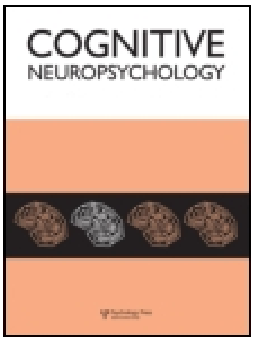

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PURE ALEXIA AND COVERT READING: EVIDENCE FROM STROOP TASKS

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Patients with pure alexia (also referred to as letter-by-letter readers) show a marked word-length effect when naming visually presented words, evidenced by a monotonic increase in response time (or decrease in accuracy) as a function of the number of letters in the string. Interestingly, despite the difficulty in overtly reporting the identity of some words, many patients exhibit fast and above-chance access to lexical and/or semantic information for the same words. To explore the extent of this covert reading, we examined the degree of interference afforded by the inconsistent (word identity and colour label do not match) versus neutral condition in a Stroop task in a pure alexic patient, EL. EL shows evidence of covert reading on a semantic categorisation task and a lexical decision task. She also demonstrates covert reading by exhibiting Stroop interference of the same magnitude as a matched control subject, when naming the colour of the ink in which a word is printed. When the word shares some but not all letters with the colour name (BLOW instead of BLUE), neither subject shows interference. In contrast with the control subject, EL does not show Stroop interference when various orthographic changes (degraded visual input, cursive font) or phonological or semantic changes are made to the word. These findings indicate that although some implicit processing of words may be possible, this processing is rather rudimentary. Not surprising, this implicit activation may be insufficient to support overt word identification. We explain these findings in the context of a single, integrated account of pure alexia.

INTRODUCTION

Pure alexia is a neuropsychological disorder in which premorbidly literate adults exhibit severe reading impairments in the absence of other obvious language deficits (for a recent review, see Behrmann, Plaut, & Nelson, 1998b; Coslett & Saffran, 2001). The disorder is a consequence of brain damage typically located in the left occipital lobe but can also result from damage to callosal fibers in the splenium of the corpus callosum or forceps major (Black & Behrmann, 1994; Damasio & Damasio, 1983). The lesion site is also compatible with recent functional imaging data, which point to these regions as implicated in reading (for recent paper, see L. Cohen, Lehericy, Chochon, Lemer, Rivaud, & Dehaene, 2002; Hasson, Levy, Behrmann, Hendler, & Malach, 2002). Patients with this disorder are also termed letter-by-letter (LBL) readers because they appear to process

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letters sequentially when attempting to read a word. This LBL reading behaviour may manifest in the overt articulation of individual letters but, more often, is evident in measures of the accuracy or reaction time of their word processing (for example, in naming or lexical decision tasks). Whereas normal readers require minimal, if any, extra time to read a word as the length increases (up until approximately nine letters; Frederiksen, 1976; Weekes, 1997), suggesting parallel processing of the letters, LBL readers show a linear increase in their reading time and eye movements (Behrmann et al., 2001) as a function of the number of letters in the string. This monotonic relationship between word length and naming latency is assumed to reflect the sequential processing of the individual letters in the string (Warrington & Shallice, 1980).

Covert processing in LBL readers

Despite the apparent failure to process letters in parallel with normal efficiency and the subsequent adoption of the serial processing of letters, some patients with pure alexia demonstrate covert or unconscious processing of words. Although they may not be able to identify a word overtly, they appear to have available to them both lexical and semantic information about the word even when it is presented at exposure durations too brief to support explicit identification. Additionally perplexing is that, when assessed in these covert processing conditions, the word length effect is often absent (Bub & Arguin, 1995; Coslett & Saffran, 1989).

An early demonstration of this implicit reading phenomenon comes from work by Landis, Redard, and Serrat (1980) in a description of a LBL reader who, when shown a word for 30 ms, could not identify it and sometimes denied even seeing the word. Yet, when instructed to match the presented word to an object displayed amidst an array of several objects, he was accurate a significant proportion of the time. Shallice and Saffran (1986), in a more systematic study of covert word reading, described a patient ML who could not explicitly identify five- and six-letter words at an exposure duration of 2 s. However, ML was able to make a lexical decision to similar five- and six-letter words and nonwords at above-chance levels. This ability was also mediated by the frequency of the words, in that ML was more accurate at classifying high- as opposed to low-frequency words. ML was also able to make semantic classifications (e.g., does the word represent a living or nonliving thing?) of briefly presented words at levels much higher than would be expected by guessing, even though he still could not explicitly identify the target word.

Another surprising finding that is apparent in several LBL readers is the presence of the word superiority effect. The word superiority effect, defined as the increase in accuracy and decrease in response time to detect an individual letter within a word as opposed to a nonword, is thought to arise from the activation of the entire letter string, with greater activation for words than for nonwords. The presence of the word superiority effect in LBL readers is counterintuitive. If LBL reading is accomplished purely in a bottom-up sequential fashion through activating individual letters, there is no obvious reason that lexical status would exert any influence on performance. However, there are now many reports of individuals in whom a word superiority effect has been documented (Bub, Black, & Howell, 1989; Reuter-Lorenz & Brunn, 1990; for the same finding using a different paradigm, see Behrmann & Shallice, 1995).

Although reports of covert processing in LBL are fairly common nowadays, many LBL readers do not show implicit reading, performing at chance levels on lexical and semantic decision tasks (see Arguin et al., 1998, for discussion of this point). It has been suggested that the absence of these covert effects occurs because the individual attempts to read sequentially (even when instructed not to) and that this serial strategy inhibits the output of the covert processing system. According to Coslett and colleagues (Coslett & Saffran, 1994; Coslett, Saffran, Greenbaum, & Schwartz, 1993), there is a fundamental opposition between the strategies involved in covert word processing and those for overt word recognition. The implication is that covert processing is more reliably revealed when the patient is not simultaneously attempting to identify the stimulus explicitly. The use of a paradigm that does not engage explicit reading is therefore advantageous in uncovering covert word processing. One technique that has proven fairly profitable in a number of recent studies is the use of a priming paradigm in which the patient does not respond to the prime (and hence supposedly does not engage in serial processing) but responds to the probe (for example, Arguin et al., 1998). However, given that the probe is also a word and that the patient is engaging in some word processing, one might imagine that the patient is attempting to read the prime too. To better understand the nature of covert processing in LBL reading, the task we adopt in the current paper does not require word reading in the conditions of interest and may be especially useful for revealing implicit reading.

The task we have adopted is a Stroop paradigm and the particular condition of interest is the one in which subjects name the colour of the ink rather than read the word. In the original Stroop task (Stroop, 1935), subjects performed both word and ink naming tasks in blocked fashion. In the *word naming* task, participants read the word presented, while ignoring the ink colour of the words. In the *ink naming* task, participants named the stimulus ink colour, while ignoring the word in which it was presented. Of particular interest is the comparison in naming the ink colour in two conditions: the *control* condition, in which nonword stimuli are used (e.g., several Xs or rectangles) and the *incongruent* condition (for example, the word BLUE, written in red ink). This comparison is especially relevant because, under these conditions, subjects do not name the word but only name the colour ink and therefore do not explicitly engage word recognition processes. Any cost in latency observed in the incongruent over control condition, when subjects are required to name the ink colour, is taken as evidence for the automaticity of word reading (Kahneman & Henik, 1981; but see Besner, 2001). If LBL patients are able to activate any lexical or semantic information covertly, ink colour naming will be significantly slower in the incongruent than in the control condition.

Covert processing and representational precision

Even if one can demonstrate the presence of covert processing using this Stroop paradigm, an open question concerns the extent and precision of the representations activated during implicit reading. Some researchers have argued that the representations activated implicitly are well specified and precise whereas others have suggested that this is not the case. For example, recent studies using the implicit priming paradigm have explored whether words that differ from the target stimulus by a single letter are activated when a word is presented (Bowers, Arguin, & Bub, 1996a; Bowers, Bub, & Arguin, 1996b). If so, this might suggest that a less precise representation is activated. To evaluate the specificity of the representation, these studies use a priming paradigm in which subjects name a briefly presented (100 ms) upper-case word. Prior to the appearance of this target, a prime in lower case, is shown and then backward masked. Even though the exposure duration of the target was brief, substantial reductions in RT (reaction time) were observed when the prime and target were the same compared with when they were different (even if the case was mixed, Arguin et al., 1998). However, if the prime differed from the probe by just a single letter in any position of the word, no priming was evident. Given the absence of priming by a near orthographic neighbour, these studies conclude that the entire string must have been precisely and covertly activated.

A somewhat different result has been obtained in further studies by some of the same investigators. Using the same masked priming task, Arguin et al. (1998) have shown that, in contrast to normal readers, there is no facilitation in the performance of their LBL patient, IH, if the prime is homophonically related to the target. IH also does not show facilitation from increased orthographic neighbourhood size, again suggesting that covert activation is not entirely normal.

Whether or not activation is rich and precisely specified, however, has important theoretical significance. As alluded to previously, at least one account of covert processing in LBL readers, the "right hemisphere account," has argued that the covert reading arises from a different procedure from that used for LBL reading. Whereas the former reflects parallel processing in the right hemisphere, the latter depends on serial and sequential processing generated by the damaged left hemisphere. Additionally, the left hemisphere is responsible for explicit word identification and phonological processing, while the right hemisphere supports covert word processing. Clearly, most LBL readers encode the visual stimuli in the right hemisphere initially due to the right visual field defect, which is present in most, although not all, LBL readers. According to this view, the right hemisphere processing extends beyond perceptually encoding the stimulus and may, in fact, be responsible for all implicit reading. The right hemisphere activation is sufficient to give rise to the covert processing seen in these patients, but cannot mediate the output of the phonological form for overt production, hence the failure to explicitly report the word. On this view, then, the representation activated implicitly is detailed and rich but the information is not transmitted to the left hemisphere for output (Coslett & Monsul, 1994; Coslett & Saffran, 1994; Saffran & Coslett, 1998). Note that, on this account, the sequential processing may interfere with the covert activation and inhibit the ability to derive lexical and semantic representations in the right hemisphere.

An alternative view argues against two separate processes, one for implicit and one for explicit reading, and claims that the covert reading arises from the residual function of the normal reading system. Because of the brain damage, a rather coarse and imprecise representation might be activated implicitly by the conjoint functioning of the right hemisphere and the residual left hemisphere, and this activation may suffice for some tasks but not for others. The failure to report the word explicitly might then arise because naming requires a more precise and refined representation of the input and this is not sufficiently specified. According to this account, even when the patient is not engaged in serial word processing, word processing is mediated by a single unified system that reflects the residual capabilities of the left hemisphere working in tandem with the intact right hemisphere (Behrmann et al., 1998b). Because of the brain damage, full elaboration of the representation of the word is not possible and any covert effects arise from the partial activation of the input that is derived under the brief exposure conditions.

In addition to using the Stroop paradigm to explore covert processing, the further goal of this paper is to explore the precision of the activated representation. To do so, we compared EL's performance with that of a matched control subject in the control and incongruent conditions of the Stroop ink naming task in a series of experiments in which we manipulate the phonological, lexical, orthographic, and semantic status of the word in an attempt to document the range and extent of implicit reading.

GENERAL METHODS

Participants

Patient EL, previously diagnosed as a LBL reader, participated in this study. A detailed case report of EL (as well as scans of her lesion site) is available in previous publications (Behrmann, Nelson, & Sekuler, 1998a; Montant & Behrmann, 2001). EL is a 50-year-old, native English speaking, right-handed female with 18 years of schooling. She was admitted to the hospital in April 1996 for right arm weakness, blurred vision, and slurred speech caused by two embolic events. A CT scan performed at the time of admission revealed a large infarction in the territory of the left posterior cerebral artery involving the left peristriate inferotemporal visual association cortex, the posterolateral temporal cortex, and the dorsal parietal cortex in the vicinity of the occipitoparietal cortex. EL does not exhibit any obvious visual agnosia although, in certain experimental conditions, her ability to name pictures is affected by their structural complexity (Behrmann et al., 1998a). EL does not display any writing or spelling difficulties but, as expected, she fails to read easily what she herself has written on a previous occasion. Premorbidly, EL was an avid reader. Ironically and sadly, she was trained as a remedial specialist and worked with children who had developmental reading problems.

EL is able to identify single letters extremely well, even under brief presentation. At the time of this testing, we re-measured EL's word length effect by having her read aloud words of three, five, and seven letters, presented to the left of a fixation cross on a computer screen for an unlimited exposure duration. EL made no errors in reading but required an additional 403.7 ms per letter in the word (calculated by setting string length against RT in a regression analysis). Her mean RT was 1490.81 ms, 2345.07 ms and 3103.70 ms for three-, five-, and seven-letter words, respectively. This linear increase has roughly remained the same for several years now (Behrmann, 1998a; Montant & Behrmann, 2001) and puts her in the class of mild to moderate LBL readers (Behrmann et al., 1998; Shallice, 1988).

To compare EL's performance with that of a non-brain-damaged individual, we tested QK, who was also right-handed and was matched to EL on age, gender, and education.

Apparatus and materials

All experiments were conducted on a Macintosh G3 PowerBook. Stimuli were presented on a 14.1 in (35.8 cm) colour monitor using PsyScope experimental software version 1.2.1 (J. D. Cohen, MacWhinney, Flatt, & Provost, 1993). All voice responses were obtained using a desktop computer microphone (RadioShack, Fort Worth, TX) and voice onset time and key responses were obtained using a Button Box (New Micros, Dallas, TX). Participants were seated approximately 50 cm from the monitor. The experimenter noted the verbal responses made by the participants.

EXPERIMENT 1

Before adopting the Stroop procedure, we first document EL's ability to show covert word processing using the more standard techniques of lexical decision and binary semantic classification.

Methods

Lexical decision. EL completed three blocks of a lexical decision task, using the same set of words used in the naming latency task described above. Each block consisted of randomly presented three-, five-, and seven-letter words and nonwords, derived from the words with one or two vowel changes, for a total of 150 trials in the experiment. A trial was initiated with a centrally located fixation cross, which remained on the screen for 1000 ms. A word or non-word, displayed in Arial 24pt font, then replaced the fixation cross in the same location on the screen, and was presented for 300 ms, an exposure duration far too brief for EL to identify the word (her naming latencies indicate that she requires roughly 400 ms per letter). The stimulus was then replaced by a mask of seven instances of the letter "X" that appeared in the same position as the previous stimuli. This mask remained until response. EL was instructed to determine whether the letter string was a real word or a nonword and to respond with an appropriate button press. Accuracy and RT were recorded.

Semantic classification. This procedure has been used repeatedly to establish whether LBL readers can assign words to a semantic category despite the failure to read them explicitly (Behrmann & Shallice, 1995; Patterson & Kay, 1982; Shallice & Saffran, 1986). This task consisted of 100 words, half of which are food items and half body parts, divided equally into items of four, five or six letters in length. Trials followed the same procedure and timing as the lexical decision task above. EL was instructed to determine whether the word referred to a food item or body part and to respond with an appropriate button press. This task was repeated twice, 2 weeks apart.

Results

Lexical decision. EL performed significantly above chance with 114 out of 150 trials correct (76%), $\chi^2(1, N) = 150) = 20.7$, $p < .0001$. Even under this brief duration, she showed an effect of word length, with higher accuracy for three- compared to five- letter words, $\chi^2(1, N) = 100) = 8.41, p < .003$. She also showed an effect of lexicality, with greater accuracy for nonwords than words, $\chi^2(1, N) = 150) = 6.2, p < .012$; however, this may reflect a bias to respond "no" when she is uncertain ($d' = 1.58$).

Semantic decision. EL attempted to read aloud 36/200 words. She was incorrect on 26 of these, but all of these were excluded from the analysis of interest. Of the remaining 164 words, she correctly classified 101 (62%), a result suggesting that she performed significantly above chance, $\chi^2(1, N = 164) = 8.8, p < .003$, and has access to the semantic information of words that she cannot overtly identify. These findings suggest that EL has some covert processing ability on these more standard implicit tasks. The question is whether we will observe interference in the Stroop colour naming task.

EXPERIMENT 2

The goal of this next experiment is to examine whether EL shows Stroop interference and, if so, whether the interference is comparable in magnitude to that obtained in a normal reader. If this were the case, it would suggest that the extent of the implicit (automatic, in this case) representation is not different from that activated by normal readers.

Methods

Words were printed in capital letters in Chicago 48 pt font. The list of words used in this experiment included the colour words blue, green, purple, red, and yellow. The ink colours chosen were the same as each of the colour words. In this first experiment, we collected data from the word and ink naming task.

In the word naming task, participants were required to read aloud the printed word presented centrally on the screen as quickly and as accurately as possible. In the congruent condition, the ink colour matched the words presented (e.g., the word BLUE printed in blue ink). All words in the control condition were printed in black ink. In the incongruent condition, the words displayed did not match the ink colour but were in one of the other possible ink colours used (e.g., the word BLUE, printed in yellow ink).

In the ink naming task, participants were required to name the ink colour of the words that were presented on the screen. The stimuli used in both the ink naming congruent and incongruent conditions were the same set of stimuli as in the congruent and incongruent word naming task. The control condition for ink naming consisted of a string of the letter "X" (with the Xs printed in the appropriate colour), which varied in length to match the number of letters in each of the colour words used.

The design in this study was entirely within-subject, with the independent variables being task (word naming and ink naming) and congruency condition (congruent, control, and incongruent). This resulted in a total of six different conditions, which were blocked. Each block was prefaced with the task instructions and was followed by 20 randomised trials followed by a short break. Prior to the experiment, participants were given two blocks of 20 practice trials, one each of word and ink naming. The subjects were told to respond as quickly as possible without sacrificing accuracy. RT was measured from the time the words were presented on the screen until a response was made. The experimenter recorded word and ink naming errors. Participants completed the experiment and then, after at least 2 weeks, repeated the entire experiment (with the block order reversed) resulting in a total of 240 trials, 40 in each condition.

Results and discussion

Error trials, trials on which the microphone did not trigger at the correct time, and trials yielding RT values greater than 4 *SD*s from each subject mean were all excluded from the analysis, resulting in a removal of 5% of the data for QK and 8.3% for EL. No subject made more than two naming errors in any of the conditions, so accuracy performance is not analysed. The data for each subject were entered into a 2 × 3 (Task × Condition) analysis of variance, comparing the tasks of word naming and ink naming. All pairwise comparisons were done using Tukey post hoc comparisons with an alpha level of .05. The results are shown in Figure 1.

The mean RT for the task of word naming for the control subject, QK, (460.1 ms) was faster than the mean RT for ink naming (626.6 ms), $F(1, 222) = 210.8, p < .0001$. A main effect of congruency was also observed, $F(2, 222) = 69.8$, $p < .0001$. Importantly, the task by condition interaction for QK was also significant, $F(2, 222) = 49.8$, $p < .0001$. QK did not show any differences between conditions in the word naming task ($p > .05$). She did, however, show the Stroop effect, with ink naming-control (542.8 ms) being faster than ink naming-incongruent (804 ms), an increase of 261.2 ms ($p < .05$). In the ink naming task, QK did not show facilitation in the congruent condition ($p > .05$) compared to the control condition. Overall, EL responded faster for word naming (599.2 ms) than ink naming (724.9 ms), $F(1, 214) = 43.4$, $p < .0001$. EL's word naming in this task is faster compared to her response times for word naming latency in other reading tasks; however, this is expected given the small set of words used in this Stroop task. EL also showed a main effect of congruency, $F(2, 214) = 17.6, p < .0001$, and the task by condition interaction was significant as well, $F(2, 214) = 7.1, p < .0001$. Like QK, EL did not show any differences among the three word naming conditions ($p > .05$) but showed significant interference in ink naming, with the RT for the ink naming-incongruent condition (867.2 ms) 194.5 ms slower than for ink naming-control (672.8 ms) ($p < .05$). EL also did not show facilitation in the ink naming-congruent condition ($p > .05$) (see Figure 1). While EL is slower than QK in both tasks, $F(1, 440) = 93.8, p < .0001$, there is no task by subject interaction nor a three-way interaction with condition ($p > .05$).

In sum, both subjects showed a similar pattern of data, with no effect in the word naming condition as a function of congruency, but a large Stroop effect as shown by an increase in RTs in the ink naming-incongruent condition compared to the control condition. These results are similar to those typically found in Stroop experiments (see Macleod, 1988). The findings indicate that the

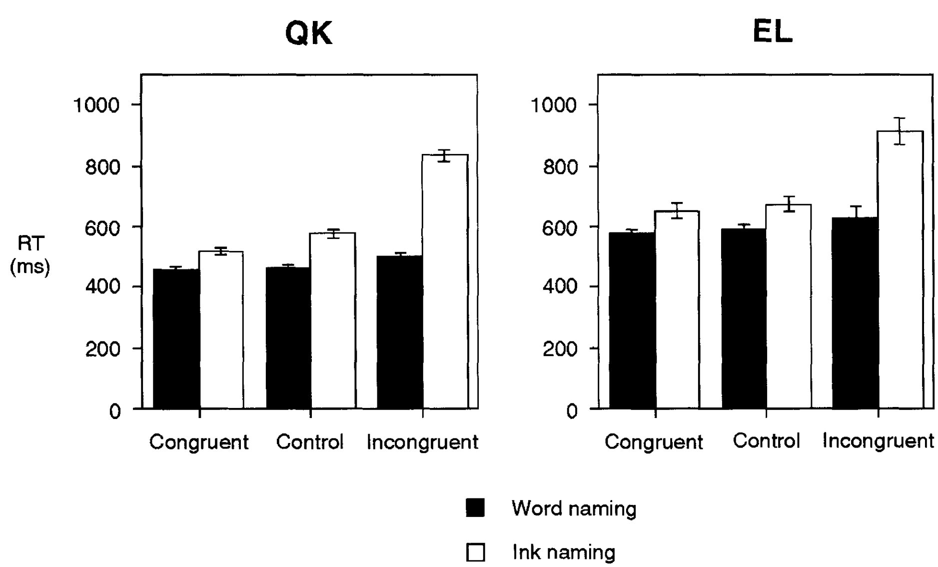

Figure 1. *Response time in a colour Stroop task as a function of task (word naming and ink naming) and condition in EL and control subject QK.*

Stroop paradigm is indeed effective in revealing the covert processing in a LBL reader and that EL appears to activate representations of words implicitly to the same extent as the control subject.

EXPERIMENT 3

Having demonstrated that EL is subject to interference from the incongruent word in the ink naming task, suggesting covert processing of letter strings, we now explore the nature and extent of this interference. This next experiment was designed to replicate the results in Experiment 2. Additionally, this condition was intended to eliminate the possibility that the Stroop interference seen in EL was merely a result of interference caused by reading the first letter(s) and not the entire word. To do this, we included an ink naming onset control condition in which words were chosen to share the first letter(s) with colour words (e.g., BLOW for BLUE and PURITY for PURPLE) (for similar control conditions, see Berti, Frassinetii, & Umiltà, 1994; Patterson & Kay, 1982).

Methods

The onset control words used in this study were chosen to match both the word length and also the first or first few letters of the colour words. The onset control words chosen were BLOW for blue, GROUP for green, PURITY for purple, RAW for red, and YEARLY for yellow. Because both participants failed to show any effect in the word naming task as a function of congruency, and also because we are interested in the extent of Stroop interference in ink naming, we did not collect data for word naming in any of the subsequent experiments. This version of the task has the additional benefit of removing further any interference from serial processing of words as no word naming is involved in any of the conditions.

Stimuli were printed in capital letters in Arial 48 pt font. The experiment was prefaced by instructions and a presentation of the colours used in the task to ensure that the participants knew the names of the colours. The design in this study was entirely within-subjects, with the independent variables being ink naming condition (standard words and onset control words) and congruency condition (congruent, control, and incongruent). Subjects completed three blocks of each of the ink naming conditions with a long break between each block. Each of the three conditions was balanced so that an equal number appeared in each block. There were 36 trials in each condition, which resulted in a total of 216 trials for each participant, with an equal distribution of both stimulus type and congruency condition.

Each trial began with a centrally positioned fixation cross that appeared for 500 ms. The coloured word stimuli then immediately replaced the cross and remained on the screen until the participant responded. Participants were told to name the colour of the stimuli verbally as quickly as possible without sacrificing accuracy. RT was measured from the time the colour word stimuli was presented on the screen until a voice response was made. The experimenter recorded ink naming errors and microphone errors.

Results and discussion

Trials on which the microphone did not trigger at the correct time and trials with RT values greater than 4 *SD*s from each subject mean were excluded from the analysis, resulting in a removal of 3.2% of the data for QK and 3.7% for EL. Naming errors occurred infrequently, so accuracy performance is not analysed. The RT data were entered into a 2 × 3 (Word Type × Congruency Condition) analysis of variance. All pairwise comparisons were done using Tukey post hoc comparisons at an alpha level of .05.

For the control subject, QK, an analysis of variance revealed a significant effect of word type (standard, onset control), $F(1, 203) = 21.2$, $p < .0001$, a significant effect of congruency condition, $F(2, 203) = 48.6$, $p < .0001$, and a significant interaction between the two factors, $F(2, 203) = 20.4$, $p < .0001$. She did not show any significant differences when comparing the control and congruent conditions for either standard words or onset control words ($p > .05$). Again, however, she showed evidence of Stroop interference, with ink naming-incongruent (792.5 ms) significantly slower than ink naming-control (588.9 ms), an increase of 203.7 ms ($p < .05$). QK did show interference to some extent based on the first letters of the word, as shown by a longer mean RT in ink naming onset-incongruent (633.8ms) compared to the ink naming onset-control condition (575.5 ms), a difference of 58.2 ms ($p < .05$), but this was less than her interference seen in the standard Stroop task (203.7 ms). This slight interference based on this first letter has been previously demonstrated in the literature (see Macleod, 1981).

An analysis of variance of EL's data revealed a significant effect of word type, $F(1, 202) = 31.1, p < .0001$, a significant effect of congruency condition, $F(2, 202) = 9.7$, $p < .0001$, and no interaction. There were no significant differences between the control and congruent conditions ($p > .05$). EL demonstrated Stroop interference, with ink naming-incongruent (961.6 ms) significantly slower than ink naming-control (747.1 ms), an increase of 214.5 ms ($p < .05$) (see Table 1). EL did show an increase of 81.7 ms in RT from ink naming onset-control to ink naming onset-incongruent; however, this difference did not reach significance ($p > .05$) and is much less than her interference seen in the standard ink naming condition (214.5 ms). Given that EL did not show a significant interference effect with the onset control words and that any interference obtained is considerably less than the extent observed in the standard Stroop task, we can conclude that the covert activation obtained in ink naming for EL is not merely a result of processing the first letter(s) of the word.

EXPERIMENT 4

In this experiment, we manipulated visual/perceptual aspects of the presented words by degrading the stimuli in one condition and by displaying them in cursive font in another condition. The rationale for these manipulations stems from work by Farah and Wallace (1991), who demonstrated that a LBL patient was especially sensitive to stimulus degradation, as evidenced by the disproportionate increase in naming latency across word length when the words were masked. Farah and Wallace (1991) argued that serial letter-by-letter reading results from a deficit in perceptual analysis of visual material and that visual changes to the stimuli exacerbate the serial processing procedure. It is also the case that the performance of LBL readers is slowed, relative to normal subjects, as more visually complex fonts are used (Behrmann

Table 1. *Response times (ms) for control and incongruent (Incog) Stroop conditions, and difference (Diff: incongruent–control) for Experiments 3–6 for EL and control subject QK*

	QK			*EL*		
	Control	*Incong*	*Diff*	*Control*	*Incong*	*Diff*
Experiment 3						
Normal	588.85	792.50	203.65	747.12	961.63	214.51
Onset control	575.53	633.75	58.22	628.48	710.16	81.68
Experiment 4						
Degrade	577.13	678.58	101.44	731.25	765.94	34.68
Cursive	545.22	622.20	116.97	693.86	726.40	32.54
Experiment 5						
Pseudohomophone	626.60	761.37	134.77	661.97	740.02	78.05
Experiment 6						
Uncommon	604.83	687.94	83.11	703.20	757.77	54.57

& Shallice, 1995), that visual similarity among letters influences reading performance (Arguin & Bub, 1993), and that the patients make predominantly visual errors in their word reading. We are interested in whether this vulnerability to visual/perceptual degradation was also evident in EL's covert word processing.

Methods

In the degrade condition, all stimuli were degraded using the PsyScope degrade function at a level of 0.7. This gives the appearance of random noise overlaid on the stimuli, making identification more difficult. In the second condition, we presented all words in cursive Swing 48 pt font. The two visual/perceptual manipulation conditions were presented in separate sessions, each containing 108 randomly presented trials with an equal number from each of the three congruency conditions. All other aspects of this experiment were the same as in the previous experiment.

Results and discussion

We removed 1.4% of the data for QK and 3.7% for EL from the analysis because of naming errors, failure of the microphone to trigger properly, or because RT values were greater than 4 *SD*s from the mean. Neither subject made more than two naming errors in any of the conditions, so accuracy performance is not analysed. The RT data were entered into two separate one-way analyses of variance. All pairwise comparisons were done using Tukey post hoc comparisons at an alpha level of .05.

The control subject, QK, showed a significant effect of congruency in both the degrade, $F(2, 103) = 16.2$, $p < .0001$ and cursive conditions $F(2, 104) = 22.6$, $p < .0001$. In neither condition was there a significant difference between the control and congruent condition ($p > .05$; however, QK demonstrated a significant increase ($p < .05$) in RT in the incongruent compared to control condition for both the degrade and cursive conditions, an increase of 101.4 ms and 116.9 ms, respectively (see Table 1).

EL showed no effect of congruency in the degrade condition ($p > .05$); however, she did exhibit an effect of congruency in the cursive condition, $F(1, 100) = 3.891$, $p < .024$. Like QK, EL showed no difference in either the degrade or cursive condition when comparing control and congruent conditions. In contrast to QK's performance, EL did not show significant Stroop interference in either the degrade or cursive condition: There is an increase in RT from the control to incongruent condition of 34.68 ms in the degrade condition and 32.54 ms in the cursive condition, but this is not statistically significant ($p > .05$).

When orthographic manipulations are applied to the stimulus, EL no longer demonstrated covert reading, as evidenced by the lack of Stroop interference. In contrast, the control subject QK still showed robust Stroop interference, although this was not as great as in the standard Stroop task. One possible explanation is that the alteration of the visual input renders the stimuli too taxing on the processes used for word recognition. Consequently, in the time required to generate a response for ink naming, the written word is not sufficiently processed to exert an inhibitory effect on the response when the colour and the word identity are incongruent. Because the normal subject is not as dramatically affected by these orthographic manipulations, she processes the written word fast enough for it to have an adverse effect on ink naming performance. EL, on the other hand, does not have enough processing time on the word for its output to have any influence on her speed of ink colour naming. This experiment points out a limitation in the extent of covert activation in EL.

EXPERIMENT 5

To determine whether EL has implicit access to the phonological representation of words, in this experiment we manipulated phonological aspects of the presented words by using pseudohomophones of colour words. Prior studies (Montant & Behrmann, 2001) have demonstrated that EL does benefit from being primed with pseudohomophones, as measured by her decrease in naming latency for associated words; for example, having seen a pseudohomophone prime, her RT is 200 ms faster compared to being primed with an unrelated nonword. Thus, in an explicit word reading task, she is able to derive strong enough phonological representations and to be primed by related representations.

The pseudohomophone Stroop task has three conditions: a congruent condition which paired congruent ink colour and pseudohomophone (e.g., BLOO in blue ink), an incongruent condition (e.g., BLOO in red ink), and a control condition that was the same as in the previous experiments. The word stimuli consisted of WRED for RED, BLOO for BLUE, GREAN for GREEN, and YELOE for YELLOW. All other aspects of the design and procedures for this experiment were the same as in the previous experiments.

Results and discussion

We removed from the analysis all error trials, microphone trigger failure responses, and all trials in which all RT values exceeded 4 *SD*s from each subject mean. This resulted in a removal of 2.7% of the data for QK and 1.8% for EL. The RT data were entered into a one-way analysis of variance, comparing congruency conditions. All pairwise comparisons were done using Tukey post hoc comparisons at an alpha level of .05.

The control subject QK showed a main effect of condition, $F(2, 101) = 26.5$, $p < .0001$, with no difference between control and congruent conditions ($p > .05$). QK did demonstrate Stroop interference, with an increase in RT of 134.8 ms in the incongruent condition compared to the control condition ($p < .05$) (see Table 1).

EL showed a main effect of condition, $F(2, 103) = 5.5$, $p < .005$, with no difference between control and congruent conditions ($p > .05$). While EL's response times in the incongruent condition are 78.1 ms slower than in the control condition, this difference failed to reach significance ($p > .05$) and is considerably less than the amount of Stroop interference seen in QK. This amount of interference is also much reduced relative to the extent of EL's interference in the standard Stroop (Experiment 2 and 3) task. EL's apparent failure to show covert activation with a homophonically related prime also points to a boundary condition in her ability to process words implicitly.

We note that, on the right hemisphere account, the right hemisphere is capable of generating lexical and semantic representations and, to a lesser extent (if at all), phonological representations. In light of this, the reduced phonological Stroop effect in EL might not necessarily be a good indicator of right-hemisphere covert processing (even though the task does not require word reading per se) and so, in the next task, we return to an exploration of lexical and semantic interference effects.

EXPERIMENT 6

In this final experiment, we determine whether EL has implicit access to lexical-semantic representations of words. To do so, we examined her Stroop interference from words less common than those used in the previous Stroop experiments. LBL readers, like normal subjects, are slower to name words that are lower in frequency as compared to higher in frequency, although frequency appears to interact with word length such that as length increases, frequency effects are exaggerated (Behrmann et al., 1998). In this frequency Stroop task, common colour words were replaced with words of the same length but of lower frequency. The words used were TAN, PURPLE, BLACK, and GRAY. The mean occurrence of common colour words, as measured by Kuçera and Francis (1967), was 127.8 compared to 76.3 in the uncommon colour word condition. All other aspects of the design and procedures for this experiment were the same as in the previous experiments.

Results and discussion

Two trials were removed from EL's analysis, one for a naming error, and the other because of microphone trigger problems, resulting in a removal of 1.8% of the data. Neither subject had responses that exceeded 4 *SD*s from each subject mean. QK did not have any data removed because there were no naming errors or microphone trigger problems. The data for each subject were entered into a one-way analysis of variance, comparing conditions. All pairwise comparisons were done using Tukey post hoc comparisons at an alpha level of .05.

QK showed a main effect of congruency, $F(2, 105) = 17.17$, $p < .0001$, with no difference between the control and congruent conditions ($p > .05$). QK demonstrated Stroop interference, with an increase of 83.11 ms from the control condition to the incongruent condition ($p < .05$) (see Table 1). However, this interference is less than that she exhibited to the more common words (Experiment 2, 261.2 ms; Experiment 3, 203.7 ms). This reduction in Stroop interference is compatible with the results reported in the literature (Macleod, 1991).

EL also showed a main effect of congruency, $F(2, 103) = 3.077$, $p < .05$. There was no significant difference between the control and congruent condition ($p > .05$). EL failed to show Stroop interference, with a 54.6ms increase from the control to the incongruent condition ($p > .05$). This is much less compared to the Stroop interference seen in common colour words (Experiment 2, 194.5 ms; Experiment 3, 214.5 ms). This difference is also less than the interference effect seen in QK, which was statistically significant.

GENERAL DISCUSSION

Patients with pure alexia, also known as LBL readers, read in a laborious and sequential manner, as is evident in their increase in naming latency as a function of the number of letters in a word string. However, counterintuitive and perplexing evidence has amassed showing that some of these patients do in fact exhibit some level of covert reading in which words are processed rapidly and perhaps even in parallel. Indeed, under some circumstances, the patients appear to have considerable information about a word (for example, its semantic category) despite being unable to identify it explicitly. But not all patients show this covert processing and, even when they do, the extent and nature of the implicit representation is not particularly well understood. While some researchers have suggested that this covert processing gives rise to rich and detailed representations, others have argued that this is not so and that the representation is, at best, partial and imprecise. On this latter account, the failure of the patients to explicitly identify the word is a direct consequence of the partial and impoverished representation, which arises from the residual function of the normal reading system.

We have adopted a Stroop interference paradigm with a LBL patient, EL, with two major goals. The first is to explore whether, using a procedure in which subjects are required to name the colour of the ink of a letter string without reading the word, we can elicit evidence of covert processing in an individual who does show some covert processing in the more standard implicit tasks (such as lexical decision and binary semantic classification) although this is not as strong as that observed in some other LBL readers (see Coslett & Saffran, 1989). The critical finding is that this procedure, which does not engage word recognition (and serial processing), produces Stroop interference in EL of the same magnitude as in the matched control subject. Moreover, as with the control subject, when only the first letter(s) of the word matches the colour name, very little interference is obtained, indicating that more than the first letter must be activated implicitly in order to give rise to the Stroop interference effect. The implication of this is that EL must be processing more than the first letter of the word covertly.

The second goal is to explore the nature and extent of the representations that are activated covertly. To this end, we explore whether the Stroop interference is of the same magnitude as in the normal reader when we manipulate various aspects of the word stimulus in relation to the colour of the ink. Understanding this will allow us to determine the extent of the orthographic, phonological, and semantic activation that is possible at an implicit level in a LBL reader. We found that, first, the extent of the Stroop interference is reduced in the matched control subject under these various conditions but that in all cases, she still showed a significant difference between ink naming speed in the control versus the incongruent condition. Second, and perhaps more relevant, EL did not show Stroop interference when the written words are less frequent than the common colour words, when the written words are degraded or presented in cursive font, or when the written words are homophonically related to the colour word.

That we observe Stroop interference in only some conditions for EL, in contrast with the control subject, suggests that while some aspects of the written word are activated, not all aspects are adequately represented to support covert processing. Many interpretations of the interference effect in Stroop tasks rely on the finding that word reading proceeds at a faster pace than ink naming (due to the increased experience with word reading) and, hence, the processed written word can adversely impact the ink naming when the outputs are incongruent (see, for example, J. D. Cohen, Servan-Schreiber, & McClelland, 1991). The presence or absence of the Stroop effects in EL, then suggests that in the amount of time the word is present before the ink colour is read, only a limited amount of word processing can be completed. It is only the standard Stroop task, in which word processing conditions are ideal and the most information can be extracted from the word, which may offer sufficient time for word processing for EL. We also note that in the standard Stroop task, only a small number of highly common words are used and this, too, can facilitate the speed of word processing in EL. But of great relevance is that manipulating aspects of the word, including frequency, visual input, or the relationship between orthography and phonology, no longer provides sufficient time for word processing and the automatic inhibition of ink naming in the incongruent case. In sum, when all components of the word are favourable (high frequency, small set of items, accessible font, consistent phonology and semantics), enough factors can combine to activate a covert representation that can influence ink naming. When one explores further, however, the representation that is activated covertly is found to be weaker or less precise than that activated by a normal control and so this underlying representation may not be sufficiently robust to support word naming, which requires precision.

Before discussing the theoretical implications of these findings, we need to point out that we are not the first to run a Stroop experiment with a LBL reader: Patterson and Kay (1982) ran a Stroop experiment using ink naming with one of their LBL readers, MW, but obtained no evidence of Stroop interference. Surprisingly, and in contrast with our results, they observed a congruency effect (better performance on congruent than control condition); however, as we suggest below, they too argued that this covert facilitation might arise from partial processing of the word. The absence of an interference effect in their patient, however, is somewhat surprising given that we have claimed that it is a particularly useful paradigm, which does not evoke sequential processing of letters. That MW did not show this effect may suggest that this might not be as watertight and robust a procedure as we have proposed. Alternatively, it may still be possible that even if the procedure is robust, covert word reading might not be evident in all individuals. In particular, because MW was so severely impaired (she took 12.8 seconds to read a three- to four-letter word), covert effects may not be possible in very profoundly impaired LBL readers. These suggestions are speculative, however, and remain to be explored further.

As mentioned previously, one prominent theory about pure alexia argues for two different modes of word processing: a right-hemisphere based parallel mode that is the source of covert processing, and a left-hemisphere based sequential mode that is the source of the laboured serial reading pattern. Given that covert processing is mediated by the right hemisphere and that the letters are processed in parallel, one might expect that the extent of this covert activation would be normal (the hemisphere is intact) if it is not subject to any interference by the sequential word process that usually opposes it. The alternative perspective does not differentiate between two modes of processing and presupposes that all forms of reading emerge from the residual function of the normal reading system, which has been damaged. Any covert processing, then, will reflect whatever activation the system is capable of generating given the exposure duration of the stimulus and it will probably be partial and imprecise.

Given the abnormal covert activation observed in EL, the findings seem more compatible with the latter perspective of a single, integrated, reading system. This perspective has been fleshed out in some detail recently by Behrmann and colleagues (Behrmann et al., 1998b; Montant & Behrmann, 2001). This view holds that a general visual perceptual deficit, which degrades the quality of the input, sustained by virtue of the left posterior hemisphere damage, is fundamental to LBL reading. As a result of this perceptual deficit, only weak parallel activation is possible and, to increase this activation, patients need to make multiple fixations to allow the higher spatial resolution of the fovea to be applied to the input. Indeed, a recent study has documented that LBL readers make more frequent fixations on longer than shorter words than do normal readers (Behrmann, Shomstein, Black, & Barton, 2001). Any covert effects emerge from whatever weak parallel activation is possible under the limited exposure duration used for stimulus presentation.

The notion that there may be some parallel activation, which is weak and insufficient to mediate reading, also derives support from several very recent studies on the topic. Lambon Ralph, Hesketh, and Sage (2004 this issue) present data from pure alexic patient FD, who demonstrated decreased performance in a brief presentation lexical decision and semantic categorisation task as a function of decreasing word frequency, imageability, and familiarity. These data led the authors to conclude that FD's fast access to lexical and semantic aspects of words is evidence for a weak parallel activation of words: however, this is insufficient to drive normal word processing, which is the reason for the severe LBL reading.

Arguin, Fiset, and Bub (2002) demonstrated that their LBL reader IH, like controls, was faster at naming words that had many as compared to few orthographic neighbors (i.e., words of the same length that differ by one letter) and that this was independent of word length. The authors conclude that a decreased naming latency for words with many orthographic neighbours is evidence for an intact parallel letter processor. However, unlike controls, IH was slower at naming words that contained many versus a few confusable letters (i.e., a similarity of letters within a word with other letters of the alphabet). The claim is that parallel letter processing may still be possible but that it gives rise to considerable background noise and that this noise prevents the system from resolving differences between visually similar letters. It is this noise that makes the sequential processing of letters mandatory. The relevant aspect of this is that the parallel activation that arises is simply too weak and it is possible that it may only support rudimentary covert processing.

Consistent with this is the claim by Osswald, Humphreys, and Olson (2002) that attempts to read at the supra-letter level (in parallel even if to a limited extent) has detrimental consequences for word recognition in LBL readers. Their patient, DM, who appears to be very similar in severity to EL as defined by the slope of the naming latency function (roughly 400 ms in both cases), performed better when letters were presented sequentially than simultaneously. The interpretation of this is that simultaneous letters give rise to increased lateral masking and disrupt the extraction of individual letters. Interestingly, DM also performed better when a few letters, corresponding to a functional spelling unit, are presented at a time than under simultaneous conditions, suggesting that some supra-letter processing is possible but that it breaks down when larger units are presented. Again, the relevant finding here is that parallel activation of visual input may not only be too weak but can also be detrimental.

The data from FD, IH, and DM, like EL, suggest that parallel activation of many letters is not sufficiently strong to mediate covert processing. Rather, the output of these individuals suggest that there may be some limited parallel activation, which is insufficient and which compels a sequential procedure. Rather than thinking about two independent reading routes, then, the findings from EL might more profitably be explained as reflecting the residual capabilities of an integrated reading system struggling to produce a coherent response. When all factors point in the same direction, there is sufficient activation to support covert reading. When one digs a little deeper, however, it becomes more apparent that the covert representations are not sufficiently detailed or rich. Instead of conceptualising LBL reading as arising from two distinct sources, a sequential left hemisphere processor and an intact parallel right hemisphere processor, the pattern of findings might well be accounted for by a single reading system that, following damage, is only partially functional.

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