Inducing Letter-by-letter Dyslexia in Normal Readers

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Abstract

■ Letter-by-letter (LBL) dyslexia is an acquired reading disorder characterized by very slow reading and a large linear word length effect. This suggests the use of a sequential LBL strategy, in sharp contrast with the parallel letter processing used by normal subjects. Recently, we have proposed that the reading difficulty of LBL dyslexics is due to a deficit in discriminating visually similar letters based on parallel letter processing [Arguin, M., Fiset, S., & Bub, D. Sequential and parallel letter processing in letter-by-letter dyslexia. *Cognitive Neuropsychology, 19*, 535–555, 2002]. The visual mechanisms underlying this deficit and the LBL strategy, however, are still unknown. In this article, we propose that LBL dyslexic patients have lost the ability to use, for parallel letter processing, the optimal spatial frequency band for letter and word recognition. We claim that, instead, they rely on lower spatial frequencies for parallel processing, that these lower spatial frequencies produce confusions between visually similar letters, and that the LBL compensatory strategy allows them to extract higher spatial frequencies. The LBL strategy would thus increase the spatial resolution of the visual system, effectively resolving the issue pertaining to between-letter similarity. In Experiments 1 and 2, we succeeded in replicating the main features characterizing LBL dyslexia by having normal individuals read low-contrast, high-pass-filtered words. Experiment 3, conducted in LBL dyslexic L.H., shows that, indeed, the letter confusability effect is based on low spatial frequencies, whereas this effect was not supported by high spatial frequencies. ■

INTRODUCTION

Letter-by-letter (LBL) dyslexia is a reading disorder that can appear following a brain lesion in previously literate adults. The brain regions critically concerned in this pathology are the left fusiform gyrus (Cohen et al., 2003) or the white matter fibers conducting visual information to this region (Binder & Mohr, 1992; Damasio & Damasio, 1983). Given the posterior localization of the lesion, a homonymous hemianopia is also frequently found, constraining the patient to process the orthographic stimuli with his or her right visual cortex. The behavioral diagnostic criteria for this pathology are very slow reading and an abnormally large word length effect (i.e., reading time is proportional to the number of letters in the word). Depending on the patient, the time needed to read a word aloud can increase from 300 msec to several seconds for each additional letter in the stimulus (see Lambon Ralph, Hesketh, & Sage, 2004). This performance pattern suggests an LBL strategy that contrasts with normal reading, where the number of letters has no significant impact on reading latencies, at least with relatively short (six letters or less) words (Weekes, 1997). This suggests that normal subjects process letters in parallel for word recognition.

Several authors thus assume LBL dyslexia to be the result of damage to the mechanisms responsible for the parallel processing of letters and, consequently, to reflect serial encoding of the component letters in words (Rayner & Johnson, 2005; Cohen et al., 2003; Behrmann, Shomstein, Black, & Barton, 2001). This neuropsychological disorder could result from a number of functional deficits, as is suggested by the individual differences between LBL dyslexics (e.g., Price & Humphreys, 1992, 1995). Alternatively, LBL dyslexics might have a common functional impairment, with relatively superficial differences (Behrmann, Plaut, & Nelson, 1998). This last position is the one that we adopt throughout the article.

The research conducted in our laboratory on the functional cause of LBL dyslexia has highlighted the fact that these patients confound visually similar letters (see also Perri, Bartolomeo, & Silveri, 1996; Patterson & Kay, 1982; Levine & Calvanio, 1978) and this especially when they try to recognize several letters simultaneously (Arguin & Bub, 2005; Fiset, Arguin, Bub, Humphreys, & Riddoch, 2005). In fact, all the patients examined so far ($n = 7$) showed a letter confusability effect (letter confusability is defined as the visual similarity between a particular letter and the remaining letters of the alphabet; see Arguin, Fiset, & Bub, 2002[1]) in word recognition, but no such effect in single-letter identification. Note also that the diagnostic word length effect can be eliminated if words of different lengths are matched

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on the sum of the confusability of their constituent letters, suggesting a fundamental role of letter confusability in the abolition of parallel letter processing (Fiset et al., 2005). We have argued that the purpose of the LBL strategy is to avoid confusion between visually similar letters by increasing the signal-to-noise ratio (see Arguin & Bub, 2005; Fiset et al., 2005; Arguin et al., 2002). However, the visual mechanisms subtending this sequential strategy remain unknown. In this article, we propose a theory of the visual impairment in LBL reading.

By contrast with LBL dyslexic patients, normal readers show no letter confusability effect with normal, broadband words (Fiset, Arguin & McCabe, 2006; Arguin et al., 2002). That a letter confusability effect is only present in LBL dyslexics emphasizes the abnormal sensitivity of these patients to the visual similarity between letters and suggests that a low-level visual deficit interferes with letter encoding (see Behrmann, Plaut, et al., 1998; Farah & Wallace, 1991; Friedman & Alexander, 1984; Levine & Calvanio, 1978; Kinsbourne & Warrington, 1962, for similar suggestions). We therefore argue that a coherent theory of LBL dyslexia requires a clear understanding of the determinants of their letter confusability effect.

One powerful approach to test a hypothesis regarding a neuropsychological disorder consists in attempting to induce the critical pathological behavior in normal subjects (McLeod, Shallice, & Plaut, 2000; Vecera & Gilds, 1998). Thus, the hypothesis that a visual deficit is at the origin of LBL dyslexia may be assessed by asking normal subjects to read visually deteriorated words. If the reading pattern characterizing LBL dyslexia occurs when normal subjects process degraded stimuli, it may be concluded that both patient and normal data reflect the malfunctioning of the same (or similar) mechanisms (McLeod et al., 2000).

Nelson, Behrmann, and Plaut (1999) succeeded in producing a substantial word length effect—the diagnostic criterion of LBL dyslexia—in normal readers using stimuli with a reduced luminance contrast. Fiset, Arguin, and Fiset (unpublished data), however, failed to replicate this result when controlling for *n* size, a control that had not been performed by Nelson et al., although word length is known to have a strong negative correlation with *n* size (Frauenfelder, Baayen, Hellwig, & Schreuder, 1993; see also Weekes, 1997).

Fiset, Arguin, and Fiset (in press) attempted to produce LBL dyslexia in normal readers by using low-contrast, low-pass-filtered words matched for *n* size and all other relevant variables. This stimulus degradation was chosen for its capacity to induce a significant letter confusability effect on the word-reading performance of normal subjects of a magnitude comparable to that found in LBL dyslexics. A significant word length effect (68.5, 186.3, and 456.1 msec for high-frequency words, low-frequency words, and pseudowords, respectively) was observed, but its size was far less than what is usually encountered in LBL dyslexics. Moreover, the significant word length effect was not statistically significant in the majority of normal subjects in single-case analyses. Task difficulty was not the cause of these weak slopes, however, because mean reaction times were similar to those of dyslexics (mean RT = 2250 msec) and error rates were greater than those usually observed in patients (between 10% and 35% errors compared to 5% and 10% in most dyslexic patients).

These previous studies lacked a firm theoretical foundation. With hindsight, it seems obvious that presenting low-contrast or low-pass-filtered words, two manipulations exacerbating low spatial frequencies in words, would not be optimal for inducing LBL reading: Low spatial frequencies are better processed in periphery (De Valois & De Valois, 1988), whereas LBL dyslexic patients tend to fixate letters centrally one after the other (Rayner & Johnson, 2005; Behrmann et al., 2001).

Here, we propose that dyslexic patients have lost the ability to use the spatial frequencies most useful for letter and word recognition. We shall develop this idea in the General Discussion. We claim instead that they rely on a lower range of spatial frequencies for their residual parallel letter processing ability, and that these lower spatial frequencies produce confusions between visually similar letters. This point is well supported by the study of Fiset et al. (in press), which shows that low-pass filtering causes a letter confusability effect to emerge in the word-reading performance of normal subjects. More crucially here, we also argue that the compensatory LBL strategy allows dyslexics to extract low-energy, high spatial frequencies by focusing attention on each letter, thereby increasing the spatial resolution of the visual system and minimizing the between-letter similarity (e.g., Yeshurun & Carrasco, 1998). If the LBL strategy is what patients require to extract high spatial frequencies not readily available for parallel processing, then a word length effect with a magnitude close to that observed in LBL dyslexics should be obtained in normal readers when they are presented with stimuli that only comprise spatial frequencies higher than what they usually employ in reading. Experiment 1 tests this prediction.

METHODS

Normal Subjects

Thirty French-speaking university students, aged between 19 and 32 years (mean = 22.9 years), took part in Experiments 1 and 2. All were right-handed, had normal or corrected-to-normal vision, and had no history of learning disabilities. In Experiment 1, broadband words were presented to 10 participants, and high-pass-filtered words to 10 other participants. In Experiment 2, 10 participants were exposed to high-pass-filtered words.

Case Report

L.H., an LBL dyslexic, participated in Experiment 3. L.H. is a 45-year-old right-handed, French-speaking man who, in 1998, suffered a cerebral vascular accident in the context of a resection of the left vertebral artery. A magnetic resonance imaging scan revealed a region of loss of brain parenchyma with cerebrospinal fluid density in the territory of the left posterior cerebral artery. L.H. shows a word length effect of about 660 msec per letter (see Fiset et al., 2006, for more details).

Materials and Stimuli

The stimuli were created by using the Image Processing Toolbox for Matlab (MathWorks, Natick, MA) and were displayed on a calibrated 17-in. DELL monitor. Words were printed in uppercase Arial 40 point, and were either high-pass filtered (Butterworth filter with a cutoff at 6 cycles per letter [cpl]), low-pass filtered (cut-off at 1.5 cpl), or broadband. In Experiments 1 and 2, the energy of our stimuli was set to a level close to that typically found in the high spatial frequencies of words (Põder, 2003; maximum luminance of 40.6 cd/m^2 against a background of 54.7 cd/m^2). The experiments were controlled by E-Prime (Psychology Software Tools, Pittsburgh, PA). Subjects were seated 57 cm away from the monitor. Letters subtended $0.73° \times 1.0°$ of visual angle.

In Experiment 1, a total of 140 four- to seven-letter words were used. In Experiment 2, two lists of 240 words were used. The first list manipulated word length (four- to seven-letter words) and lexical frequency (low = lower than 1000 per 100 million; high = higher than 5000 per 100 million; Content, Mousty, & Radeau, 1990). The second list modulated word length (five- to seven-letter words) and imageability (low = values lower than 2 and high = values higher than 5 on a 7-point scale, where 1 means *a very low imageability* and 7 *a very high imageability*; see Fiset et al., in press). We chose words of relatively low lexical frequency (average of 900 per 100 million, ranging from 0 to 4000; median at 300 per 100 million) because the imageability effect is larger with low-lexical-frequency words (Strain, Patterson, & Seidenberg, 1995). In Experiment 3, three word lists were created for testing the letter confusability effect on word recognition in L.H. We used 120 four to seven-letter words manipulating average letter confusability (low = below 0.43; high = 0.52 or higher). In all the lists (Experiments 1–3), words were matched on all the variables that were not a factor of interest but which are otherwise known to have an effect on reading performance (i.e., lexical frequency, bigram frequency, number of phonographic neighbors, number of letters, and letter confusability; all Fs < 1). Post hoc analysis demonstrated no difference between lists on imageability when this was not a factor examined.

Procedure

All subjects were submitted to 50 practice trials except those presented with broadband words in Experiment 1 who had none. Each practice and experimental trial began with a fixation cross displayed at the center of the computer monitor for 500 msec, and was immediately followed by the stimulus displayed at the center of the monitor until response. The task was to name the target aloud as fast and as accurately as possible. A voice key recorded response latencies. After each response, the experimenter entered the response of the participant via the computer keyboard.

EXPERIMENT 1

Ten normal subjects read low-contrast, high-pass-filtered words (see Figure 1). The cutoff of the filter for these stimuli was sufficiently high to remove most spatial frequencies useful for word recognition.^{2} This visual alteration should force subjects to use a reading strategy similar to the one we believe is used by LBL dyslexic patients, that is, to focus their attention on each letter to improve the spatial resolution of their visual system in order to extract the low-energy, high spatial frequencies.

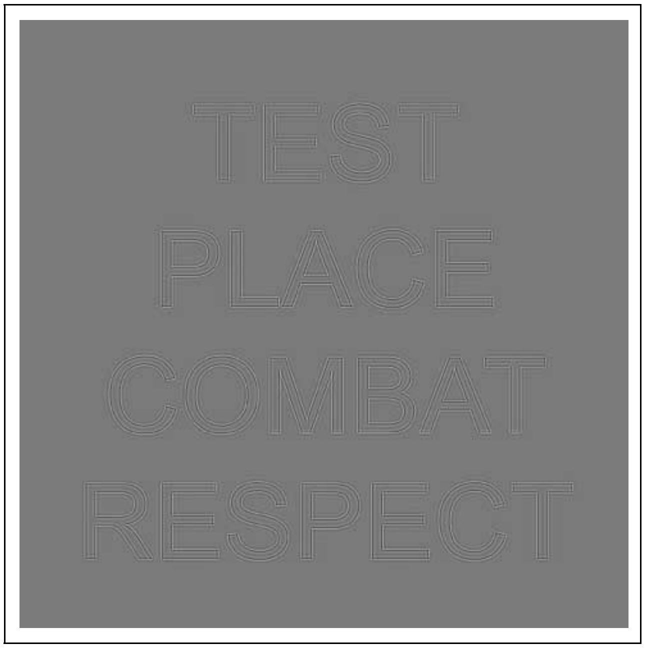

Figure 1. Sample of the French words used in Experiments 1 and 2. The first line consists in a four-letter, uppercase Arial word, the second in a five-letter one, and so on. The word length effect observed in normal individuals reading low-energy, high-passed words implies that the latency difference between reading line L and line L-1 should be roughly constant. Note, however, that the contrast and the spatial frequency content of these words differ from those of the stimuli presented in the Experiments 1 and 2 reported in this article. Stepping back a little from the figure will help the reader to experience the word length effect.

We compared the performance of these participants with 10 others reading broadband words.

Results

Table 1 shows average correct RTs for high-pass filtered and broadband words. For broadband words, 0.6% of all trials were discarded because of a voice-key problem; and for high-pass-filtered words, 1.9% were discarded for the same reason. Trials with RTs more than three standard deviations away from the subject's average in a given condition were also eliminated, resulting in the exclusion of 1.1% and 2.8% of the remaining correct trials for broadband and for high-pass-filtered words, respectively.

Separate analyses of variance (ANOVAs) based on means per subject (F_1) or item (F_2) were conducted on RTs, with presentation type (broadband vs. high passed) as between-subjects factor and word length as within-subject factor. These analyses showed main effects of presentation type, $F_1(3,54) = 52.1, p < .001$; $F_2(3,272) = 1587.05$; $p < .001$, and of word length, $F_1(3,54) = 13.6, p < .001$; $F_2(3,272) = 24.9$; $p < .001$, with longer RTs for high-pass-filtered words and a significant word length effect. Moreover, these factors interacted significantly, $F_1(3,54) = 13.3, p < .001$; $F_2(3,272) = 24.3$; $p < .001$.

Simple effects analyses were performed to determine the word length effect for each presentation type. With broadband words, a small but reliable word length effect of 4 msec per letter ($r^2 = .36$) was observed, $F_1(3,54) = 6.5, p < .01$; $F_2(3,272) = 3.1, p < .05$. A post hoc analysis showed that this small word length effect can be explained by longer RTs for seven-letter words, with no difference among the shorter words, thus closely replicating the observation of Cohen et al. (2003) (see also Fiset et al., 2006). With high-pass-filtered words, a large word length effect of 807 msec per letter ($r^2 = .99$) was observed, $F_1(3,54) = 13.4, p < .005$; $F_2(3,272) = 24.6, p < .001$. In single-case analyses performed on the data of participants who read high-pass words, all of the participants except one (Subject 4) exhibited a significant and linear effect of word length on reading latency (see Table 2).

Table 1. Reaction Times (in Milliseconds) for Normal Subjects for Visually Degraded and Normal Presentation as a Function of Word Length in Experiment 1

String Length	*Degraded*	*Normal*
4 letters	3443	472
5 letters	4230	477
6 letters	4895	468
7 letters	5911	489

Table 2. Single-case Analysis of the 10 Subjects Participating in Experiment 1

Subject	*Word Length Effect (msec/letter)*	R^2	*p (RT)*	*Error Rate (%)*
1	491	.94	<.05	0.7
2	1069	.77	<.001	3.6
3	463	.99	<.001	2.1
4	267	.16	.06	6.4
5	981	.99	<.05	6.4
6	898	.96	<.01	2.8
7	1071	.97	<.005	7.9
8	2209	.91	<.001	10.0
9	262	.98	<.001	3.6
10	358	.86	<.001	0.7

ANOVAs were conducted on error rates with presentation type as between-subjects factor and word length as within-subject factor. These analyses showed main effects of presentation type with more errors for high-pass-filtered words (error rate of 4.5% and 0.7% for high-pass filtered and broadband words, respectively), $F_1(1,18) = 13.0, p < .005$; $F_2(3,271) = 34.7$; $p < .001$, but no word length effect, $F_1(3,54) < 1$; $F_2(3,271) < 1$. These two factors did not interact, $F_1(3,54) < 1$; $F_2(3,271) < 1$; *ns.*

Discussion

Experiment 1 demonstrated that low-contrast, high-pass-filtered words induce word length effects and error rates similar to those observed in LBL dyslexic patients (see Table 2; Fiset et al., 2005; Lambon Ralph et al., 2004; Behrmann, Plaut et al., 1998). The participant with the weakest slope (Subject 9) had a word length effect of 262 msec per letter (see Sekuler & Behrmann, 1996, for cases of LBL dyslexia with similar or even smaller word length effects), whereas other subjects (Subjects 2, 5, 6, and 7) had word length effects reaching 1 sec per letter or even more (Subject 8, 2209 msec per letter). It is worth emphasizing that to the best of our knowledge, the visual degradation used here is the only one so far to have produced such word length effects and error rates in normal readers. As discussed in the Introduction, low-pass-filtered words produce word length effects that are smaller, and error rates that are larger, than those of most LBL dyslexics (Fiset, et al., in press), and reducing contrast simply fails to produce a reliable length effect independent of *n* size (Fiset, Arguin, & Fiset, unpublished data).

The reading rates of LBL dyslexic patients and, consequently, their word length effects are often, although not always, modulated by high-level variables. In Experiment 2, we examine whether high-level variables can also modulate the reading performance of normal subjects when they are presented with high-passed words.

EXPERIMENT 2

The average RTs as well as the word length effects observed in LBL dyslexics are not identical for all word categories. The reading latencies of LBL dyslexics are shorter for high- relative to low-lexical-frequency words (Fiset et al., 2006; Behrmann, Plaut et al., 1998; Sekuler & Behrmann, 1996; Behrmann & Shallice, 1995), and for high- relative to low-imageability words (Fiset et al., 2006; Behrmann, Plaut et al., 1998). Furthermore, interactions between these high-level variables and word length are often observed in reading latencies, with a smaller word length effect for high- than low-frequency/imageability words (see Behrmann, Plaut et al., 1998, for a literature review). The aim of Experiment 2 was thus to test whether the stimulus alteration used in Experiment 1 produces the high-level effects of lexical frequency and imageability as well as their interaction with word length.

Results

Lexical Frequency × Word Length

Figure 2A shows the correct RTs obtained in 10 participants. Of the trials, 2.5% were discarded because of voice-key problems, and 2.6% of the remaining correct trials were eliminated because the RTs were more than three standard deviations away from the subject's average for a given condition.

Separate ANOVAs based on means per subject (F_1/t_1) or item (F_2/t_2) were conducted on RTs, with word length and lexical frequency as within-subject factors. These analyses revealed main effects of lexical frequency, $F_1(3,27) = 27.6$, $p < .005$; $F_2(3,232) = 16.2$; $p < .001$, and word length, $F_1(3,27) = 20.3$, $p < .001$; $F_2(3,232) = 18.3$; $p < .001$, with longer RTs for low vs. high lexical frequency, and a significant and linear word length effect of 686 msec per letter ($r^2 = .96$). Moreover, these factors interacted significantly, $F_1(3,27) = 5.4$, $p < .005$; $F_2(3,232) = 4.2$; $p < .01$.

Simple effects analyses were performed to determine the word length effect for each level of lexical frequency. For low lexical frequency words, a word length effect of 963 msec per letter ($r^2 = .99$) was observed, $F_1(3,27) = 17.7$, $p < .001$; $F_2(3,232) = 14.4$, $p < .001$, whereas for high lexical frequency words, a word length effect of 359 msec per letter ($r^2 = .83$) was observed, $F_1(3,27) = 5.9$, $p < .01$; $F_2(3,232) = 4.8$, $p < .005$.

ANOVAs were conducted on error rates with lexical frequency and word length as factors. These analyses revealed no main effect of lexical frequency (error rate of 9.9% and 7.5% for low lexical frequency and high lexical frequency words, respectively), $F_1(3,27) = 2.5$, *ns*; $F_2(3,232) = 2.7$, *ns*, but a reliable word length effect, $F_1(3,27) = 6.5$, $p < .005$; $F_2(3,232) = 2.6$, $p = .052$, indicating increasing error rates with word length. These factors did not interact, $F_1(3,27) < 1$; $F_2(3,232) < 1$.

Imageability × Word Length

Figure 2B shows the correct RTs obtained in 10 participants. 2.0% of all trials were discarded due to voice-key problems and 2.3% of the remaining correct trials were eliminated because the RTs were more than three standard deviations away from the subject's average for a given condition.

Separate ANOVAs based on means per subject (F_1/t_1) or item (F_2/t_2) were conducted on RTs, with word length and imageability as within-subject factors. These analyses revealed main effects of imageability, $F_1(2,18) = 27.7$, $p < .005$; $F_2(2,234) = 8.7$; $p < .005$, and of word length, $F_1(2,18) = 21.7$, $p < .001$; $F_2(2,234) = 16.9$, $p < .001$,

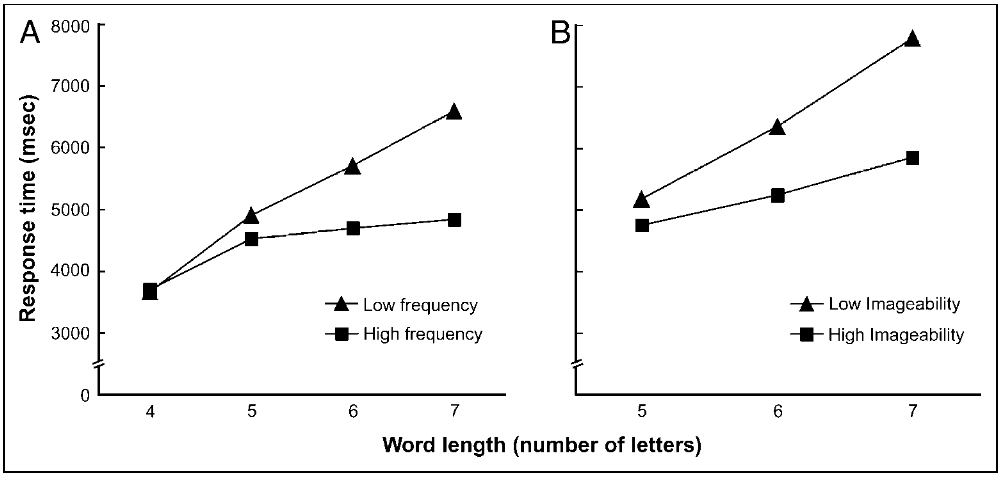

Figure 2. Average correct response times (milliseconds) in normal subjects reading visually degraded words (A) as a function of word length and lexical frequency and (B) as a function of word length and imageability.

with longer RTs for low vs. high imageability and a significant and linear word length effect (734 msec per letter, $r^2 = .98$). Word length and imageability did not interact significantly, $F_1(2,18) = 2.9$, *ns*; $F_2(2,234) = 2.7$, *ns*. Given the rather large difference between the word length effect of low- (1393 msec per letter) and high- (638 msec per letter) imageability words, this is somewhat surprising. However, we did not expect *all* participants to exhibit this interaction considering that LBL dyslexics do not always exhibit it either (Behrmann, Plaut et al., 1998). Inspection of the individual subject's data revealed two clusters of subjects: Five showed a clear interaction between word length and imageability (on average, 1971 and 316 msec per letter for low- and high-imageability words, respectively; $F_1(2,8) = 6.6$, $p < .05$; $F_2(2,234) = 2.7$, $p < .05$) whereas the other subjects did not (average of 816 msec vs. 962 msec per letter for low and high imageability, respectively; $F_1(2,8) < 1$; $F_2(2,234) < 1$).

ANOVAs were conducted on error rates (overall average of 14.1%) with imageability and word length as within-subject factors. These analyses showed no main effects of imageability, $F_1(3,27) < 1$; $F_2(2,234) < 1$, and no word length effect, $F_1(3,27) = 1.3$, *ns*; $F_2(2,234) < 1$. These factors did not interact, $F_1(3,27) = 1.8$, *ns*; $F_2(2,234) < 1$.

Discussion

The reading of high-pass-filtered words by normal individuals produces a word length effect as well as an interaction between this variable and lexical frequency comparable to what is observed in many LBL dyslexic patients (but see Arguin, Bub, & Bowers, 1998). In the imageability task, only 5 subjects out of 10 showed a reliable interaction between word length and imageability. This is consistent with the fact that such an interaction is not observed in all LBL dyslexic patients; slower LBL readers tend to exhibit a larger interaction between word length and imageability (Behrmann, Plaut et al., 1998). Interestingly, 4 of our 5 slowest subjects clearly show such significant interactions between word length and imageability.

In this article, we propose that the confusability effect observed in LBL dyslexics is attributable to the use of low spatial frequencies, which do not contain enough information to reliably discriminate visually similar letters. They are thus forced to resort to an LBL strategy that resolves the letter-discrimination problem by extracting high spatial frequencies that allow the discrimination of visually similar letters. The results of Experiments 1 and 2 provided strong support for the second part of this theory by showing that access to high-spatial-frequency information requires serial, LBL processing, even in normal readers. The aim of Experiment 3 was to assess directly the first part of the theory, which is that LBL dyslexics eliminate their difficulty with visually similar letters by using high-spatial-frequency information. This test will be conducted in L.H., an LBL dyslexic.

EXPERIMENT 3

In this final experiment, we assessed the letter confusability effect in a word naming task with L.H., using high-passed, low-passed, and broadband words. Given that we believe that L.H. is incapable of processing the low-energy, residual low spatial frequencies (see footnote 2) in parallel, we predicted no confusability effect with high-pass-filtered words. With low-pass words, we predicted that L.H. would show a large confusability effect because the LBL strategy is inefficient with this type of information. With broadband words, we predicted that the profile should be mixed because both strategies are available.

Results

Figure 3 shows the correct RTs obtained in L.H. A total of 3.3% of all trials were discarded because of voice-key problems; in addition, 3.2% of the remaining correct trials were eliminated because the RTs were more than three standard deviations away from the subject's average for a given condition.

A two-way ANOVA was performed on correct RTs with type of stimulus and confusability as within-subject factors. This analysis revealed an interaction between these factors, $F(2,336) = 8.3$, $p < .001$. Simple effect analyses indicated that increased letter confusability had a large inhibitory effect with broadband words, $F(1,336) = 12.3$, $p < .001$, and low-pass words, $F(1,336) = 26.8$, $p < .001$, but not with high-pass words, $F(1,336) < 1$. Further analyses revealed a significantly larger letter

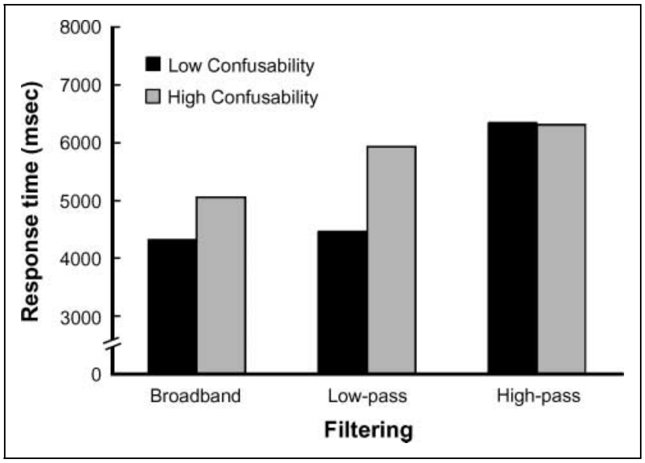

Figure 3. Average correct response times (milliseconds) in L.H. with broadband, low-pass, and high-pass words as a function of letter confusability (Experiment 4).

confusability effect with low-pass than with broadband words, $F(2,220) = 4.5, p < .05$. The number of errors in the data of L.H. was insufficient (0.83% of trials) for a chi-square analysis.

Discussion

The reading performance of L.H. with low-pass, low-confusability words (RT) is similar to his performance with broadband, low-confusability words (RT), suggesting that L.H. is capable of using low spatial frequencies with this type of words. However, his letter confusability effect is exacerbated with low-pass relative to broadband words, which is congruent with the notion that the letter confusability effect originates from the low spatial frequencies content of the stimuli. In additional remarkable support for this view, the letter confusability effect in L.H. is eliminated with high-pass words. This is consistent with the hypothesis put forth in the Introduction, which states that LBL dyslexics must use higher spatial frequencies, only available through LBL reading, to avoid confusing visually similar letters.

GENERAL DISCUSSION

In an attempt to simulate what is experienced by patients after their brain lesion, we asked normal subjects to identify degraded orthographic stimuli. The visual degradation, which consisted in a high pass more than 6 cpl, was selected so that little energy in the spatial frequency band optimal for letter and word identification would be available. High-pass-filtered words should be readable by normal subjects only by focusing their attention on one letter at a time, thus mimicking the LBL strategy.[3]

We succeeded in replicating the main performance features characterizing LBL dyslexia. In Experiment 1, an average word length effect of 807 msec per letter was obtained in 10 subjects. To our knowledge, this is the first time that a word length effect with a magnitude similar to that of LBL dyslexic patients is induced in normal readers. All subjects except one were clearly incapable of processing letters in parallel and were made to use LBL reading. We replicated this main result in all 10 subjects from Experiment 2. Anecdotically, several subjects reported having read words from left to right, one letter at a time, and some even noted resorting to a strategy of low-voice spelling. These observations are in line with how dyslexic patients describe their reading attempts (Jodzio, Albinger, Nyka, & Lass, 2001). The individual differences observed in the word length effect of the subjects are intriguing because similar differences were found in LBL dyslexic patients (Lambon Ralph et al., 2004; Behrmann, Plaut et al., 1998). The variations observed in our experiments might be due to subtle differences of visual acuity in our subjects.

In Experiment 2, we attempted to replicate the imageability and lexical frequency effects often observed in LBL dyslexics as well as the interaction between these variables and word length. In normal subjects reading high-pass-filtered words, the word length effect was significantly stronger for low-frequency words than for high-frequency words and showed a similar trend for low-imageability words relative to high-imageability words. According to the theory proposed by Behrmann, Plaut et al. (1998) based on the interactive activation model of McClelland and Rumelhart (1981), the weak and degraded orthographic input propagates upward through the semantic and orthographic lexicons and then facilitates bottom-up processing by top-down influences. This model explains with parsimony the interaction between the high-level variables (e.g., lexical frequency, imageability) and the word length effect obtained in normal subjects presented with high-pass-filtered words as well as in dyslexic patients. It states that the longer the words, the more time they have to benefit from the activation of high-level knowledge, which facilitates letter identification. One strength of this theory is certainly to recognize the importance of early visual processing in LBL dyslexia. However, its main weakness is that it does not specify the exact visual mechanisms subtending LBL reading, which is precisely what our current proposal does.

The spatial information of letters is believed to interact with the contrast sensitivity function (CSF) of readers to produce typically a bias toward the medium spatial frequencies of letters (e.g., Majaj, Pelli, Kurshan, & Palomares, 2002). For Arial letters of 0.25° of visual angle, the approximate size of printed letters viewed at arm length, the most useful spatial information is centered on 7.43 cycles per degree (or 1.63 cpl) with one- to two-octave-wide tuning. Here we propose that the confusability effect observed in LBL dyslexics is attributable to a more or less extended hole in the CSF of these individuals around 7.43 cycles per degree.[4] This implies a general visual deficit, but one involving spatial frequencies too high to be a real nuisance for other classes of objects (see Behrmann, Plaut et al., 1998, for similar views). Indeed, everyday objects tend to be discriminated at a much lower spatial frequency range: Faces tend to be recognized at spatial frequencies less than 5.63 cycles per degree (e.g., Smith, Cottrell, Gosselin, & Schyns, 2005; Boutet, Collin, & Faubert, 2003; Schyns, Bonnar, & Gosselin, 2002), and natural scenes at spatial frequencies less than 1.8 cycles per degree (e.g., McCotter, Gosselin, Sowden, & Schyns 2005). There are, however, exceptions to this rule. Recognizing complex natural objects, for example, requires medium rather than low spatial frequencies and should, according to our theory, cause problems to LBL dyslexics. Behrmann, Nelson and Sekuler (1998) have gathered evidence data corroborating this prediction.

We believe that the residual capacity of LBL dyslexics for parallel letter processing rests solely upon a range of low, suboptimal spatial frequencies, which do not contain enough information to reliably discriminate visually similar letters. This prevents the identification of target words on the basis of parallel letter processing. LBL dyslexics are thus forced to resort to a compensatory processing strategy that resolves the letter-discrimination problem. This alternative strategy involves serial focused attention at the letter level, which we argue allows the extraction of high spatial frequencies that permit the discrimination of visually similar letters (e.g., Yeshurun & Carrasco, 1998; Carrasco, Luola, & Ho, in press).

The results of Experiment 1 provided support for this proposal by showing that access to high-spatial-frequency information requires serial, LBL processing even in normal readers. The data from Experiment 2 go further in demonstrating the capacity of high-pass filtering of the stimuli in replicating (in normal readers) other key features of LBL dyslexia.

Finally, Experiment 3 provides the crucial demonstration in dyslexic patient L.H. that the high-pass filtering of words effectively abolishes the otherwise conspicuous letter confusability effect characteristic of the disorder. This provides a strong demonstration that high-spatial frequencies do not support the letter confusability effect in LBL dyslexia. It also supports the hypothesis that the compensatory serial letter processing used by patients, which we argued is aimed at extracting high spatial frequencies, is effectively capable of resolving the discrimination deficit that affects parallel letter processing. In this experiment, we also showed that the reading performance of L.H. with low-pass, low-confusability words is similar to his performance with broadband, low-confusability words, suggesting that he is capable of using low spatial frequencies with this type of words and that his letter confusability effect is larger with low-pass than with broadband words, suggesting that low spatial frequencies provide a poor support for the identification of visually similar letters. This implies that L.H. has to employ higher spatial frequencies, only available through LBL reading, to avoid confusing visually similar letters. Interestingly, after having read more than a hundred low-pass-filtered words, L.H. reported being capable of processing groups of adjacent letters simultaneously, a feat he claims to have been incapable of performing beforehand. This opens the door for a neuropsychological rehabilitation program based on the reading of filtered words (see also Adolphs et al., 2005).

How can the theory of LBL dyslexia presented in this article be implemented in the brain? Two broad dichotomies often encountered in cognitive neuroscience implicate differential sensitivities to spatial frequencies and constitute obvious candidates: the magnocellular vs. parvocellular pathway dichotomy and the left- vs. right-hemisphere dichotomy. It has been shown that the magnocellular pathway responds better to low spatial frequencies, whereas the parvocellular pathway responds more to high spatial frequencies (e.g., Merigan & Maunsell, 1993). Some researchers have speculated that *developmental dyslexia*—but never LBL dyslexia, as far as we know—might be due to a malfunctioning of the magnocellular pathway (Stein & Walsh, 1997; Livingstone, Rosen, Drislane, & Galaburda, 1991; Lovegrove, Bowling, Badcock, & Blackwood, 1980). The evidence for this theory, however, has been seriously challenged (e.g., Stuart, McAnally, & Castles, 2001). For example, Sperling, Lu, Manis, and Seidenberg (2005) have recently demonstrated that children with developmental dyslexia perform as well as children without developmental dyslexia both with magnocellular and with parvocellular visual stimuli in low noise, and that the former are worse than the latter both with magnocellular and with parvocellular visual stimuli in high noise. These results suggest that deficits in noise exclusion, not magnocellular processing, are at the origin of developmental dyslexia.

We believe that the right- vs. left-hemisphere dichotomy provides a more likely candidate for the neural mechanism of the theory of LBL dyslexia put forth in this article. The right hemisphere would be more sensitive to low spatial frequencies, whereas the left hemisphere would be more sensitive to medium and high spatial frequencies (Ivry & Robertson, 1998; Sergent, 1983). First, LBL dyslexia results from a left-hemisphere lesion. Second, the right hemisphere of LBL dyslexics is more activated than the left hemisphere during word reading, whereas the opposite is observed in normal individuals (Cohen et al., 2003). Our theory could be articulated as follows: The left-hemisphere lesion of LBL dyslexics would be located precisely where medium spatial frequencies are processed (i.e., around 7.43 cycles per degree), sparing the locus of processing of high spatial frequencies; the low-energy, high spatial frequencies of letters would be extracted via the slow LBL compensatory strategy; and the intact right hemisphere of LBL dyslexics would be responsible for the parallel processing of the low spatial frequencies of letters. This neural interpretation of our theory remains highly speculative and will necessitate more research to be confirmed.

Our proposal also offers a framework for understanding other results obtained with LBL dyslexic patients. Lambon Ralph et al. (2004), for example, attempted a neuropsychological rehabilitation on F.D., an LBL dyslexic patient, by instructing him first to use a "global" reading strategy. After several weeks of training, his reading largely rested on a whole-word strategy. At this time of the therapy, the performance of F.D. remained abnormal, however, being characterized by several semantic, visual, and visual-then-semantic errors, which are diagnostic of deep dyslexia. The ideas developed in the present article can parsimoniously account for this result: By focusing on global information, F.D. favored processing his lower over his higher spatial frequencies. We proposed that low spatial frequencies in words are sufficient to activate some semantic and probably lexical knowledge, but are insufficient to discriminate visually similar letters necessary for explicit letter recognition. Indeed, the use of low spatial frequencies in LBL dyslexic patients could be the visual basis of rapid lexical or semantic decisions (Saffran & Coslett, 1998; Coslett, Saffran, Greenbaum, & Schwartz, 1993; Coslett & Saffran, 1989; Shallice & Saffran, 1986), of semantic and orthographic repetition priming (Bowers, Arguin, & Bub, 1996), and of the presence of a Stroop effect (McKeef & Behrmann, 2004) and the word-superiority effect (Bowers, Bub, & Arguin, 1996; Reuter-Lorenz & Brunn, 1990). Interestingly, during the second phase of the therapy, Lambon Ralph et al. encouraged F.D. to concentrate on individual letters within words, and the reading profile returned to its pretherapy state. This suggests that the strategy influences the visual information used for visual word recognition, at least for some LBL dyslexic patients.

We can also explain the outcome of an experiment carried out by McLeod et al. (2000). The authors asked their subjects to identify words satisfying the semantic criterion, ''things not normally found inside a house,'' in a list of words shown in a rapid serial visual presentation (RSVP) stream. They observed several visual and semantic errors, diagnostic of deep dyslexia. The emergence of symptoms associated with deep dyslexia in normal subjects in this experimental condition suggests that the visual information necessary for semantic activation can be coarser than the visual information necessary for recognizing words with a high degree of certainty. It is known that RSVP tasks exacerbate low spatial frequencies (Bacon, Gosselin, Vinette & Faubert, 2003; Mazer, Vinje, McDermott, Schiller, & Gallant, 2002). When we presented low-pass-filtered words to subjects in our laboratory (Fiset et al., in press), we also observed errors typical of deep dyslexia. Again, we propose that the low spatial frequencies of words not only activate some semantic and probably lexical knowledge, but that they also confuse visually similar letters. More research will be required to test this hypothesis.

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Notes

1. The letter confusability scores were obtained by averaging the letter confusion matrices published in Van Der Heijden, Malhas, and Van Den Roovaart (1984), Loomis (1982), Gilmore, Hersh, Caramazza, and Griffin (1979), and Townsend (1971). They correspond to the total error rates for each individual letter of the alphabet. These values range between .24 (for the letter L) and .71 (for the letter B), with an average of .47 and a standard deviation of .13.
2. High-pass filtering does not entirely remove low spatial frequencies, but it significantly reduces the energy of these low spatial frequencies (Peli, 1992).
3. Because only orthographic stimuli were used in the present study, we cannot, however, address the question of whether LBL dyslexia comes from a deficit specific to orthographic stimuli or from a more general visual impairment.
4. For broadband Arial letters of 0.73° of visual angle, that is, the size of the filtered letters used in the experiments reported in this article, the most useful spatial information is centered on 3.64 cycles per degree (or 2.65 cpl) with one- to two-octave-wide tuning. This is considerably lower than the hypothesized 7.43-cycles-per-degree hole in the CSF of LBL dyslexics and should therefore lead to less impairment in reading. You will remember, however, that to reproduce the word length effect observed in LBL dyslexics, we high-pass filtered the words with a cutoff at 6° per letter or, equivalently, at 8.22 cycles per degree, that is, above the postulated CSF hole.

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