities. Thus, we compared the high-level effects for two exposure conditions. In the sequential condition, each letter of the target word appeared sequentially from left to right in order to prevent the parallel processing of letters. In the control condition, all letters were presented simultaneously so that parallel processing of letters could occur. The results are clear: The reading performance of LH is modulated by the high-level variables with simultaneous letter onset but not with sequential letter presentation, which effectively prevents any contribution of parallel letter processing. This indicates that the high-level effects studied here are based upon parallel letter processing, thereby demonstrating that such processing does indeed contribute to overt word recognition performance in the disorder. Obviously, though, parallel processing fails to reliably support word recognition on its own in LBL dyslexia and recourse to a compensatory process of sequential letter identification is generally required. Experiment 3 will offer indications as to why this is so.

Experiment 3: The modulation of high-level effects by letter confusability

Experiment 3 examined whether high-level effects, which are associated with the parallel processing of letters, are modulated by the factor of letter confusability. The results obtained in our laboratory in anglophone patients (Arguin & Bub, 1996, in press; Arguin et al., 2002) have shown that a facilitatory effect of the number of orthographic neighbours occurs with low-confusability words but is absent with words made of high-confusability letters. Since the results of Expt 1a suggest that the facilitatory effect of N size is actually based on the number of PhN, we will assess the interaction of this variable with letter confusability in LH. Two additional tasks will assess separately the impact of letter confusability on the lexical frequency and imageability effects. All three tasks of Experiment 3 were performed by LH and seven neurologically intact normal subjects (the same as in the previous experiments assessing the word length effect). The comparison with normal subjects was necessary to confirm that letter confusability has no effect on the reading performance of normal subjects, as shown previously by Arguin et al. (2002) and, most importantly, that it does not interact with the high-level effects that normal readers may demonstrate. The procedure used for these three tasks was the same as in Experiment 1.

Method

Subjects. Subjects were LH and a group of seven neurologically intact university students.

Procedure. For LH, the procedure was identical to that of Experiments 1 a–c. For the young neurologically intact readers, the stimuli were centred on the location of ocular fixation.

Experiment 3a: Phonographic neighbourhood size × confusability

Stimuli

The targets were 240 four- to seven-letter words with low or medium lexical frequency (less than 3000/100 million), varying orthogonally on their number of PhN (low: 0; high: more than 3) and their average letter confusability (low: below 0.43; high: 0.52 or higher). There were 60 targets in each condition. Across conditions, words were matched according to number of letters, lexical frequency, and bigram frequency, all Fs $(1, 236) < 1$. A post hoc analysis demonstrated no difference between conditions on imageability.

Figure 2a shows the correct RTs obtained in LH in each condition of Experiment 3a. Correct RTs that were more than three standard deviations away from the mean of their condition (0.9% of trials) were rejected as outliers. The correlation between correct RTs and error rates was of +.79 (*ns*, see Footnote 3 earlier), thus showing no speed–accuracy trade-off. A two-way ANOVA performed on correct RTs with PhN size and confusability as factors showed a

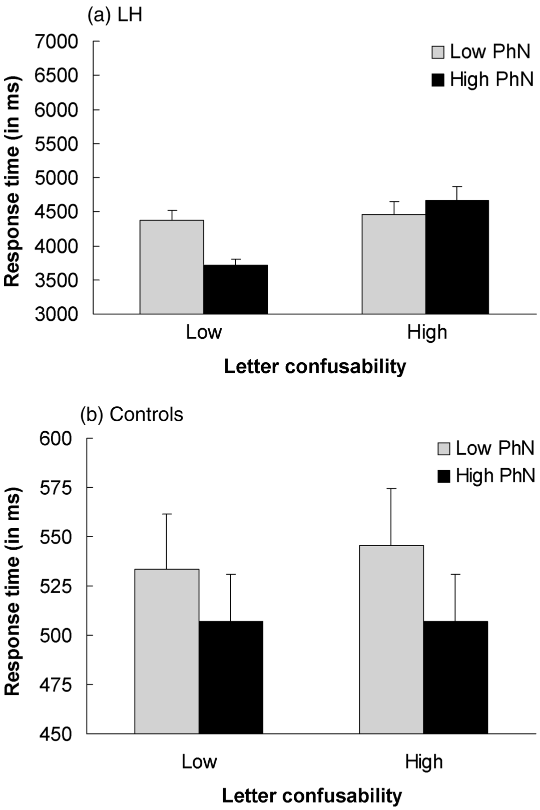

Figure 2. *Average correct response times (ms) in (a) LH and (b) young neurologically intact readers as a function of the PhN size and letter confusability (Expt 2a).*

main effect of letter confusability, $F(1, 210) = 10.1$, $p < .005$, but no main effect of PhN size, $F(1, 210) = 1.9$, *ns*. The interaction between PhN size and letter confusability was significant, $F(1, 210) = 6.7$, $p = .01$. Simple effect analysis indicated that increasing the number of PhN had a large facilitatory effect with low-confusability words, $F(1, 210) = 13.7$, $p < .001$, but no effect with high-confusability targets, $F(1, 210) < 1$. A chi-square analysis of error rates as a function of PhN size showed no significant effect of this factor, $\chi^2(3) = 5.28$, *ns*.

Figure 2b shows the correct RTs obtained with neurologically intact readers in each condition. Correct RTs that were more than three standard deviations away from the mean of their condition (1.7% of trials) were rejected as outliers. The correlation between correct RTs and error rates was of +.18 (*ns*), thus showing no speed−accuracy trade-off. The ANOVA applied on the correct RT's observed in these subjects with factors of letter confusability and PhN size showed a significant effect of PhN size, $F(1, 6) = 8.0$, $p < .05$, no effect of letter confusability, $F(1, 6) = 1.2$, *ns*, and no interaction between these two factors, $F(1, 6) = 2.2$, *ns*. The significant PhN size effect indicates shorter RTs for targets that have many PhN than for targets that have few. Importantly, ANOVAs performed on the individual data of each normal subject demonstrated that none of them showed the same pattern of interaction between PhN size and confusability as LH (all Fs < 1). The analysis applied on error rates showed no main effect of letter confusability $F(1, 6) = 1.0$, *ns*, but a trend for a facilitatory effect of increased PhN, $F(1, 6) = 4.2$, $p = .09$. The interaction between these two factors was not significant, $F(1, 6) < 1$.

Experiment 3b: Lexical frequency × confusability

The targets were 240 five-, six-, and seven-letter words varying orthogonally on their lexical frequency (low: below 500 per 100 million; high: more than 5000 per 100 million in the Brulex database; Content et al., 1990) and their average letter confusability (low: below 0.43; high: 0.52 or higher). There were 60 targets in each condition. Across conditions, words were matched according to number of letters, bigram frequency, and PhN size, all Fs $(1, 236) < 1$. A post hoc analysis demonstrated no difference between conditions on imageability.

Figure 3a shows the correct RTs obtained in LH in each condition. Correct RTs that were more than three standard deviations away from the mean of their condition (1.4% of trials) were rejected as outliers. The correlation between correct RTs and error rates was of +.57 (*ns*), thus showing no speed−accuracy trade-off. A two-way ANOVA performed on correct RTs with frequency and confusability as factors showed a main effect of frequency, $F(1, 208) = 8.8$,

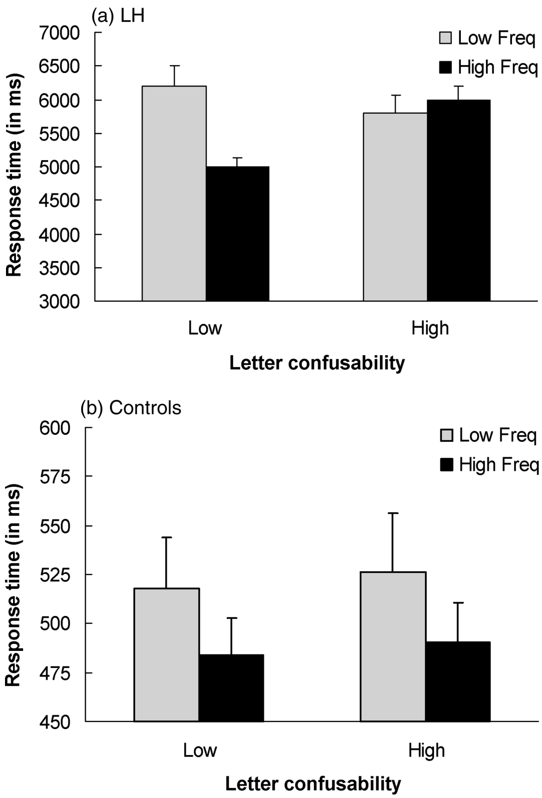

Figure 3. *Average correct response times (ms) in (a) LH and (b) young neurologically intact readers as a function of lexical frequency and letter confusability (Expt 2b).*

$p < .01$, and no confusability effect, $F(1, 208) = 1.6$, *ns*. The interaction between frequency and confusability was significant, $F(1, 208) = 4.4$, $p < .05$. Simple effect analysis indicated that increased lexical frequency had a large facilitatory effect with low-confusability words, $F(1, 208) = 13.8$, $p < .001$, but no effect with high-confusability targets, $F(1, 208) < 1$. A chi-square analysis of error rates showed no significant difference between conditions, $\chi^2(3) = 1.23$, *ns*.

Figure 3b shows the correct RTs obtained in the neurologically intact readers. Correct RTs that were more than three standard deviations away from the mean of their condition (1.0% of trials) were rejected as outliers. The correlation between correct RTs and error rates was of +.13 (*ns*), thus showing no speed–accuracy trade-off. The ANOVA applied on correct RTs with factors of letter confusability and frequency showed a significant effect of lexical frequency, $F(1, 6) = 11.3$, $p < .05$, no effect of letter confusability, $F(1, 6) = 1.6$, *ns*, and no interaction between those two factors, $F(1, 6) < 1$. The significant lexical frequency effect indicates shorter RTs with high-frequency than with low-frequency targets. Importantly, ANOVAs performed on the individual data of each normal subject demonstrated that none of them showed the same pattern of interaction between lexical frequency and confusability as LH (largest $F = 1.95$, *ns*). The analysis applied on error rates showed no main effect of letter confusability, $F(1, 6) = 2.1$, *ns*, but a tendency for a facilitatory effect of increased lexical frequency, $F(1, 6) = 4.1$, $p = .09$. The interaction between these two factors was not significant, $F(1, 6) = 1.1$, *ns*.

Experiment 3c: Imageability × confusability

Targets were 200 five-, six-, and seven-letter words varying orthogonally on their imageability (low: below 2; high: more than 6 on a 1 to 7 scale) and their average letter confusability (low: below 0.43; high: 0.52 or higher). There were 50 targets in each condition. Across conditions, words were matched according to number of letters, lexical frequency, bigram frequency, and PhN size, all *F*s $(1, 196) < 1$.

Figure 4a shows the correct RTs obtained in LH in each condition of Experiment 3c. Correct RTs that were more than three standard deviations away from the mean of their condition (0.5% of trials) were rejected as outliers. The correlation between correct RTs and error rates was of +.42 (*ns*), thus showing no speed–accuracy trade-off. A two-way ANOVA performed on correct RTs with imageability and confusability as factors showed a main effect of imageability, $F(1, 180) = 15.6$, $p < .001$, and no significant confusability effect, $F(1, 180) = 1.6$, *ns*. The interaction between frequency and confusability was significant, $F(1, 180) = 6.7$, $p < .05$. Simple effect analysis indicated that increased imageability had a large facilitatory effect with low-confusability words,

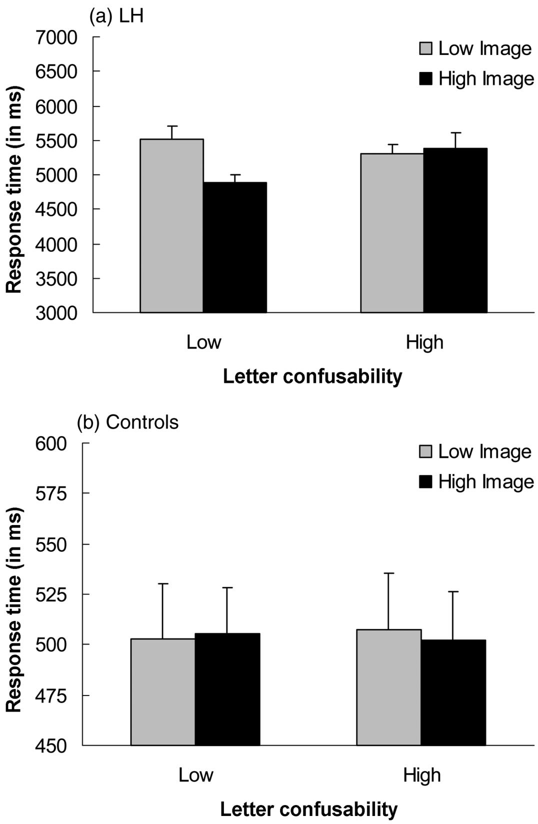

Figure 4. *Average correct response times (ms) in (a) LH and (b) young neurologically intact readers as a function of imageability and letter confusability (Expt 2c).*

$F(1, 180) = 17.4$, $p < .001$, but no effect with high-confusability targets, $F(1, 180) = 1.6$, *ns*. A chi-square analysis of error rates showed no significant effect of imageability, $\chi^2(3) = 3.63$, *ns*.

Figure 4b shows the correct RTs obtained in the young neurologically intact readers in each condition. Correct RTs that were more than three standard deviations away from the mean of their condition (1.5% of trials) were rejected as outliers. The correlation between correct RTs and error rates was of +.07 (*ns*), thus showing no speed–accuracy trade-off. The ANOVA applied on the correct RTs observed in these subjects with factors of letter confusability and imageability showed no imageability effect, $F(1, 6) < 1$, no effect of letter confusability, $F(1, 6) < 1$, and no interaction between those two factors, $F(1, 6) < 1$. Thus normal subjects showed no imageability effect in this task. Importantly, ANOVAs performed on the individual data of each normal subject demonstrated that none of them showed the same pattern of interaction between imageability and confusability as LH (largest $F = 1.56$, *ns*). The analysis applied on error rates showed a main effect of imageability, $F(1, 6) = 6.8$, $p < .05$, and a strong trend for a letter confusability effect, $F(1, 6) = 5.5$, $p = .06$. The interaction between these two factors is, however, not significant, $F(1, 6) = 1.2$, *ns*. The main effects indicate that increased imageability and decreased letter confusability lead to a reduction of the number of errors.

Discussion

The present observations replicate the finding of Arguin et al. (2002), indicating that the word naming performance of neurologically intact normal readers is resistant to the effect of letter confusability. Indeed, except for error rates in Experiment 3c, letter confusability had no impact either on the overall reading performance of these subjects, or on the effects of high-level variables they demonstrate. In contrast, the results of LH show that each of the high-level effects assessed here (PhN size, lexical frequency, and imageability) is absent with high-confusability target words. This impact of letter confusability is the same as that obtained in Experiment 2 with serial letter presentation, which demonstrated that these high-level effects are based upon parallel letter processing. This correspondence between the effects of letter confusability and serial letter presentation implies that a high-confusability letter content within a word interferes with or blocks parallel letter processing. Specifically, we suggest that parallel letter processing is impaired in LH, in that it provides a visual input of poor quality when attention is spread over the entire spatial extent of the target word. It is this altered visual input that would be responsible for the abnormal sensitivity of LBL dyslexics, like LH, to letter confusability (Arguin et al., 2002; Fiset, Arguin, Bub, Humphreys, & Riddoch, in press). With low-confusability words, the quality of the visual input based on parallel letter processing would be sufficient to activate high-level knowledge, as demonstrated by our findings and those of Arguin et al. (2002). However, with high-confusability words, the poor quality of the visual input would not permit a proper activation of high-level knowledge. Given the impoverished input it provides to the lexical-orthographic system, parallel letter processing cannot reliably support overt word recognition, which forces the patient to examine the constituent letters of the target in sequence. We propose that the purpose of this sequential strategy is to improve the visual quality of the orthographic input (by increasing the signal-to-noise ratio) in order to permit visual word identification.

Other authors have already proposed that a sequential strategy could eliminate high-level effects as well as the implicit reading capacities of dyslexic patients. For example, Howard (1991) has suggested that this particular strategy can diminish and possibly even eliminate lexical/semantic effects (see also Behrmann et al., 1998). Farah and Wallace (1991) also noted this in relation to the presence/absence of the word superiority effect in some LBL subjects. Relatedly, Coslett et al. (1993) suggested that LBL readers must abandon their usual serial strategy to rapidly access the lexical and semantic information required to allow them to make rapid semantic or lexical decisions. We will address the theoretical implication of these observations in the General Discussion.

Experiment 4: Letter confusability effect with serial letter presentation

Experiment 4 will provide a test for the hypothesis that the role of the sequential letter-by-letter strategy was to increase the quality of the visual input toward the higher-level representation system of reading (phonology, lexicon, and semantic). If this hypothesis is correct, then the letter confusability effect should be strongly reduced or even eliminated when the lexical access occurs through the sequential processing of letters. In this experiment, the methodology was the same as in Experiment 2.

Stimuli

The targets were 80 five- to seven-letter words divided equally into two conditions defined according to letter confusability (low: below 0.43; high: 0.52 or higher). There were 40 targets in each condition. Across conditions, words were matched pairwise according to their number of letters, lexical frequency, bigram frequency, and PhN size (all Fs < 1). The results of Experiment 3b suggest that the magnitude of the letter confusability effect is maximised with high-frequency words (Figure 3a). In order to maximise the power of Experiment 4 of revealing a letter confusability effect, we consequently chose words of very high frequency (minimum of 1000 per million; average of 9000).

Results

The data from sequential and simultaneous presentations were considered jointly for statistical analysis. Correct RTs that were more than three standard deviations away from the mean of their condition (1.3% of correct trials) were rejected as outliers. The correlation between correct RTs and error rates was of $-.16$ (*ns*), thus showing no speed–accuracy trade-off. A two-way ANOVA performed on correct RTs with the type of presentation (sequential vs. simultaneous) and letter confusability (high vs. low) as factors showed a significant interaction between these factors, $F(1, 145) = 5.7$, $p < .05$, a significant effect of type of presentation, $F(1, 145) = 86.5$, $p < .001$, and a significant effect of letter confusability, $F(1, 145) = 5.1$, $p < .05$. Simple effect analysis indicated that the modulation of LH's performance by letter confusability was significant when letters in a word were presented simultaneously (mean RTs of 3242 ms and 3972 ms for low- and high-confusability words respectively), $F(1, 145) = 17.8$, $p < .001$, but not when letters were presented sequentially (mean RTs of 1658 ms and 1778 ms for low- and high-confusability words respectively), $F(1, 145) < 1$.

A chi-square analysis of error rates showed no significant difference between conditions, $\chi^2(3) = 2.08$, *ns*.

The results of Expt 4 indicate that a key role of sequential letter processing strategy is to resolve the letter identification problem (signalled by sensitivity to letter confusability) created by the impoverished visual input offered by parallel letter processing. This finding points to an extremely important role of attentional mechanisms in the reading of letter-by-letter dyslexics. Indeed, parallel letter processing implies that attentional resources are spread across all the letters of the word whereas serial processing is necessarily associated with focused attention on individual letters. Relatedly, Yeshurun and Carrasco (1998) have shown that focused attention increases the spatial resolution of the visual system, thereby increasing the signal/noise ratio. With respect to letter processing, this should translate to a decreased probability of confusing visually similar letters; in other words, to a reduction or elimination of the letter confusability effect.

GENERAL DISCUSSION

The aim of this study was to answer two major questions regarding letter-by-letter dyslexia. (1) What is the nature of the functional impairment responsible for the incapacity of LBL dyslexics to reliably recognise words through parallel letter processing? (2) What is the function of sequential letter processing in the disorder? In continuity with Arguin et al. (2002), we have shown that three high-level variables usually associated with parallel letter processing influence LH's overt word recognition performance, but that these effects (and consequently parallel letter processing) are restricted to words constituted of low-confusability letters. It is worth underlining that although we are not the first laboratory to observe that visually similar letters may be problematic for LBL dyslexics (e.g., Karanth, 1985; Patterson & Kay, 1982; Perri, Bartolomeo, & Silveri, 1996), we are the first to propose that letter confusability might be central to LBL dyslexia and that its effect may account for the breakdown of parallel letter processing.

The central purpose of Experiment 1 was to show that the reading latency of LH was affected by high-level knowledge. More specifically, as usually observed in normal subjects, the reading performance of LH is improved with high PhN size, high-frequency, and high-imageability words. In addition, Expt 1a aimed at specifying the cause of the neighbourhood size effect. The results showed that a facilitatory effect of orthographic neighbours is essentially dependant upon PhN (orthographic neighbours that are also phonological neighbours), whereas pure orthographic neighbours have no effect, which suggests a rapid access to lexical phonology (Peereman & Content, 1995). An important question remains: Does the rapid access to phonological knowledge provided with a large PhN size influence the probability of a word being recognised in parallel? An interesting answer to this question is provided in the doctoral thesis of Marie Montant (1998). She has asked normal subjects to identify briefly presented letter strings (80 ms). Using the technique of viewing position effect (see Montant, Nazir, & Poncet, 1998, for the use of this technique in letter-by-letter dyslexia), she showed that phonological information facilitates parallel letter processing in visual word recognition. Thus, when the pronunciation of a string of letters was easily retrievable (known word), the reading accuracy of normal subjects with a brief exposure duration varied in an inverted U-shaped manner as a function of the initial location of ocular fixation across the spatial extent of the word, an effect that is typical of parallel processing. However, a U-shaped function of the location of fixation, which is characteristic of sequential processing, was obtained when the pronunciation of the target was difficult or impossible to retrieve (as with nonwords). These results suggest that an adequate activation of phonological knowledge may act as a form of perceptual glue (Montant, 1998) to increase the probability of an efficient parallel processing of the target.

Experiment 2 was designed to demonstrate the plausibility of the proposed association between parallel processing and the high-level effects studied here and, more specifically, to show that these high-level effects are eliminated when words are read using a strictly sequential strategy. The results clearly show that the reading performance of LH is not influenced by the high-level variables studied when words are presented in an incremental, letter-by-letter manner that prevents parallel letter processing from occurring. Thus, it seems that the facilitatory effects of increased frequency, imageability, and PhN size may only occur when lexical access is conducted through parallel letter processing.

Experiment 3 was designed to investigate the limitations of parallel letter processing that prevent it from consistently supporting overt word recognition performance in LBL dyslexia. This investigation took, as its starting point, previous observations suggesting an impairment affecting letter identification as well as data from Arguin et al. (2002) on the interaction between letter confusability and N size. The results of Expt 3 confirmed the cost of increased letter confusability on the overt word identification performance of LH. In particular, they showed that high-level effects occur only with low letter confusability words whereas they are not apparent with high letter confusability words. Thus, it seems that, in LH, the parallel processing of letters in a word is possible and useful when these letters are of low confusability, but hard and/or useless when the letters are of high confusability.

These observations suggest a theory of LBL dyslexia whereby the first attempt to recognise a word is through the simultaneous processing of letters, which is the default mechanism for normal literate adults. However, parallel letter processing does not reliably permit overt word recognition in LBL dyslexia because the mechanisms involved are unable to discriminate between visually similar letters. This difficulty results in a low signal-to-noise ratio that prevents the reliable absolute identification of the target word (Arguin & Bub, 1996; Luce, 1959, 1977). This low signal-to-noise ratio obliges LBL readers to focus sequentially on each letter to avoid perceptual confusions between visually similar letters. This dual-process hypothesis received strong support from a study by Lambon Ralph, Hesketh, and Sage (2004). These authors have used a therapy with LBL dyslexic patient FD that focused on word reading exercises in which they asked FD to read words using a global reading strategy. After several weeks of training, FD's reading largely rested on a whole-word strategy. Performance, which remained abnormal nevertheless, was characterised by many semantic, visual, and visual-then-semantic errors, which are diagnostic of deep dyslexia. Congruent with our own observations, these results suggest that parallel letter processing is possible in LBL dyslexics and that (1) it is sufficient to activate semantic representations but (2) it fails to reliably activate the exact internal orthographic representation corresponding to the stimulus.

The results obtained in our study could be explained, albeit in a different manner, according to two types of formal models of normal reading (modular and connectionist). According to the modular dual-pathway model (DRC, Coltheart, Curtis, Atkins, & Haller, 1993; Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001), only the lexical pathway can process words in parallel whereas processing in the sublexical pathway is sequential (Coltheart et al., 1993, 2001; Rastle & Coltheart, 1998, 1999). In the dual-pathway model, then, the lexical frequency, imageability, and phonological effects investigated here are readily considered to be associated with parallel processing of letters. For this model, the presence of these three effects in LH would be an indication that the lexical pathway is at least partially functional in this patient. This model is therefore entirely compatible with the current findings.

An account of the present findings according to a PDP model also appears possible. In fact, connectionist models based on attractor networks (Harm & Seidenberg, in press; Hinton & Shallice, 1991; Plaut & Shallice, 1993; Plaut, McClelland, Seidenberg, & Patterson, 1996) offer a very interesting single-mechanism account of our results. A key functional element in PDP models is the fact that the activation of representations in the brain is not all or none (Munakata, 2001).

Thus, even if some visual deficit decreases the capacity of the cognitive system to correctly interpret an input based on parallel letter processing, the corresponding knowledge may be partially activated nonetheless, which may in turn facilitate the recognition of the target word when a letter-by-letter strategy is applied afterwards. Thus, even if the cognitive system, because of the cerebral lesion, is initially incapable of correctly interpreting the visual input on the basis of parallel letter processing, the high-level knowledge (attractors) will gradually clean up the signal and direct it towards its proper representational space (Plaut & Shallice, 1993). For example, in the study of deep dyslexia by Plaut and Shallice (1993), the use of semantic attractors allowed the network to minimise the effect of noise on the direct pathway (from orthography to semantic) and eventually to provide a correct interpretation of the stimulus. Within the context of connectionist networks, it is widely assumed that a general consequence of brain damage is to amplify the amount of noise in the system. According to Plaut and Shallice (see also Hinton & Shallice, 1991), high-imageability words would be represented with more semantic features than low-imageability words and would thus be more efficient in the activation of semantic attractors (i.e., they have a larger basin of attraction) than low-imageability words, thereby accounting for the greater ease of deep dyslexic patients in reading high-imageability words.

A similar logic may apply to letter-by-letter dyslexia. In this case, the visual deficit affecting parallel letter processing increases the amount of noise present in the reading pathways (from orthography to phonology and from orthography to semantic). As noted previously, we suggest that the amount of noise present in the reading system is proportional to the summed confusability of each letter in the stimulus. With low-confusability words, the propagation of activation would be sufficiently precise to activate some phonological and semantic attractors, which would allow overt word recognition to be based on parallel letter processing some of the time (cf. Howard, 1991), and otherwise to improve reading performance involving the compensatory sequential process. In contrast, with high-confusability words, the activation is so dispersed (i.e., low signal-to-noise ratio) that attractors fail to help the reading system in the interpretation of the visual stimulus. The problem of a too low signal-to-noise ratio can be resolved, however, by maximising the quality of the visual representation of the input through the sequential processing of individual letters, which possibly involves focused attention. When this serial strategy is used, phonological and semantic activations are very precise and thus minimise the influence of phonological attractors and semantic feedback upon word identification performance. This would explain why the facilitatory effects of PhN size, lexical frequency, and imageability in LH are exclusively associated with parallel letter processing.

Only orthographic stimuli were used in the present study. Consequently, our observations cannot address the important question of whether LBL dyslexics suffer from a deficit specific to orthographic stimulation (Arguin & Bub, 1993; Arguin et al., 2002; Behrmann & Shallice, 1995; Cohen et al., 2003) or from a general visual impairment that applies equally to all stimulus classes (Behrmann et al., 1998; Farah & Wallace, 1991). However, this study adds to a growing body of evidence (Arguin & Bub, in press; Arguin et al., 2002; Fiset et al., in press) that letter confusability is a fundamental determinant of reading performance in LBL dyslexia. In this respect, what would stand as a critical test of the issue of material-specific vs. general visual impairment in LBL dyslexia is whether confusability within classes of nonorthographic stimuli affect the perceptual performance of patients similarly to letter confusability. Clearly, a positive answer would strongly argue for a general deficit whereas a negative one would support the hypothesis of a material-specific disorder. Such tests have yet to be conducted.

CONCLUSION

The present study has shown that PhN size, lexical frequency, and imageability effects are present in an LBL dyslexic, but only with low letter confusability words and only when all the letters in the word are presented simultaneously. The elimination of the high-level effects investigated by sequential letter presentation indicates that these effects are based on a residual capacity for parallel letter processing in the patient. Moreover, the elimination of these high-level effects with high-confusability words suggests that LBL dyslexia may rest on a letter encoding impairment that causes an excessive level of background noise in the activation of lexical-orthographic representations when letters are processed in parallel. We suggest a PDP interpretation in which phonological and semantic attractors would be sufficiently activated by parallel letter processing in LBL dyslexia to allow a subset of words with appropriate linguistic properties to be read through parallel letter processing (see Howard, 1991). However, because of the letter encoding deficit, which would be exacerbated by high letter confusability, the orthographic input to the phonological and semantic systems generally fails to properly activate attractors, which then forces LBL patients to revert to sequential letter processing through focused attention on individual letters in order to increase the signal-to-noise ratio, and thereby permit overt word recognition.

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