Available online at www.sciencedirect.com

ScienceDirect

Brain and Language 98 (2006) 251–263

Brain and Language

www.elsevier.com/locate/b&l

An attempt to simulate letter-by-letter dyslexia in normal readers

Stéphanie Fiset [a,b], Martin Arguin [a,b,*], Daniel Fiset [a,b]

[a] Groupe de Recherche en Neuropsychologie et Cognition, Département de psychologie, Université de Montréal, C.P. 6128, succ. Centre-ville, Montréal QC, Canada H3C 3J7
[b] Centre de recherche, Institut Universitaire de Gériatrie de Montréal, Canada

Accepted 15 May 2006
Available online 16 June 2006

Abstract

We attempted to simulate the main features of letter-by-letter (LBL) dyslexia in normal readers through stimulus degradation (i.e. contrast reduction and removal of high spatial frequencies). The results showed the word length and the letter confusability effects characteristic of LBL dyslexia. However, the interaction of letter confusability and N size (i.e. a facilitatory effect only for low confusability targets) previously observed in LBL dyslexics [Arguin, M., Fiset, S., & Bub, D. (2002). Sequential and parallel letter processing in letter-by-letter reading. *Cognitive Neuropsychology*, *19*, 535–555; Arguin, M., & Bub, D. (2006). Parallel processing blocked by letter similarity in letter dyslexia: a replication. *Cognitive Neuropsychology*, *22*, 589–602; Fiset, D., Arguin, M. & McCabe, E. (2005a). The breakdown of parallel letter processing in letter-by-letter dyslexia. *Cognitive Neuropsychology*, *22*, 1–22] was not found. Our results suggest that the type of visual degradation employed here may only partially correspond to the visual deficit present in LBL dyslexia and that this degradation may have prevented the normal readers from accessing visual information available to LBL dyslexics when they use the compensatory strategy of serial letter processing.

Keywords: Simulation in normal readers; Visual processing; Pure alexia; Letter-by-letter dyslexia; Dyslexia; Reading; Word recognition

1. Introduction

Letter-by-letter (LBL) dyslexia is an acquired reading disorder that is caused by left occipito-temporal damage in previously literate adults (Beversdorf, Ratcliffe, Rhodes, & Reeves, 1997; Binder & Mohr, 1992; Black & Behrmann, 1994; Cohen et al., 2003; Damasio & Damasio, 1983; Dejerine, 1892). It is usually associated with a right homonymous hemianopia. No other functional impairment has been systematically associated with LBL reading, although achromatopsia and agraphia may be observed occasionally (Behrmann, Plaut, & Nelson, 1998). The main behavioural feature of LBL dyslexia is very slow reading that is characterised by a large word length effect i.e. a 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). Depending on the patient, the time needed to read a word aloud can increase from 500 ms to several seconds for each additional letter in the stimulus (Arguin & Bub, 1993a; Bowers, Bub, & Arguin, 1996b; Farah & Wallace, 1991; Friedman & Lott, 2000; Patterson & Kay, 1982; Reuter-Lorenz & Brunn, 1990; Warrington & Shallice, 1980; but see Sekuler & Behrmann, 1996, for cases with a weaker length effect). Thus, these patients have lost the ability to read words and text quickly and efficiently.

To many, the presence of a word length effect suggests that LBL readers decode words as a sequence of isolated letters, without any access to the spatially parallel process (i.e. simultaneous encoding of all the letters in a word) of normal readers. Indeed, a very weak (6–63 ms/letter; depending on the study) or absent word length effect is found in neurologically intact readers (Fiset, Arguin, & McCabe, 2006; Forster & Chambers, 1973; Frederiksen & Kroll, 1976; Henderson, 1982; Weekes, 1997). When

---

[*] Corresponding author. Fax: +1 514 343 5787.
E-mail address: martin.arguin@umontreal.ca (M. Arguin).

doi:10.1016/j.bandl.2006.05.003

assessed separately, high frequency words fail to show a length effect, whereas this effect may be observed with low frequency words (Content & Peereman, 1992), except if items of different lengths are matched on their numbers of orthographic neighbours (N size—Weekes, 1997).[1]

In terms of functional anatomy, LBL dyslexia is associated with damage affecting the left fusiform gyrus or the fibers conducting visual information to this region, which is conceived as the anatomic site for the so-called "visual word form system" (Beversdorf et al., 1997; Binder & Mohr, 1992; Cohen et al., 2003). This would constrain reading to be performed through the alternate route of the right fusiform gyrus, which is assumed to be only capable of processing written input in a sequential letter-by-letter manner (Ellis, Young, & Anderson, 1988; Lavidor & Ellis, 2002). With respect to the detailed features of the functional impairment responsible for LBL dyslexia, a wide variety of proposals have been formulated over the years but its cause is still being debated. Most functional accounts assume an early visual impairment occurring prior to orthographic-lexical access that either applies equally to all stimulus classes (Farah & Wallace, 1991; Friedman & Alexander, 1984; Kinsbourne & Warrington, 1962; Levine & Calvanio, 1978; Rapp & Caramazza, 1991) or that is specific to written materials (Arguin & Bub, 1993b; Arguin & Bub, 1994; Arguin, Fiset, & Bub, 2002; Behrmann et al., 1998; Behrmann & Shallice, 1995; Kay & Hanley, 1991; Montant & Behrmann, 2001; Reuter-Lorenz & Brunn, 1990; Patterson & Kay, 1982). Rival theories rather propose that the crucial functional impairment has a central origin which would concern the orthographic word-form system itself (Warrington & Shallice, 1980) or lexical-phonological access (Bowers, Arguin, & Bub, 1996a). These varied accounts of LBL dyslexia may relate to between-patient variability in the core deficit responsible for the disorder (e.g. Price & Humphreys, 1992), which in turn may be a function of whether damage is to the left fusiform gyrus or to its afferent fibers. Alternatively, they may also be a function of relatively superficial differences across patients that mask a common underlying impairment.

The research reported in this paper is based on a functional theory of LBL dyslexia suggested by the work carried out in our laboratory in the last few years, and which attributes the disorder to a visual encoding impairment affecting letter recognition. Specifically, the present study examines whether a form of stimulus degradation that appears to simulate this visual impairment in normal readers leads to the symptoms that are characteristic of LBL dyslexia. Below, we review the past research that is at the origin of the present study.

1.1. Letter confusability and its impact in LBL dyslexia

Studies conducted in our laboratory have highlighted the crucial influence of letter confusability upon the reading performance of LBL patients (Arguin & Bub, 2005, 2002; Fiset et al., 2006, Fiset, Arguin, Bub, Humphreys, & Riddoch, 2005). Letter confusability is defined as the shape similarity between a particular letter and the remaining letters of the alphabet. The confusability values are determined from empirical letter confusion matrices that were obtained in studies of neurologically intact observers (Gilmore, Hersh, Caramazza, & Griffin, 1979; Loomis, 1982; Townsend, 1971; Van der Heijden, Malhas, & Van den Roovart, 1984). Specifically, the confusability value for a particular letter is the probability that a normal reader will make an error in identifying it, when the target is presented very briefly. The letter confusability of a word is the average of the confusability of its constituent letters.

In standard viewing conditions (i.e. high-contrast, undegraded stimuli that remain visible until response), letter confusability has an inhibitory impact on the word reading latencies of LBL readers: words with a high letter confusability content are read more slowly than low confusability words (Arguin et al., 2002; Arguin & Bub, 2005; Fiset et al., 2006, 2005). By contrast, neurologically intact readers show no letter confusability effect with high-contrast stimuli presented in a regular format (Arguin et al., 2002; Fiset et al., 2006). The fact that a letter confusability effect is only present in LBL dyslexics reveals that these patients are abnormally sensitive to the visual similarity among letters. This, in turn, points to a low-level visual deficit that interferes with letter encoding as a possible functional cause of LBL dyslexia. The study of the effect of letter confusability and its interaction with high-level stimulus variables on reading performance in LBL dyslexia has offered crucial insight regarding its functional cause.

Parallel letter processing and its breakdown in dyslexics has been studied directly through high-level lexical effects upon their reading performance. Like normal readers (Andrews, 1989, 1992; Arguin, Bub, & Bowers, 1998; Carreiras, Perea, & Grainger, 1997; Coltheart, Davelaar, Jonasson, & Besner, 1977; Sears, Hino, & Lupker, 1995), LBL dyslexics perform better with words that have many (vs. few) orthographic neighbours (Arguin & Bub, 1996; Arguin et al., 1998, 2002; Fiset & Arguin, 1998; Arguin & Bub, 2005; Fiset et al., 2006; Montant & Behrmann, 2001). If LBL reading were based on a strictly sequential identification of individual letter identities, how can such a high-level factor exert its effect? In fact, the N size effect as well as other high-level effects (lexical frequency and word imageability) occur in LBL dyslexics only if the constituent letters of the target words are displayed all at once, whereas they are abolished when letters are presented serially from left to right at a rate derived from the reading performance of individual patients (Fiset et al., 2006). These results indicate that these lexical effects in LBL dyslexics are not supported by serial processing and that they rather require parallel letter processing.

---

[1] Orthographic neighbours are words from the vocabulary that differ from a particular target word by only a single letter. N size refers to the number of such neighbours. For instance, the word "lake" has many orthographic neighbours (bake, cake, fake, lace, lame, lane, late, laze, like, make, rake, sake, take, and wake) whereas the word "data" has few (date).

Further studies have shown that the facilitatory effect of N size occurs with words made of 1 letter but that it is entirely abolished when words are made of high confusability letters (Arguin et al., 2002; Arguin & Bub, 2005; Fiset et al., 2006). Similarly, the lexical effects of word frequency and imageability are also abolished by high letter confusability (Fiset et al., 2006). Given that the N size, frequency, and imageability effects index parallel letter processing, it has been concluded that this type of processing is blocked or interfered with by high letter confusability (Arguin et al., 2002; Arguin & Bub, 2005; Fiset et al., 2006).

The above research has led to the suggestion that word recognition in LBL dyslexia generally entails two processing phases occurring in sequence [see Arguin et al., 2002; Arguin and Bub, 2005, for a detailed discussion]. The initial phase involves parallel letter processing, which is responsible for the high-level effects observed in word recognition. However, parallel processing in LBL dyslexics (unlike normal readers) is highly susceptible to the negative impact of letter confusability, and thus cannot reliably support overt word recognition. For this reason, a subsequent serial processing phase involving focused attention on individual letters is required for overt word recognition. The key attribute of this serial processing phase, which makes it capable of reliably supporting overt word recognition, is that it is not susceptible to letter confusability.

This theory attributes a fundamental role to the visual impairment indexed by the letter confusability effect in causing the symptoms that define LBL dyslexia. It therefore predicts that normal readers should exhibit the major features of the disorder provided stimulation conditions that simulate the visual deficit responsible for the letter confusability effect shown by dyslexics. The investigation reported in this paper aims to assess this prediction.[2]

Preliminary studies conducted in our laboratory have shown an inhibitory letter confusability effect in normal readers in the identification of parafoveally presented words of 10% luminance contrast (dark grey printed over lighter grey, 32 cd/m^2) $F(1,9) = 14.03$, $p < .01$. However, letter confusability had no significant impact on their reading latencies when low-contrast stimuli were displayed at the fovea, even if stimulus contrast was reduced to 3%, $F(1,9) = 1.03$, *n.s.* The requirement of parafoveal stimulation to produce a letter confusability effect in normal readers was assumed to result from the loss of high spatial frequency information that is caused by the rapid decrease of spatial acuity as one moves away from the fovea (Carrasco & Frieder, 1997). This assumption is assessed (and verified) in Experiment 1, which examines whether reduced luminance contrast in conjunction with the removal of high spatial frequency information can indeed induce a letter confusability effect in neurologically intact readers.

2. Experiment 1

In Experiment 1, two types of stimulus presentation were used: some subjects had to read aloud words of high or low letter confusability presented in a normal format, whereas others had to identify words that were visually degraded. In the latter condition, the stimuli were presented in low luminance contrast and were low pass filtered to remove their high spatial frequency content. Based on the pilot study described above, we stipulate that this manipulation will provoke an increase in reading latencies for high confusability items compared to low letter confusability stimuli, whereas no confusability effect should be obtained with undegraded stimuli (i.e. normal format).

2.1. Methods

2.1.1. Subjects

Twenty-two normal readers took part in the experiment. They were aged between 19 and 34 years (mean = 23.3 years old). All were right-handed and had a normal or corrected vision and none had a history of learning disabilities. Twenty of them were university students (Bachelor or Master's degrees). The two others had 18 years of formal education (Master's degrees).

2.1.2. Materials and stimuli

The stimuli were printed in Geneva 24 point bold font. They were either presented normally (black letters on a grey background) or in reduced contrast (luminance of 4.51 cd/m^2 against a background of 5.09 cd/m^2) and low pass filtered (2.4 pixels gaussian blur) using Adobe Photoshop (Fig. 1). For the normal format (i.e. high-contrast) displays, stimuli were shown using a Dell Dimension computer connected to a Dell 17-inch monitor. The E-Prime software (produced by Psychology Software Tools), was used to control the presentation of the stimuli. For the degraded stimulus condition, stimuli were shown on a Viewsonic E-771 screen, linked to a Power PC 7100/80. In both conditions, subjects were seated 55 cm away from the computer screen. The visual angle subtended by each letter was approximately 0.73° wide and 0.88° high.

A total of 120 five-letter words were used, with an equal number of words having a low or a high letter confusability, which is calculated as the sum of the confusability of all letters in a word divided by the number of letters (low: average

---

[2] Nelson, Behrmann & Plaut (personnal communication) have previously attempted to produce a normal model of LBL dyslexia through stimulus degradation. Thus, they provoked a substantial word length effect in normal readers using stimuli with a reduced luminance contrast. In pilot studies, we have attempted to replicate the phenomenon while controlling for N size, a control that had not been performed by Nelson et al. This type of control appeared important given that word length shows a strong negative correlation with N size (Arguin et al., 2002; Weekes, 1997). Normals showed a strong word length effect with low-contrast stimuli when N size was not controlled, but the length effect was entirely abolished when words of different lengths were matched on N size. We suggest that this relates to the incapacity of contrast reduction alone in causing an inhibitory effect of increased letter confusability on the word recognition performance of normal readers (see below).

Fig. 1. Screen shots of instances of the degraded stimuli used in the present experiments. Note that the luminance contrast and the spatial frequency content of these stimuli may differ from those presented in the experiments due changes of media and size.

confusability of 0.450 or below; high: average confusability of 0.495 or higher). Words of different letter confusabilities were matched according to log lexical frequency, their number of orthographic neighbours, and their bigram frequency, all *F*'s (1,118) < 1 (BRULEX data base for the French language; Content, Mousty, & Radeau, 1990). No word contained diacritic marks (é, è, ê, etc.), because subjects could not see them clearly with the reduced luminance contrast. In French, diacritic marks dictate word pronunciation and keeping words with accents in the present context could have led to an inflation of error rates.

2.1.3. Procedure

Subjects were separated in two groups: half viewed undegraded stimuli ("normal presentation" group) whereas the other half viewed degraded stimuli ("degraded presentation" group). Each group saw the same list of words. Subjects in the "degraded presentation" group were given 10 practice trials immediately prior to the experimental trials.

Words were presented in two blocks of 60 items each, each block comprising an equal number of low and high confusability words. The order of blocks was counterbalanced across subjects. Each trial began with a 1000 ms fixation point at the centre of the computer screen, immediately followed by the target printed in uppercase (because letter confusability matrices are exclusively based on uppercase letters) at the centre of the screen. The target remained visible until the subject's response. The task was to read the target aloud as quickly as possible while avoiding errors. Responses were registered by a voice-key (engineered in our laboratory) connected to the computer controlling the experiment. After each response, the experimenter entered the subject's response via the computer keyboard and then triggered the next trial.

2.2. Results

The data analyses were performed on 21 subjects only, because one subject (in the "degraded presentation" group) showed a dramatically high response latency (mean RT of 4750 ms, which is 2.85 *SD* away from the mean of the other subjects in his group—2270 ms). For the "normal presentation" group, 27 (1.9%) trials were lost overall because the response failed to trigger the voice-key, whereas, for the "degraded presentation" group, a total of 19 (1.4%) trials were lost for this reason. These trials were excluded from the data analyses. Average correct RTs and error rates are shown in Figs. 2 and 3, respectively. In addition, means per condition for Experiment 1 as well as for Experiments 2 and 3 are reported in table format in the Appendix A.

2.2.1. RTs analysis

For the "normal presentation" and "degraded presentation" groups, respectively, 27 data points (1.9% of all trials) and 40 data points (3.1% of all trials) were removed on an individual basis from the RT analysis because the response latency was more than 2.5 *SD*s away from the mean of their condition. In addition, one item from the "degraded presentation" data was rejected from the items analysis because of an error rate of 100% on this item.

Separate ANOVAs based upon means per subject (F_1/t_1) or item (F_2/t_2) were conducted upon RTs (and error rates),

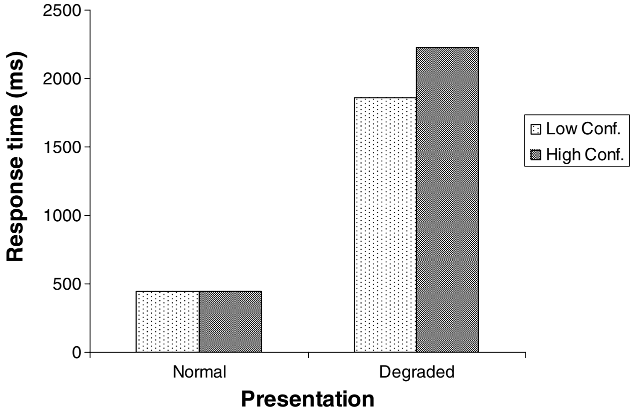

Fig. 2. Average correct response times (ms) as a function of visual presentation (normal vs. degraded) and letter confusability (Experiment 1).

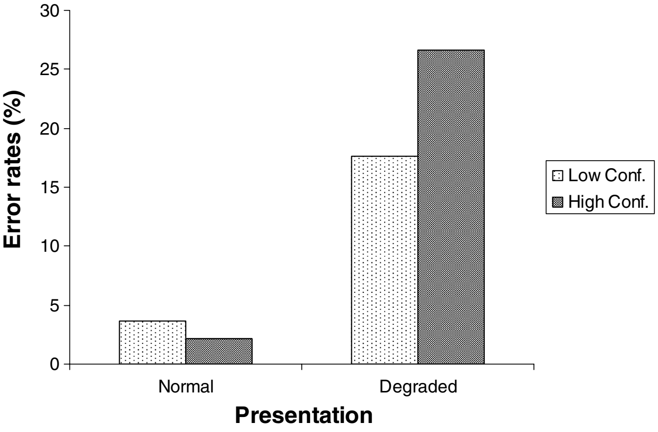

Fig. 3. Error rates (%) as a function of visual presentation (normal vs. degraded) and letter confusability (Experiment 1).

with presentation type (normal vs. degraded) and letter confusability (low vs. high) as factors. These showed main effects of presentation type, $F_1(1,19) = 188.9$, $p < .001$; $F_2(1, 235) = 26.0$; $p < .001$, and of letter confusability, $F_1(1,19) = 13.9$, $p < .01$; $F_2(1,235) = 7.2$; $p < .005$, with shorter RTs for stimuli presented normally (vs. visually degraded), and for low confusability words compared to high confusability items. Moreover, these factors interacted significantly, $F_1(1,19) = 13.96$, $p < .01$; $F_2(1,235) = 7.5$; $p < .01$. Simple effects analyses were performed to determine the confusability effect for each presentation type. For the "normal presentation" group, no confusability effect was observed, $t_1(10) = 0.1$, *n.s.*; $t_2(118) = 0.2$, *n.s.*, whereas for the "degraded presentation" group, a large confusability effect was present, $t_1(9) = 3.6$, $p < .01$; $t_2(117) = 2.8$, $p < .001$, with shorter RTs for low compared to high confusability words.

2.2.2. Error rates analysis

An ANOVA conducted on error rates, with presentation type and letter confusability as factors showed a main effect of presentation type, $F_1(1,19) = 50.0$, $p < .001$; $F_2(1,235) = 63.1$; $p < .001$, and of letter confusability, $F_1(1,19) = 7.0$, $p < .05$; $F_2(1,235) = 13.4$, $p < .001$, with fewer errors for stimuli presented normally (vs. visually degraded), and for low confusability words compared to high confusability items. These factors also interacted significantly, $F_1(1,19) = 14.2$, $p < .01$; $F_2(1,235) = 21.2$, $p < .001$. Simple effects analyses indicated that error rates were not affected by letter confusability when stimuli were presented normally, $t_1(10) = 1.3$, *n.s.*; $t_2(118) = 0.2$; *n.s.*, contrarily to when they were visually degraded, $t_1(9) = 3.6$, $p < .01$; $t_2(117) = 3.8$; $p < .001$, where error rates were significantly higher with high confusability words.

2.3. Discussion

The present results clearly indicate that the overt word reading performance of normal readers (over RTs and error rates) is negatively affected by increased letter confusability with visually degraded stimuli, but not when stimuli are presented normally. The observations with degraded stimuli replicate those obtained in LBL dyslexics, who show a substantial letter confusability effect with words in a normal format (Arguin et al., 2002; Arguin & Bub, 2005; Fiset et al., 2006).

3. Experiment 2

It was argued in the Section 1 that the letter confusability effect is a proper index of the visual impairment responsible for LBL dyslexia. If this is so, then the stimulus degradation used in Experiment 1 should be capable of reproducing the behavioural diagnostic criterion of LBL dyslexia in normal readers, namely a substantial effect of word length. The main purpose of Experiment 2 is to assess this prediction. Specifically, Experiment 2 examined the word length effect in normal subjects with stimuli of varying lengths that have been degraded in the same manner as in Experiment 1.

Another factor examined in Experiment 2 is the effect of lexical frequency. Indeed, in addition to showing an advantage for high relative to low frequency words (see Section 1), the reading latency of individual LBL dyslexics often shows interactive effects of frequency and length, with a weaker length effect with high than low frequency words (Behrmann et al., 1998). It must be noted however, that the interaction of length by frequency is not found in all LBL dyslexics (Arguin et al., 1998; Behrmann et al., 1998; Bowers et al., 1996a).

Pseudowords (i.e. pronounceable nonwords) were also used in Experiment 2, mainly in order to prevent the application of guessing strategies. Indeed, in previous pilot experiments using degraded stimuli, participants often showed very high error rates when trying to identify five- to seven-letter words. It appeared that one cause for these high error rates was that subjects frequently attempted to guess the word instead of actually identifying it. The introduction of pseudowords in the stimulus list should make such a strategy less likely.

3.1. Methods

3.1.1. Subjects

Sixteen normal readers, aged between 19 and 34 (mean = 22.8 years old) took part in this experiment. They were selected according to the same criteria as in Experiment 1. Eleven of the participants were university students. The others had 16 years of education or more. None had participated in Experiment 1.

3.1.2. Materials and stimuli

Four hundred and eighty stimuli, including 240 words and 240 pseudowords, were used in this experiment. There was an equal number of five-, six-, and seven-letter words and pseudowords.

3.1.3. Words

Half the words had a high lexical frequency (over 2145 per 100 million) and half had a low frequency (under 154 per 100 million; Content et al., 1990). Words of different lengths and lexical frequencies were matched on their letter confusability, orthographic neighbourhood size, and bigram frequency, F's $(2,234)$ and $(1,234) < 1$.

3.1.4. Pseudowords

Pseudowords were created by changing one or two letters in a word. Pseudowords of different lengths did not differ on letter confusability, neighbourhood size, or bigram frequency, all F's$(2,237) < 1$.

3.1.5. Words vs. pseudowords

Words and pseudowords differed on their letter confusability $F(1,474) = 5.0$, $p < .05$, pseudowords having a slightly higher average letter confusability than words (mean letter confusability was 0.469 and 0.461, respectively). In addition, pseudowords had a higher bigram frequency than words $F(1,474) = 10.6$, $p < .05$, (2.74 and 2.68 for pseudowords and words, respectively). These differences were very weak however, and they were considered not to be problematic since pseudowords were used mainly in order to encourage subjects to actually read the words rather than to attempt to guess them. Moreover, since bigram frequency is known not to impact overt word reading performances (Andrews, 1992), it appeared unlikely that this variable would affect the outcome of the experiment.

The complete stimulus list was divided in 6 blocks of 80 items, each comprising an equal number of words and pseudowords, of high and low frequency words, and of five-, six-, and seven-letter stimuli. Stimuli were randomised within each list and their order of presentation varied across subjects. The order of presentation of the blocks was counterbalanced across subjects. The exposure conditions of the stimuli were identical to those in the "degraded condition" of Experiment1.

3.1.6. Procedure

The course of each trial was the same as in Experiment 1. Subjects were given 10 practice trials immediately before the experimental task.

3.2. Results

The data analyses were performed on only 15 subjects: the data for one subject was discarded because he showed a dramatically high error rate (48.3%) compared to the other participants (average of 34.4%). A total of 112 (1.6%) trials overall were lost because the response failed to trigger the voice-key. These trials were not considered in the data analyses. Average correct RTs and error rates are shown in Figs. 4 and 5, respectively. The correlation between RTs and error rates was of +.92 ($p < .01$), which indicates no speed-accuracy trade-off.

3.2.1. RTs analysis

One hundred and sixty five data points (2.2% of all trials) were removed on an individual basis from the RTs analysis because the response latency was more than 2.5 *SD*s away from the mean of their condition. As for Experiment 1, separate ANOVAs based on means per subject (F_1) or item (F_2) were conducted upon RTs (and error rates), with length (five-, six-, and seven-letter words) and stimulus class (high frequency words, low frequency words and pseudowords) as factors.

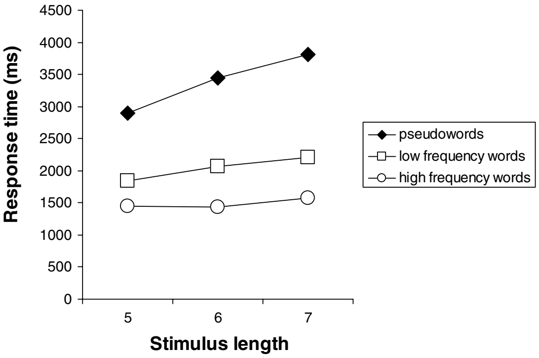

Fig. 4. Average correct response times (ms) as a function of word length and lexical frequency (Experiment 2).

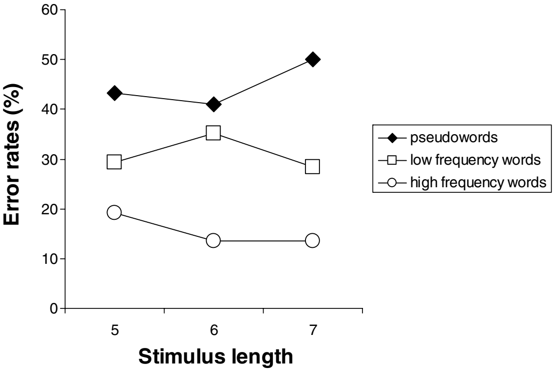

Fig. 5. Error rates (%) as a function of word length and lexical frequency (Experiment 2).

Data analyses showed main effects of length $F_1(2,28) = 18.3$, $p < .001$; $F_2(2,468) = 8.4$; $p < .001$—shorter words being read faster than longer words—and of stimulus class $F_1(2,28) = 27.9$, $p < .001$; $F_2(2,468) = 186.1$; $p < .001$—shorter RTs with high frequency words than with low frequency words, which in turn were read faster than pseudowords. The results also indicated a significant interaction of length by stimulus class $F_1(4,56) = 10.4$, $p < .001$; $F_2(4,468) = 3.4$; $p < .01$.

Simple effects analyses were performed to determine the length effect for each stimulus class. In the analyses per subjects, the length effect was significant for each type of stimulus: high frequency words $F_1(2,28) = 5.7$, $p < .01$ low frequency words $F_1(2,28) = 9.4$, $p < .001$; pseudowords $F_1(2,28) = 17.0$, $p < .001$. In the analyses per items, the length effect was significant for low frequency words, $F_2(2,117) = 3.4$, $p < .05$, and for pseudowords, $F_2(2,234) = 11.6$, $p < .001$, but not for high frequency words, $F_2(2,117) = 1.3$, *n.s.* Pairwise contrasts on the effect of word length across stimulus classes revealed significant differences in analyses performed over subjects, but not over items. Thus, a two-way ANOVA, with length and lexical frequency as factors, revealed a marginally significant interaction of length × frequency in the subjects analysis, $F_1(2,28) = 3.3$, $p = .05$; $F_2(2,234) = 1.6$, *n.s.*, suggesting a greater length effect with low frequency words (slope = 186.3 ms/letter, $r^2 = .99$—i.e. percentage of the variance of mean RTs accounted by a linear function—for low frequency words; slope = 68.5 ms/letter, $r^2 = .71$ for high frequency words). An additional ANOVA was performed to contrast the length effect across low frequency words and pseudowords. This analysis indicated a highly significant interaction of length × stimulus type in the subjects analysis, $F_1(1,28) = 10.6$, $p < .001$: larger length effect for pseudowords than for low frequency words (slope = 456.1 ms/

letter, $r^2 = .99$, for pseudowords). However, this interaction failed to reach significance in the items analysis, $F_2(2,357) = 2.1$, *n.s.*

3.2.2. Error rates analysis

The analyses conducted on error rates showed no main effect of length $F_1(2,28) < 1$; $F_2(2,468) < 1$, but the main effect of stimulus class was significant $F_1(2,28) = 218.86$, $p < .001$, $F_2(2,468) = 66.8$; $p < .001$, with the lowest error rates on high frequency words and the highest on pseudowords. The length × class interaction was significant in the analysis per subject whereas it failed to reach significance in the analysis per item, $F_1(4,56) = 9.0$, $p < .001$; $F_2(4,468) = 2.0$, $p < .10$. Simple effects analyses showed a reversed length effect with high frequency words which was significant in the analysis per subject but not in that per item, $F_1(2,28) = 5.1$, $p < .05$; $F_2(2,117) = 1.3$, *n.s.* (see Fig. 5). For low frequency words, the length effect was also significant in the subject analysis but not in that per item, $F_1(2,28) = 3.6$, $p < .05$; $F_2(2,117) < 1$, with higher error rates for six-letter words than for five- and seven-letter words (see Fig. 5). Finally, pseudowords showed a significant length effect over subjects but not over items, $F_1(2,28) = 9.4$, $p < .001$; $F_2(2,117) = 2.1$, *n.s.*, with monotonically increasing error rates with increasing length.

Pairwise contrasts of the length effect across low and high frequency words revealed a significant difference over subjects but not over items, $F_1(2,28) = 5.0$, $p < .05$; $F_2(2,234) = 1.6$, *n.s.* This interaction is attributed to the differing patterns of length effects described above. A similar outcome was observed in contrasting low frequency words and pseudowords on the length effect, $F_1(2,28) = 17.9$, $p < .001$; $F_2(2,234) = 2.2$, *n.s.*

3.3. Discussion

The main result of Experiment 2 is that the visual degradation of stimuli used here triggers, in neurologically intact readers, the word length effect characteristic of LBL dyslexia. The average length effect obtained on reading latencies for words (low and high frequency combined) is of 127.4 ms for each additional letter. This is considerably greater than that found in neurologically intact readers under normal reading conditions (Forster & Chambers, 1973; Frederiksen & Kroll, 1976; Weekes, 1997), which ranges from 6 to 63 ms for each additional letter. Most significantly, the length effects observed here were obtained using words of different lengths that were closely matched on N size. This type of control is known to abolish all word length effects in normal readers with undegraded stimuli, even with low frequency words (Weekes, 1997).

The results of Experiment 2 also revealed a stimulus class effect: reading was facilitated (in terms of both response latencies and error rates) for high frequency compared to low frequency words, and for low frequency words compared to pseudowords. Moreover, the RTs analyses also indicated an interaction of stimulus length × class: the length effect was more pronounced with pseudowords than low frequency words, and with low frequency words than high frequency words—differences which were significant over subject analyses but not over items.[3] A similar modulation of the length effect according to lexical frequency has been reported previously in some but all LBL dyslexics (Arguin et al., 1998; Behrmann et al., 1998; Bowers et al., 1996a). The interaction between word length and lexical frequency has been interpreted by Behrmann et al. within the context of their unitary interactive account of LBL dyslexia. Assuming that the crucial deficit of LBL dyslexics affects prelexical processing in an otherwise normal reading system, they proposed that the interaction of word length and lexical frequency reflects facilitatory top-down influences on letter processing. Thus, because long words take longer to process than shorter ones, there is additional time for top-down effects such as lexical frequency to interactively affect reading performances.

4. Experiment 3

As noted in the Introduction, the modulation of the N size effect by letter confusability in LBL dyslexics is highly revealing with respect to key functional features that characterise the disorder. Specifically, the beneficial impact of increased N size with low letter confusability words indicates a residual capacity for parallel letter processing that provides a significant contribution to reading performance. In turn, the elimination of the N size effect with high letter confusability words indicates that the increased perceptual discrimination demands imposed by high letter confusability strongly interferes with, or may even block parallel letter processing in LBL dyslexics. Experiment 3 examines whether this pattern of findings is replicated in normal readers with degraded stimuli—with standard print, their N size effect is independent of letter confusability (Arguin et al., 2002). As in Experiment 2, pseudowords were used in addition to words to discourage a guessing strategy.

4.1. Methods

4.1.1. Subjects

Fifteen normal readers took part in this experiment. They were aged between 19 and 27 years old (mean = 22.6 years). All of them, except two, were university students. The others had 16 and 17 years of formal education. The

---

[3] In some instances in the data analyses of Experiment 2 as well as in those of Experiment 3, effects which are significant when analysed over subjects failed to reach significance when analysed over items. This indicates that whereas performance patterns are rather consistent across subjects, they are less so across items. This relative inconsistency of performance patterns over items with respect to the effects of some factors or factor combinations most likely originates from other unknown intrinsic stimulus properties that correlate with these factors or that interact with them in their effects on performance. Most importantly, we underline that there is no instance of a discrepancy between analyses over items or subjects that contradict the main thrust of the conclusions proposed here.

inclusion criteria were the same as in Experiments 1 and 2. None had participated in either Experiment 1 or 2.

4.1.2. Stimuli

4.1.2.1. Words. The targets were 168 words varying orthogonally on their letter confusability (low confusability: below 0.45; high confusability: 0.52 or higher) and their number of orthographic neighbours (low N size: 0 neighbour; high N size: 4–8 neighbours). Also, we used stimuli of different lengths (four-, five-, six-, and seven-letter items), since not enough words of the same length were available in French to construct the task while controlling for other relevant lexical variables. Words were matched across conditions according to their length, lexical frequency (Content et al., 1990), and bigram frequency. Conditions did not differ on these variables $F(3,164) < 1$, except for bigram frequency $F(3,164) = 14.04$, $p < .001$, which was higher for high N size words. Bigram frequency shows a large positive correlation with N size and thus a perfect match on this variable across low and high N size words is extremely difficult to achieve. As noted previously, bigram frequency on its own does not significantly affect word reading performance (Andrews, 1992).

4.1.2.2. Pseudowords. Pseudowords were created by changing one or two letters in a word. There were 168 pseudowords of four to seven letters in length, which varied orthogonally on their number of orthographic neighbours (low N size: 0 neighbour; high N size: 3–9 neighbours) and their letter confusability (low: 0.47 or lower; high: 0.48 or higher).

Across corresponding conditions, words and pseudowords were matched on length, $F(1,328) < 1$, letter confusability $F(1,328) < 1$, N size $F(1,328) < 1$, and bigram frequency $F(1,328) < 1$.

The stimuli were divided into four blocks comprising 84 stimuli each. Each block contained equal numbers of words and pseudowords of low or high letter confusability, and of low or high N size. The order of presentation of the blocks was counterbalanced across subjects.

4.1.2.3. Procedure. The course of trials was the same as in Experiments 1 and 2.

4.2. Results

A total of 73 (1.5%) trials were lost because responses failed to trigger the voice-key. These trials were excluded from the data analysis. Average correct RTs and error rates are shown in Figs. 6 and 7, respectively. The correlation between RTs and error rates was of +.86 ($p < .01$), which indicates the absence of a speed-accuracy trade-off.

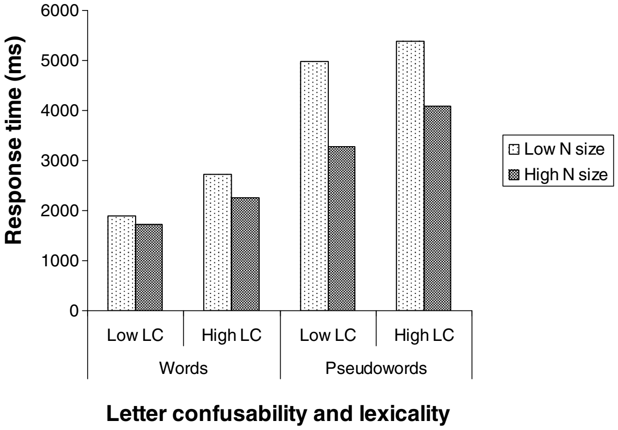

Fig. 6. Average correct response times (ms) as a function of letter confusability (LC) and orthographic neighbourhood size (N size) (Experiment 3).

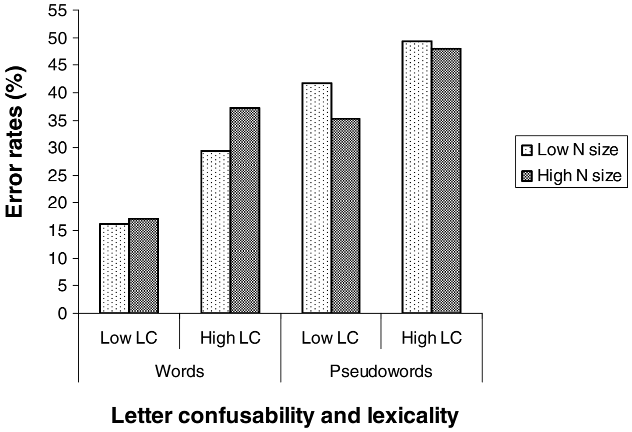

Fig. 7. Error rates (%) as a function of letter confusability (LC) and orthographic neighbourhood size (N size) (Experiment 3).

4.2.1. RTs analysis

Ninety-seven data points (1.9% of all trials) were removed on an individual basis from the RTs analysis because the response latency was more than 2.5 *SD*s away from the mean of their condition. Three-way ANOVAs (F_1 over subjects; F_2 over items) performed on correct RTs, with lexicality (words vs. pseudowords), letter confusability (low vs. high) and neighbourhood size (low vs. high) as factors showed main effects of lexicality, $F_1(1,14) = 25.51$, $p < .001$; $F_2(1,322) = 272.9$, $p < .001$, of letter confusability, $F_1(1,14) = 18.29$, $p < .001$; $F_2(1,322) = 16.0$, $p < .001$, and of neighbourhood size,$F_1(1,14) = 21.35$, $p < .001$; $F_2(1,322) = 52.5$, $p < .001$, with shorter RTs with words, low confusability stimuli, and targets having a large neighbourhood size. The results also indicated that the interaction of lexicality and N size was significant, $F_1(1,14) = 21.42$, $p < .001$; $F_2(1,322) = 24.5$, $p < .001$, (with a larger N size effect for pseudowords). In addition, the interaction of lexicality × letter confusability × neighbourhood size was significant over subjects but not over items, $F_1(1,14) = 4.76$, $p < .05$; $F_2(1,322) = 1.7$, *n.s.* The overall experimental design was broken down to allow the analysis of the interaction of letter confusability with N size for words and pseudowords separately.

4.2.1.1. Words. Two-way ANOVAs performed on words only, with letter confusability and neighbourhood size as factors, revealed main effects of letter confusability, $F_1(1,14) = 17.2$, $p < .001$; $F_2(1,163) = 29.6$, $p < .001$, and N size, $F_1(1,14) = 5.8$, $p < .05$; $F_2(1,163) = 7.8$, $p < .01$, with shorter RTs with low confusability targets and with words having a high N size. The interaction term was not quite significant over subjects, $F_1(1,14) = 3.7$, $p = .08$, but was clearly nonsignificant over items, $F_2(1,163) < 1$. A priori simple effects analyses of this interaction showed a significant facilitatory effect of increased N size with high confusability words, $F_1(1,14) = 7.9$, $p < .05$; $F_2(1,81) = 5.2$, $p < .05$, but no effect with low confusability words, $F_1(1,14) = 1.6$, *n.s.*; $F_2(1,82) = 2.6$, *n.s.*

4.2.1.2. Pseudowords. For pseudowords, the analysis revealed main effects of letter confusability, $F_1(1,14) = 9.4$, $p < .01$; $F_2(1,159) = 3.7$, $p = .05$, and of N size, $F_1(1,14) = 24.4$, $p < .001$; $F_2(1,159) = 43.9$, $p < .001$, with shorter RTs for low confusability items and for targets having a large N size. These variables did not interact significantly, $F_1(1,14) = 2.8$, *n.s.*; $F_2(1,159) < 1$.

4.2.2. Error rates analysis

A three-way ANOVA conducted on error rates, showed main effects of lexicality, $F_1(1,14) = 95.6$, $p < .001$; $F_2(1,322) = 37.9$, $p < .001$, and letter confusability, $F_1(1,14) = 71.9$, $p < .001$; $F_2(1,322) = 19.7$, $p < .001$, but no N size effect, $F_1(1,14) < 1$; $F_2(1,322) < 1$. The significant main effects indicate lower error rates with words than with pseudowords and with low than high letter confusability items. The triple interaction term was not significant over neither subjects nor items, $F_1(1,14) = .15$, *n.s.*; $F_2(1,322) < 1$. Over items, no other interaction reached significance, confusability × lexicality: $F_2(1,322) < 1$; confusability × N size: $F_2(1,322) = 1.9$, *n.s.*; lexicality × N size: $F_2(1,322) < 1$. However, over subjects, lexicality and letter confusability interacted significantly, $F_1(1,14) = 10.3$, $p < .01$, (greater confusability effect for words than pseudowords) as well as lexicality and N size, $F_1(1,14) = 8.8$, $p = .01$ (trend for an inhibitory N size effect with words and for a facilitatory effect with pseudowords; see below for additional details). Also, the interaction of confusability by N size was marginally significant, $F_1(1,14) = 4.3$, $p = .056$, reflecting a trend for an inhibitory N size effect with low confusability targets and for a facilitatory N size effect with high confusability items.

4.2.2.1. Words. A priori analyses of error rates conducted on words only indicated a cost of increased letter confusability, $F_1(1,14) = 92.4$, $p < .001$; $F_2(1,163) = 20.8$, $p < .001$. Over items, the effect of N size, $F_2(1,163) = 1.0$, *n.s.*, and the confusability × N size interaction, $F_2(1,163) < 1$, were not significant. However, over subjects, the inhibitory effect of increased N size, $F_1(1,14) = 5.6$, $p < .05$, as well as the interaction of confusability × N size, $F_1(1,14) = 5.8$, $p < .05$, were significant. With high confusability words, an N size effect (increased error rates with high N size words) was observed over subjects but not over items, $F_1(1,14) = 13.4$, $p < .005$; $F_2(1,81) = 1.2$, *n.s.*, whereas the N size effect was not significant with low confusability words, $F_1(1,14) < 1$; $F_2(1,82) < 1$.

4.2.2.2. Pseudowords. For pseudowords, a cost of increased letter confusability was present, $F_1(1,14) = 25.1$, $p < .001$; $F_2(1,159) = 3.9$, $p = .05$. Error rates did not differ according to N size, $F_1(1,14) = 2.7$, *n.s.*; $F_2(1,159) < 1$, and letter confusability and N size did not interact, $F_1(1,14) = 1.6$, *n.s.*; $F_2(1,159) < 1$.

4.3. Discussion

The results of Experiment 3 revealed a letter confusability effect, with shorter RTs and reduced error rates for low confusability items compared to high confusability targets. This replicates the results of Experiment 1 and is congruent with the performance of LBL dyslexics (Arguin et al., 2002; Arguin & Bub, 2005; Fiset et al., 2006). Moreover, the RTs analysis showed that increased N size had a facilitatory effect on word and pseudoword reading: targets with a large neighbourhood size were read faster than those with few neighbours. This latter finding replicates the performance of normal readers with normally printed stimuli (Andrews, 1989, 1992; Arguin et al., 1998; Carreiras et al., 1997; Sears et al., 1995) as well as that of LBL dyslexics (Arguin & Bub, 1996; Arguin et al., 1998, 2002; Arguin & Bub, 2005; Fiset et al., 2006; Montant & Behrmann, 2001). In contrast to our predictions however, the RTs did not show the expected interaction of letter confusability and N size, i.e. a reduction or elimination of the N size effect with high confusability items. Indeed, letter confusability failed to modulate the N size effect for pseudowords, whereas the trend was in a direction opposite to that predicted for words. These observations depart from those obtained in LBL readers, who showed a facilitatory N size effect only with words of low letter confusability. It appears that this nonreplication may be accounted in part by individual differences regarding the impact of stimulus degradation.

A detailed examination of individual subject means revealed an important variation in response times (range of overall individual RT means: 1609–5680 ms, words and pseudowords combined). Relatedly, there is a relatively substantial, significant correlation of +.56 ($p < .05$) between mean RTs for words and the degree by which the advantage for high N size items (relative to low N size) is reduced with high (relative to low) letter confusability items (Fig. 8).[4] This reduction generally tends to be large (up to 837 ms) in the slower subjects but null or even markedly reversed for the faster subjects (i.e. amplified advantage of high N size words with high letter confus-

---

[4] The reduction of the N size effect by high letter confusability which is reported in Fig. 8 was calculated from mean individual correct RTs as: (LoN_LoLC–HiN_LoLC)-(LoN_HiLC–HiN_HiLC) where LoN and HiN indicate low and high N sizes, respectively; and LoLC and HiLC indicate low and high letter confusability, respectively.

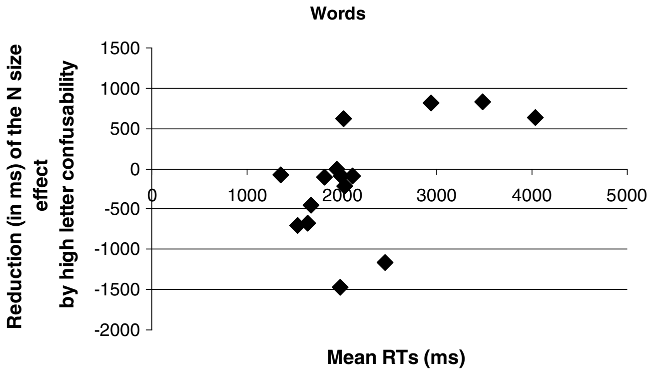

Fig. 8. Reduction (in ms) of the N size effect by high letter confusability as a function of individual mean reading latency for words (Experiment 3).

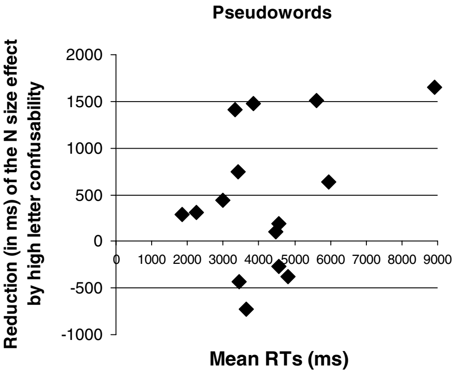

Fig. 9. Reduction (in ms) of the N size effect by high letter confusability as a function of individual mean reading latency for pseudowords (Experiment 3).

ability). For pseudowords, the correlation of RTs with the reduction of the N size effect by high letter confusability is not as strong as for words ($r = +.38$; $p < .05$) (Fig. 9). However, the interaction between N size and letter confusability for pseudowords has never been directly tested in LBL dyslexics and we may only speculate as to whether it would be in the same direction as for words. Given this, the data with pseudowords does not appear as determinant as that obtained with words.

Congruently with the correlation reported above, if subjects are divided into two groups according to their mean RTs to words (more vs. less than 2200 ms), we observe that the slowest readers ($n = 4$) tend to show an interaction similar to that documented in LBL dyslexia (N size effect for low and high letter confusability words of 354 and 73 ms, respectively), whereas the faster subjects tend to present an interaction in the opposite direction i.e. larger facilitatory effect of increased N size for high (324 ms) than low (25 ms) letter confusability words.[5] It thus appears that the degree to which subjects are affected by the visual degradation may transform the way N size and letter confusability jointly affect reading performances.

5. General discussion

The research reported in the present paper has focused on an attempt to simulate LBL dyslexia in normal readers by degrading stimuli visually. According to the peripheral hypothesis of LBL dyslexia, this reading disorder is provoked by a functional impairment prior to the activation of the orthographic representation of words, thereby preventing normal lexical access. It was thus hypothesised that visually degrading the stimuli by reducing their contrast against the background and by removing their high spatial frequencies could induce the reading pattern characteristic of LBL dyslexia in neurologically intact readers.

Congruently, Experiment 1 demonstrated that contrast-reduced low passed stimuli provoke the letter confusability effect that has been previously observed in LBL dyslexics. Furthermore, Experiment 2 showed that the stimulus degradation used causes, in normal readers, a substantial word length effect which is the hallmark of LBL dyslexia. Another interesting aspect of the results of Experiment 2 was the production of a lexical frequency effect, which is congruent with that usually found in LBL dyslexics. The production of well-controlled effects of word length and of letter confusability in normal readers under degraded stimulus conditions is a novel finding that closely approximates crucial features of LBL dyslexia. These results therefore add weight to the hypothesis of an early visual deficit as the functional cause of LBL dyslexia.

Experiment 3 was designed to replicate the interaction between letter confusability and N size that was observed by Arguin et al. (2002), Arguin and Bub (2005), and Fiset et al. (2006) in LBL dyslexics, i.e. a facilitatory N size effect with low confusability items and the elimination or reduction of this effect with high confusability items. The mean results of the subject group tested in Experiment 3 failed to show the expected pattern: although significant effects of letter confusability and N size were observed, these variables did not interact significantly. A detailed examination of individual data however, revealed major individual differences in reading ability with our degraded stimuli, which seems to have affected the way in which N size and letter confusability jointly affected performances. Thus, the slowest readers tend to show the same interaction pattern between N size and letter confusability as LBL readers, while the faster readers tend to present an interaction in the opposite direction. An account for this observation will be elaborated hereafter.

5.1. *Does low pass filtering replicate the visual disorder of LBL dyslexics?*

Averaged over low and high frequency words, the length effect obtained in Experiment 2 is of 127.4 ms/letter. This

---

[5] Among these differences, only the facilitatory effect of increased N size with high confusability items in the fast-reader subgroup was statistically significant, $F(1, 10) = 6.1$; $p < .05$. In the slow-reader subgroup, the smallness of the sample (four subjects) played an important role in the fact that the inhibitory effect of increased N size with high confusability items was nonsignificant.

word length effect is substantially weaker than what is found in the vast majority of LBL dyslexics. This is particularly true for high frequency words, which showed an especially weak length effect of only 68.5 ms/letter. One possible explanation for this weakness of length effects could be that the task was not difficult enough to force normal readers to resort to a strict letter-by-letter strategy such as the one employed by LBL dyslexics. However, this account is incompatible with the fact that, throughout Experiments 1–3, the error rates obtained by our subjects were higher (ranging from 15% to 38% for words depending on lexical frequency and N size) than the ones usually observed in LBL readers. Thus, the relatively weak length effect of Experiment 2 seems not to be a function of low task difficulty. Another explanation for the small amplitude of the word length effect and high error rates in normal readers may be directly linked to the limitations implied by attempting to simulate the impact of a relatively central (i.e. cortical) visual impairment through stimulus degradation.

Given the nature of the impact of letter confusability on the reading performance of LBL dyslexics, it appears relatively evident that their disorder originates from a visual impairment that interferes with orthographic encoding. However, as noted in Section 1, this impairment seems to be well compensated by resorting to sequential letter processing, involving foveation (Behrmann, Shomstein, Black, & Barton, 2001; Rayner & Johnson, 2005) and the narrowing down of attention at the level of individual letters, instead of attempting to encompass the whole word at once (see Arguin et al., 2002 for a detailed explanation). It has been shown that attention can improve visual performance by enhancing spatial acuity (Yeshurun & Carrasco, 1998). Thus, the focusing of attention sequentially on individual letters may enhance the ability of LBL dyslexics to extract midrange spatial frequencies, which appear optimal for letter identification and less susceptible to visual confusions than low spatial frequencies (Majaj, Pelli, Kurshan, & Palomares, 2002; Solomon & Pelli, 1994).

With the stimulus degradation used here however, normal readers could not benefit from such strategic compensation: specifically, they could not use focused attention or sequential foveation on individual letters to improve the encoding of mid-to-high spatial frequencies since they were absent from the stimuli to begin with. Thus, the incentive of using a serial letter processing strategy may have been much weaker than in LBL dyslexia. We argue that this incapacity of subjects to fully compensate for stimulus degradation through an alteration of their visual encoding strategy may be responsible for the weaker word length effects and higher error rates observed here than those typical of LBL dyslexics. In other words, parallel and serial processing would be involved in both sets of subjects, but the contribution of serial processing to performance may be less in the normal readers than in LBL dyslexics because of the weakness of the potential benefits of using this compensatory strategy.

This relative reluctance of normal readers to rely on serial processing may explain why, in Experiment 3, the interaction of N size and letter confusability tended to be in the opposite direction of what is usually found in LBL readers (Arguin et al., 1998, 2002; Arguin & Bub, 2005; Fiset et al., 2006). Indeed, as argued previously (see Section 1) the loss of the N size effect with high letter confusability in LBL dyslexics is attributable to a blockage of parallel processing caused by a high-level of noise at the letter identification stage. If however, normal readers largely rely on parallel letter processing even in the most difficult visual conditions of Experiment 3 because serial processing brings no information gain, then high-level lexical effects, such as the facilitatory effect of increased N size, should still largely influence word reading, as we have found here. This interpretation seems to apply to the majority of the subjects in our study, mainly the fastest readers. In contrast, the other readers, who seem to show an interaction of N size and letter confusability similar to that observed in LBL dyslexia, appear more sensitive to the visual degradation employed (c.f. their longer RTs). For them, the difficulty in discriminating between letters in high confusability targets may have reached such a level that increased N size failed to remain facilitatory.

5.2. The impact of right hemianopia

The type of stimulus degradation used in the present experiments—in particular, the filtering out of high spatial frequencies from the stimulus—may be thought to possibly replicate the impact of the right hemianopia that generally accompanies LBL dyslexia. Indeed, hemianopia may imply a reduced availability of foveal vision and lead to a greater reliance of parafoveal encoding, which is associated with a decreased availability of high spatial frequencies (Carrasco & Frieder, 1997). Moreover, right hemianopia also implies that initial cortical visual processing is performed by the right cerebral hemisphere, which is biased towards a lower spatial frequency range than the left hemisphere (Ivry & Robertson, 1998). Could it be, then, that the right hemianopia that is typically associated with LBL dyslexia, is in fact be involved in its cause? A number of criticisms may be raised against such a view.

Indeed, it can be argued that even though LBL dyslexia is frequently accompanied by right homonymous hemianopia, not all LBL dyslexics are hemianopic (Henderson, Friedman, Teng, & Weiner, 1985; Leff et al., 2001; Montant, Nazir, & Poncet, 1998; Verstichel & Cambier, 1997). However, most LBL dyslexics without hemianopia manifest visual difficulties in their right visual hemifield (achromatopsia, higher threshold for detecting a flashed dot, etc.), which may imply a difficulty of the left hemisphere in properly encoding written inputs.

Observations by Leff et al. (2001) argue more decisevely against a “right-hemianopia” account of LBL dyslexia. These authors have examined patients with hemianopic alexia (a reading disorder different from LBL dyslexia which is associated with right hemianopia) and others with right hemianopia but no alexia. These did not show the large word length effect characteristic of LBL dyslexics. Such findings argue against the view that LBL dyslexic symptoms arise exclusively because of the right-hemisphere's visual encoding properties. Rather, they indicate that an account of LBL dyslexia requires the assumption of damage to a specific left hemispheric structure/process separate from that involved in maintaining a functional right visual hemifield and which is unavailable in the right hemisphere.

6. Conclusion

In support of the hypothesis that LBL dyslexia is caused by an early visual impairment, we have observed major effects of letter confusability and of word length in normal readers with visually degraded stimuli (low pass and reduced contrast). However, the interaction of N size and letter confusability found in LBL dyslexics has been reproduced only in a small subset of our slowest readers. The large individual differences in the impact of visual degradation and the absence of high spatial frequency information in the stimuli (reducing the potential benefits of a compensatory serial processing strategy) seem largely responsible for this finding.

Acknowledgments

We are grateful to all the participants who collaborated to these experiments. Thanks to Karine Tadros for her help in the final formatting of the manuscript. The present work was supported by a grant from the Canadian Institute of Health Research (CIHR) to Martin Arguin and a graduate scholarship from the CIHR to Stéphanie Fiset. Martin Arguin was chercheur-boursier of the Fonds de la Recherche en Santé du Québec when this research was conducted.

Appendix A

See Tables A.1–A.3

Table A.1
Mean RTs (ms) and error rates (percent—in parenthesis) per condition in Experiment 1

	Normal format	Degraded presentation
Low confusability	446 (4)	1856 (18)
High confusability	446 (2)	2230 (27)

Table A.2
Mean RTs (ms) and error rates (percent—in parenthesis) per condition in Experiment 2

Length	Pseudowords	Low freq. words	High freq. words
5 letters	2900 (43)	1836 (29)	1444 (19)
6 letters	3443 (41)	2061 (35)	1437 (14)
7 letters	3813 (50)	2209 (28)	1581 (13)

Table A.3
Mean RTs (ms) and error rates (percent—in parenthesis) per condition in Experiment 3

	Words		Pseudowords	
	Low conf.	High conf.	Low conf.	High conf.
Low N size	1894 (16)	2723 (29)	4983 (42)	5375 (49)
High N size	1720 (17)	2253 (37)	3276 (35)	4093 (48)

References

Andrews, S. (1989). Frequency and neighbourhood effects on lexical access: activation or search? *Journal of Experimental Psychology: Learning, Memory, and Cognition, 15*, 802–814.

Andrews, S. (1992). Frequency and neighbourhood effects on lexical access: lexical similarity or orthographic redundancy? *Journal of Experimental Psychology: Learning, Memory, and Cognition, 18*, 234–254.

Arguin, M., & Bub, D. N. (1993a). Single-character processing in a case of pure alexia. *Neuropsychologia, 31*, 435–458.

Arguin, M., & Bub, D. N. (1993b). An identity-selection deficit in pure alexia. *Brain and Language, 44*(4), 472.

Arguin, M., & Bub, D. (1994). Pure alexia. Attempted rehabilitation and its implications for interpretation of the deficit. *Brain and Language, 47*, 233–268.

Arguin, M., & Bub, D. (1996). A facilitatory effect of orthographic neighbourhood size in letter-by-letter reading. *International Journal of Psychology, 31*, 402.

Arguin, M., Bub, D., & Bowers, J. (1998). Extent and limits of covert lexical activation in letter-by-letter reading. *Cognitive Neuropsychology, 15*, 53–92.

Arguin, M., & Bub, D. (2005). Parallel processing blocked by letter similarity in letter dyslexia : a replication. *Cognitive Neuropsychology, 22*, 589–602.

Arguin, M., Fiset, S., & Bub, D. (2002). Sequential and parallel letter processing in letter-by-letter reading. *Cognitive Neuropsychology, 19*, 535–555.

Behrmann, M., Plaut, D. C., & Nelson, J. (1998). A literature review and new data supporting an interactive account of letter-by-letter reading. *Cognitive Neuropsychology, 15*, 7–51.

Behrmann, M., & Shallice, T. (1995). Pure alexia : a nonspatial visual disorder affecting letter activation. *Cognitive Neuropsychology, 12*, 409–454.

Behrmann, M., Shomstein, S. S., Black, S. E., & Barton, J. J. S. (2001). The eye movements of pure alexic patients during reading and non-reading tasks. *Neuropsychologia, 39*, 983–1002.

Beversdorf, D. Q., Ratcliffe, N. R., Rhodes, C. H., & Reeves, A. G. (1997). Pure alexia—clinical-pathologic evidence for a lateralized visual language association cortex. *Clinical Neuropathology, 16*, 328–331.

Binder, J. R., & Mohr, J. P. (1992). The topography of callosal reading pathways. a case-control analysis. *Brain, 115*, 1807–1826.

Black, S. E., & Behrmann, M. (1994). Localization in alexia. In A. Kertesz (Ed.), *Localization and Neuroimaging in Neuropsychology* (pp. 331–376). Toronto: Academic Press.

Bowers, J. S., Arguin, M., & Bub, D. (1996a). Fast and specific access to orthographic knowledge in a case of letter-by-letter surface alexia. *Cognitive Neuropsychology, 13*, 525–567.

Bowers, J. S., Bub, D., & Arguin, M. (1996b). A characterization of the word superiority effect in pure alexia. *Cognitive Neuropsychology, 13*, 415–441.

Carrasco, M., & Frieder, K. S. (1997). Cortical magnification neutralizes the eccentricity effect in visual search. *Vision Research, 37*, 63–82.

Carreiras, M., Perea, M., & Grainger, J. (1997). Effects of orthographic neighbourhood in visual word recognition: cross-task comparisons. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 23*, 857–871.

Cohen, L., Martinaud, O., Lemer, C., Lehericy, S., Samson, Y., Obadia, M., et al. (2003). Visual word recognition in the left and right hemispheres: anatomical and functional correlates of peripheral alexia. *Cerebral Cortex, 13*, 1313–1333.

Coltheart, M., Davelaar, E., Jonasson, J. T., & Besner, D. (1977). Access to the internal lexicon. In S. Dornic (Ed.), *Attention and Performance VI* (pp. 535–555). London: Academic Press.

Content, A., Mousty, P., & Radeau, M. (1990). Brulex: une base de données lexicales informatisée pour le français écrit et parlé. *L'Année Psychologique, 90*, 551–566.

Content, A., & Peereman, R. (1992). *Single and Multiple Process Models of Print to Speech Conversion*. Amsterdam: North Holland.

Damasio, A. R., & Damasio, H. (1983). The anatomic basis of pure alexia. *Neurology, 33*, 1573–1583.

Dejerine, J. (1892). Contribution à l'étude anatomo-pathologique et clinique des différentes variétés de cécité verbale. *Comptes-Rendus et Mémoires de la Société de Biologie*, 61–90.

Ellis, A. W., Young, A. W., & Anderson, C. (1988). Modes of word recognition in the left and right cerebral hemispheres. *Brain and Language, 35*, 254–273.

Farah, M. J., & Wallace, M. A. (1991). Pure alexia as a visual impairment: a reconsideration. *Cognitive Neuropsychology, 8*, 313–334.

Fiset, D., Arguin, M., & McCabe, E. (2006). The breakdown of parallel letter processing in letter-by-letter dyslexia. *Cognitive Neuropsychology, 23*, 240–260.

Fiset, D., Arguin, M., Bub, D., Humphreys, G. W., & Riddoch, M. J. (2005). How to make the word length effect disappear in letter-by-letter dyslexia. *Psychological Science, 16*, 535–541.

Fiset, S., & Arguin, M. (1998). The independence of letter and word processing in letter-by-letter reading. *Brain and Cognition, 37*, 88–91.

Forster, K. I., & Chambers, S. M. (1973). Lexical access and naming time. *Journal of Learning and Verbal Behavior, 12*, 627–635.

Frederiksen, J. R., & Kroll, J. F. (1976). Spelling and sound: approaches to the internal lexicon. *Journal of Experimental Psychology: Human Perception and Performance, 2*, 361–379.

Friedman, R. B., & Lott, S. N. (2000). Rapid word identification in pure alexia is lexical but not semantic. *Brain and Language, 72*, 219–237.

Friedman, R. B., & Alexander, M. P. (1984). Pictures, images and pure alexia: a case study. *Cognitive Neuropsychology, 1*, 9–23.

Gilmore, G. C., Hersh, H., Caramazza, A., & Griffin, J. (1979). Multidimensional letter similarity derived from recognition errors. *Perception and Psychophysics, 25*, 425–431.

Henderson, L. (1982). *Orthography and Word Recognition in Reading*. London: Academic Press.

Henderson, V. W., Friedman, R. B., Teng, E. L., & Weiner, J. M. (1985). Left hemisphere pathways in reading: inferences from pure alexia without hemianopia. *Neurology, 35*, 962–968.

Ivry, R., & Robertson, L. C. (1998). *The two sides of perception*. Cambridge: MIT Press Series in Cognitive Neurosciences.

Kay, J., & Hanley, R. (1991). Simultaneous form perception and serial letter recognition in a case of letter-by-letter reading. *Cognitive Neuropsychology, 8*, 249–273.

Kinsbourne, M., & Warrington, E. K. (1962). A disorder of simultaneous form perception. *Brain, 85*, 461–486.

Lavidor, M., & Ellis, A. W. (2002). Word length and orthographic neighborhood size effects in the left and right cerebral hemispheres. *Brain and Language, 80*, 45–62.

Leff, A. P., Crewes, H., Plant, G. T., Scott, S. K., Kennard, C., & Wise, R. J. S. (2001). The functional anatomy of single-word reading in patients with hemianopic and pure alexia. *Brain, 124*, 510–521.

Levine, D. M., & Calvanio, R. A. (1978). A study of the visual defect in verbal alexia simultagnosia. *Brain, 101*, 65–81.

Loomis, J. M. (1982). Analysis of tactile and visual confusion matrices. *Perception and Psychophysics, 31*, 41–52.

Majaj, N. J., Pelli, D. G., Kurshan, P., & Palomares, M. (2002). The role of spatial frequency channels in letter identification. *Vision Research, 42*, 1165–1184.

Montant, M., & Behrmann, M. (2001). Phonological activation in pure alexia. *Cognitive Neuropsychology, 18*, 697–727.

Montant, M., Nazir, T. A., & Poncet, M. (1998). Pure alexia and the viewing position effect in printed words. *Cognitive Neuropsychology, 15*, 93–140.

Patterson, K. E., & Kay, J. (1982). Letter-by-letter reading: psychological description of a neurological syndrome. *Quarterly Journal of Experimental Psychology, 34A*, 411–441.

Price, C. J., & Humphreys, G. W. (1992). Letter-by-letter reading? Functional deficits and compensatory strategies. *Cognitive Neuropsychology, 9*, 427–457.

Rapp, B. C., & Caramazza, A. (1991). Spatially determined deficits in letter and word processing. *Cognitive Neuropsychology, 8*, 275–311.

Rayner, K., & Johnson, R. L. (2005). Letter-by-letter acquired dyslexia is due to the serial encoding of letters. *Psychological Science, 16*, 530–534.

Reuter-Lorenz, P. A., & Brunn, J. L. (1990). A prelexical basis for letter-by-letter reading: a case study. *Cognitive Neuropsychology, 7*, 1–20.

Sears, C. R., Hino, Y., & Lupker, S. J. (1995). Neighbourhood size and neighbourhood frequency effects in word recognition. *Journal of Experimental Psychology: Human Perception and Performance, 21*, 876–900.

Sekuler, E., & Behrmann, M. (1996). Perceptual cues in pure alexia. *Cognitive Neuropsychology, 13*, 941–974.

Solomon, J. A., & Pelli, D. G. (1994). The visual filter mediating letter identification. *Nature, 369*, 395–397.

Townsend, J. T. (1971). Theoretical analysis of an alphabetical confusion matrix. *Perception and Psychophysics, 9*, 40–50.

Van der Heijden, A. H. C., Malhas, M. S. M., & Van den Roovart, B. P. (1984). An empirical interletter confusion matrix for continuous-line capitals. *Perception and Psychophysics, 35*, 85–88.

Verstichel, P., & Cambier, J. (1997). Alexie lettre à lettre après lésion hémisphérique gauche sans hémianopsie ni atteinte calleuse: deux observations. *Revue Neurologique, 153*, 561–568.

Warrington, E. K., & Shallice, T. (1980). Word-form dyslexia. *Brain, 103*, 99–112.

Weekes, B. S. (1997). Differential effects of number of letters on word and nonword naming latency. *Quarterly Journal of Experimental Psychology, 50A*, 439–456.

Yeshurun, Y., & Carrasco, M. (1998). Attention improves or impairs visual performances by enhancing spatial resolution. *Nature, 396*, 72–74.