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Cognitive Mechanisms Underlying a Case of Letter-by-Letter Surface Alexia

by

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Submitted in partial fulfillment of the requirements
for the degree of Doctor of Philosophy

at

Dalhousie University
Halifax, Nova Scotia
August, 2000

0-612-57347-8

DALHOUSIE UNIVERSITY

FACULTY OF GRADUATE STUDIES

The undersigned hereby certify that they have read and recommend to the Faculty of Graduate Studies for acceptance a thesis entitled "Cognitive Mechanisms Underlying a Case of Letter-by-Letter Surface Alexia"

by Janet Louise Ingles

in partial fulfillment of the requirements for the degree of Doctor of Philosophy.

Dated: August 4, 2000

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Title: Cognitive Mechanisms Underlying a Case of Letter-by-Letter Surface Alexia

Department: Psychology

Degree: Doctor of Philosophy

Convocation: Fall

Year: 2000

[redacted]

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Abstract

In the acquired reading disorder known as letter-by-letter reading, words can only be pronounced after each letter is identified individually. The objective of this research was to investigate the cognitive mechanisms that underlie this disorder. These mechanisms were studied in a brain-damaged patient (GM) who demonstrated letter-by-letter reading, as well as an additional impairment in reading irregular words. Comparisons were made to a control group of six brain-damaged patients without reading deficits. The first set of investigations (Experiments 1-5) examined the effects of different psycholinguistic variables in pronunciation and lexical decision tasks to confirm the diagnosis of GM's dyslexia. The second set of investigations (Experiments 6-9) evaluated several prominent hypotheses concerning the deficit that underlies letter-by-letter reading. The hypothesis that letter-by-letter reading results from difficulty processing "abstract letter identities" was tested using a letter matching task with a phonetic confusability manipulation. Comparison with individual control subjects suggested that GM was able to process letters abstractly and that previous positive results may have been due to scaling artifact. The hypothesis that letter-by-letter reading results from difficulty in rapid processing of multiple letters was tested using a rapid serial visual presentation (RSVP) paradigm. GM was found to require an extended period of time after he had processed one letter before he was able to reliably identify a second letter. The final hypothesis that letter-by-letter reading results from an impairment that is *not* specific to letters was tested using an RSVP task in which processing of letters was compared to that of numbers. GM's deficit was also found to extend to numbers, and this was confirmed in a matching task with letters and numbers intermixed. Implications of these findings for theories of letter-by-letter reading, as well as normal reading and brain organization, are discussed.

List of Abbreviations

ANOVA	**Analysis of Variance**
COGNISTAT	**Neurobehavioral Cognitive Status Exam**
LARC	**Legitimate Alternative Reading of Components**
LBL	**Letter-by-Letter**
ms	**Millisecond**
NI	**Nominal Identity**
PI	**Physical Identity**
RSVP	**Rapid Serial Visual Presentation**
RT	**Reaction Time**
SOA	**Stimulus Onset Asynchrony**
TM-TM	**Target-Mask, Target-Mask**
VPNW	**Visual-Phonological Non-Word**
VPW	**Visual-Phonological Word**
WRAT-3	**Wide Range Achievement Test – Revision 3**

Acknowledgements

I would like to thank my supervisor, Dr. Gail Eskes, and committee members, Drs. Ray Klein and Paddy McMullen, for many helpful discussions throughout the course of this project and for their insightful comments on drafts of this thesis. I am particularly appreciative of their enthusiasm about the single-case methodology that was the basis of this thesis.

I would like to thank Drs. Norman Park and Guy Proulx for introducing me to GM, arranging his testing schedule, and allowing me to use facilities at the Baycrest Centre. Brian Conrod was also very helpful in the testing of GM. I appreciate the referral of control patients from Drs. Stephen Phillips and Richard Braha.

Thanks are also due to Dr. Kimron Shapiro for providing the RSVP software, and to Dr. Billy Schmidt and John Christie for assistance with the computer programs.

This research was conducted while I was supported by a Studentship Award from the Medical Research Council of Canada and an Izaak Walton Killam Memorial Scholarship. A grant from the Dalhousie Research Development Fund helped to cover my travel expenses.

My husband and parents have been constant sources of support and encouragement, for which I am very grateful.

Finally, I would like to extend a special note of appreciation to GM and the six other patients that participated in this project for their effort and cooperation throughout many hours of testing. This thesis would not have been possible without their ongoing commitment to this work.

Introduction

Reading impairments that result from brain damage in premorbidly literate adults are referred to as acquired dyslexias. Although the acquired dyslexias have a long history (e.g., Dejerine, 1892), they have received an increasing amount of attention over the last few decades. This has been motivated, in part, by interest in expanding our understanding of the cognitive deficits that underlie these disorders, and then, in some cases, to development of appropriate rehabilitation strategies (Patterson, 1994). Recognition of the contributions that studies of acquired dyslexia (usually single-case investigations) can make to our conceptualization of the normal reading system has also stimulated the growth in this field. Studies of acquired dyslexia, together with those of normal reading performance, reading development, neuroimaging, and computational modeling have yielded important constraints and insights into how the skill of reading is performed in the brain (e.g., Klein & McMullen, 1999).

A variety of types of acquired dyslexia have been described and differentiated on the basis of the particular components of the reading process that appear to break down (Coltheart, 1981a; Marshall & Newcombe, 1973; Patterson, 1981). In one type of acquired dyslexia, known as letter-by-letter (LBL) reading, words can no longer be processed as whole forms, and they can only be pronounced after each letter is identified individually. This reading disorder is usually associated with lesions to inferior regions of the left occipital lobe (Black & Behrmann, 1994). In some cases, use of the LBL strategy is very obvious in that letters of a word are spelled aloud. In others, however, this strategy is inferred from an increase in reading latency as the number of letters in a word increases, a finding known as the word-length effect.

The presence of a word-length effect in the reading of single words has become the defining characteristic of LBL reading, but the magnitude of the effect varies greatly between patients. Shallice (1988) noted that while some patients required less than 2 seconds to read three- to four-letter words and less than 4 seconds to read seven- and eight-letter words (BY: Staller, Buchanan, Singer, Lappin, & Webb, 1978; RAV:

Warrington & Shallice, 1980), another patient required as long as 17 and 47 seconds, respectively, to read words of the same lengths (CH: Patterson & Kay, 1982). Most patients though have been found to need at least 500 milliseconds (ms) for each additional letter in a word, in striking contrast to normal readers who take a maximum of 30 ms per letter to pronounce words (Butler & Hains, 1979).

Although reading is extremely slow and laboured in this disorder, most patients do re-learn how to pronounce words reasonably accurately. When LBL reading occurs in the absence of other reading, writing, or other major language impairments, it is referred to as "pure alexia". However, other types of acquired reading deficits can accompany LBL reading, the most common of which is surface dyslexia (Bowers, Bub, & Arguin, 1996b; Friedman & Hadley, 1992; Patterson & Kay, 1982; but LBL readers with deep dyslexia (Buxbaum & Coslett, 1996) and phonological dyslexia (Friedman et al., 1993; Nitzberg-Lott, Friedman, & Linebaugh, 1994) have also been described).

In surface dyslexia, the phonological regularity of a word determines the probability that it will be read correctly (e.g., Behrmann & Bub, 1992; Patterson, Marshall, & Coltheart, 1985). Words that are spelled with irregular spelling-to-sound correspondences (e.g., "pint") are pronounced with much less accuracy than words with regular spelling-to-sound correspondences (e.g., "mint") or non-words (e.g., "rint"). When irregular words are misread, regularization errors typically occur; that is, the word is pronounced according to a more frequent spelling-to-sound correspondence (e.g., "pint" is pronounced to rhyme with "mint"). Reading irregular words of low frequency seems to be particularly difficult for these patients, resulting in a frequency-by-regularity interaction in their accuracy (e.g., Behrmann & Bub, 1992; Patterson & Hodges, 1992). The critical anatomical areas that seem to be involved in surface dyslexia are the posterior superior and middle temporal gyri of the left hemisphere (Black & Behrmann, 1994; Vanier & Caplan, 1985).

The few patients who have shown surface dyslexic reading errors, together with a word length effect in their response latencies, have been labeled LBL surface alexics (Friedman & Hadley, 1992) or type 2 LBL readers (Patterson & Kay, 1982). Three of the four cases that have been reported to have this combined reading disorder have had large temporo-occipital (IH: Bowers et al., 1996b; KC: Patterson & Kay, 1982) or temporo-parietal (TP: Patterson & Kay, 1982) hemorrhages and the specific location of the damage was imprecisely specified. The patient studied by Friedman and Hadley (BL) had an ischemic lesion in the left inferior temporal lobe and left occipital lobe.

Figure 1 illustrates a model of single-word reading that provides a general framework for studying the acquired dyslexias. This model combines the main characteristics of several prominent theories of normal reading. When a written word is presented, the visual features of the letters are analyzed and their identities are determined (McClelland & Rumelhart, 1981; Rumelhart & McClelland, 1982). Representation of the letter identities seems to be neither visual nor phonological, but rather "abstract" (independent of font and case) (Adams, 1979; Allport, 1979; Besner, Coltheart, & Davelaar, 1984; Carr, Brown, & Charalambous, 1989; Evett & Humphreys, 1981; McClelland, 1976). Identification of the letters is automatic and simultaneous in skilled readers, but generally occurs in a serial, left-to-right fashion in those learning to read (LaBerge & Samuals, 1974; Seymour & Porpodas, 1980). Abstract letter information is then transmitted to the orthographic system which represents the visual forms of words.

The next stages of this model are a topic of considerable controversy (e.g., Coltheart, Curtis, Atkins, & Haller, 1993; Plaut, McClelland, Seidenberg, & Patterson, 1996), but there is general agreement that words can be processed at least two different ways: through a phonological or a semantic pathway. The semantic route seems to be particularly important for processing of irregular words, whereas the phonological route likely suffices for processing of regular words and non-words. Although the illustrated model looks most similar to the "triangle" framework (Plaut et al., 1996), it still contains the essential features of the "dual-route" model (Coltheart, 1978; Coltheart, 1985;

Coltheart et al., 1993) (with a few less boxes and arrows); differences between the two types of models will not be discussed here. Finally, it is important to note that the systems in Figure 1 are connected by two-headed arrows. Activation can spread from lower to higher levels (i.e., bottom-up) and can also feed-back from higher to lower levels (i.e., top-down); it spreads rapidly and processing does not have to be completed at one level before it is started at another (Coltheart et al., 1993; McClelland & Rumelhart, 1981; Plaut et al., 1996).

In this functional model of reading, LBL reading has been proposed to arise from damage to a variety of different components (pathways or nodes) illustrated in Figure 1. One class of theory argues that the disorder can be attributed to visual impairments that affect the processing of letters, but importantly, are not specific to the reading process (e.g., Behrmann, Nelson, & Sekuler, 1998a; Farah & Wallace, 1991; Friedman & Alexander, 1984; Kinsbourne & Warrington, 1962; Rapp & Caramazza, 1991; Sekuler & Behrmann, 1995). Another class of theory has adopted the view that LBL reading is the result of a more central disturbance to reading-specific systems; the syndrome results because of damage to abstract letter representations (e.g., Arguin & Bub, 1993; Arguin & Bub, 1994b; Miozzo & Caramazza, 1998), to orthographic access (Patterson & Kay, 1982), to the orthographic system itself (Warrington & Langdon, 1994; Warrington & Shallice, 1980), or to phonological access (Arguin, Bub, & Bowers, 1998; Bowers, Arguin, & Bub, 1996a). In all of these accounts, LBL reading develops as a strategy that somehow compensates for the underlying impairment. When surface dyslexic symptoms occur in LBL readers, it is generally assumed that a second deficit of the type that occurs in "pure" surface dyslexia is responsible for that component of the disorder (Bowers et al., 1996b; Patterson & Kay, 1982; but for a different interpretation see Friedman & Hadley, 1992). "Pure" surface dyslexia is usually thought to arise from damage to the semantic pathway (which is important for the processing of irregular words), although the damage may be in any one of a number of different sites along this path (Coltheart & Funnell, 1987; Patterson et al., 1996). Reliance on the phonological pathway allows for accurate naming of regular words and non-words, but causes irregular words to be "regularized".

The issue of whether LBL reading results from a general disturbance in basic visual processing (i.e., *the perceptual hypothesis*) or as a consequence of an impairment specific to letters and/or words (i.e., *the orthographic hypothesis*) is a central controversy in the current literature. The debate has implications not only for the understanding of LBL reading but also for the issue of how different cognitive processes are represented in the brain. The perceptual hypothesis claims that reading relies on a neural substrate that is responsible for processing a range of visuoperceptual materials and that when this substrate is damaged results in a general perceptual impairment. The deficit may appear superficially to be reading-specific because the visuoperceptual processes that are impaired are taxed most heavily in this context; however, this deficit may also be observed under stringent testing of these general perceptual skills. The orthographic hypothesis, on the other hand, implies that the brain contains systems dedicated to reading that can be selectively damaged. A number of different perceptual and orthographic theories of LBL reading have been proposed and the most prominent of these are reviewed below.

The Perceptual Hypothesis

The perceptual view of LBL reading assumes that the disorder can be accounted for by visual impairments that are not specific to the reading process. Visuoperceptual skills in LBL readers have been fairly well investigated and numerous explanations of the precise nature of the deficit have been proposed. Evidence for a visual impairment in this disorder has been found even in studies not specifically designed to assess such abilities. A number of authors have noted that letters misidentified in reading tend to be visually similar to the targets (e.g., Coslett, Saffran, Greenbaum, & Schwartz, 1993; Hanley & Kay, 1992; Patterson & Kay, 1982), consistent with a deficit at an early processing stage. Moreover, LBL reading is sometimes associated with visual agnosia (e.g., Coslett & Saffran, 1989; Patterson & Kay, 1982); the co-occurrence of word and object identification difficulties suggests a common perceptual impairment may be responsible for both types of deficit.

Several LBL readers have been shown to have quite subtle difficulties in object identification that were only detected with careful testing. These patients required much longer exposure durations (Friedman & Alexander, 1984) or reaction times (RTs) (Behrmann et al., 1998a) to identify line drawings of objects, particularly as the visual complexity of the pictures increased (Behrmann et al., 1998a).

A distinct form of visual agnosia termed simultanagnosia has been most frequently associated with LBL reading. Simultanagnosia was originally described by Wolpert (1924) as a deficit in the perception of multiple simultaneously presented forms. His patient was a LBL reader and was also severely impaired at interpreting complex pictures, although individual items in the pictures were able to be identified correctly. Wolpert, strongly influenced by the Gestalt tradition, interpreted this syndrome as a deficit of a level of perception in which a whole was formed from its component parts.

The nature of the deficit in simultanagnosia has been more recently reviewed by Farah (1990). Specifically, she described two types of simultanagnosia that have been distinguished on the basis of their associated lesion sites. Dorsal simultanagnosia, typically occurring after bilateral parieto-occipital lesions, has been linked to a disorder of visual attention, and may be related to attentional disengagement and orienting (Humphreys & Riddoch, 1993; Rizzo & Hurtig, 1987). In fact, only one object may be perceived at a time in this form of the disorder with unattended items not seen at all. Ventral simultanagnosia, on the other hand, tends to follow left occipito-temporal damage, and although only one object may be *recognized* at a time, multiple objects may be *seen* in this form of the syndrome (Kinsbourne & Warrington, 1962). Reading is severely disturbed in both types, but it tends to be the most obvious area of impairment in ventral simultanagnosia. Moreover, since ventral simultanagnosics are able to see multiple items and recognize them given sufficient time, a LBL strategy frequently develops. This has led some investigators to consider LBL reading as a specific manifestation of ventral simultanagnosia (e.g., Farah, 1990; Farah & Wallace, 1991;

Kinsbourne & Warrington, 1962; Levine & Calvanio, 1978). The obvious implication of this classification scheme is that LBL reading may be considered as a consequence of a more basic visuoperceptual disturbance.

Kinsbourne and Warrington (1962) conducted the first detailed experimental investigation of visual function in ventral simultanagnosia. Four patients who had difficulty interpreting complex pictures and also displayed LBL reading were tested on a series of tachistoscopic tasks. They found that recognition thresholds for single letters were comparable between the simultanagnosic patients and both normal and brain-damaged controls. However, the simultanagnosics had greatly elevated thresholds compared to both control groups when two letters were presented simultaneously for identification. Similarly, when the experiment was repeated using geometric forms and object silhouettes, simultanagnosics required much longer exposure durations to identify two items, suggesting a more general perceptual deficit not restricted to reading.

In a further set of experiments, Kinsbourne and Warrington demonstrated that the perceptual deficit in simultanagnosia was not restricted to spatial processing. Spatial factors such as size and position of the stimuli had no effect on performance and simultanagnosics were shown to be impaired at identifying two stimuli presented in rapid sequence, as well as simultaneously. That is, the limitation in simultaneous perception seemed to extend beyond simultaneity per se to the processing of forms in rapid temporal succession. Furthermore, by independently varying the exposure duration and interval between the two stimuli it was shown that performance depended only on the total time taken by the sequential presentation; it seemed that sufficient time had to elapse after the presentation of the first stimulus before the second could be processed, but it made no difference whether an actual stimulus or blank screen was displayed during this interval.

The final experiment conducted by Kinsbourne and Warrington showed that patients were able to count the number of dots briefly presented in an irregularly distributed array. This type of evidence suggested that although their ventral simultanagnosics were not able to rapidly recognize multiple objects, they were able to see multiple items at one time. Similarly, in experiments in which two forms were presented either simultaneously or in rapid sequence for identification, the patients were always aware that two stimuli had been presented even though they were unable to recognize more than one. It should be noted, however, that this ability to count multiple dots at brief exposure durations has not been found in all LBL readers (e.g., HT: Price & Humphreys, 1992). Nevertheless, Kinsbourne and Warrington concluded from their original investigations that the underlying problem in ventral simultanagnosia was an increased "refractory period" between the processing of stimuli when form recognition was required. Moreover, this deficit affected the recognition of both orthographic and non-orthographic stimuli (i.e., geometrical forms and silhouette drawings). The inability to rapidly recognize multiple visual forms was assumed to be responsible for the reading deficit in these patients; because they were unable to recognize more than one letter at a time they were restricted to reading via a LBL procedure.

The basic findings of Kinsbourne and Warrington have been replicated in several studies. Levine and Calvanio (1978) showed that their three patients with "alexia-simultanagnosia" had tachistoscopic recognition thresholds for single letters that were within normal limits, even when the letters were followed by a backward pattern mask, and Price and Humphreys (1992) obtained similar results in their two LBL readers. In both of these studies, patients were impaired on tasks in which more than one form had to be recognized. They required much longer exposure durations than normals to identify pairs of letters (Price & Humphreys, 1992) and sets of three letters (Levine & Calvanio, 1978; Price & Humphreys, 1992) that were simultaneously presented. In addition, Levine and Calvanio demonstrated that performance greatly improved when a pre-stimulus position cue was given specifying one letter to be identified. However, when the cued position was given after the stimulus exposure the same benefit was not observed, suggesting that the cue had its effect during the perception of the stimuli rather than in memory or naming processes.

Behrmann and Shallice (1995; see also Behrmann, 1999) also showed that their LBL reader was able to accurately report single letters that were briefly presented, but was impaired at identification of two letters presented in rapid sequence. To assess this ability, they used a rapid serial visual presentation (RSVP) paradigm in which items were displayed individually in rapid succession all in the same spatial location. Two letters were embedded at varying positions in a stream of digits. After each item stream was presented, the patient was required to report the identities of the two letters. Behrmann and Shallice found that their patient was often able to report the identity of the first letter, but that they required more time than was normal to identify the second letter as well. That is, to obtain normal levels of accuracy in the identification of both letters, more intervening digits had to be presented between the two letters. They suggested that letter activation in their patient was slowed such that arrival of the second letter interrupted processing of the first. These findings and their interpretation bear strong resemblance to the increased "refractory period" notion suggested earlier by Kinsbourne and Warrington (1962) to underlie the difficulty in processing multiple letters in words in LBL readers.

Further studies have shown that the deficit in processing multiple stimuli may be present even when identification of the stimuli is not required. LBL readers have been found to make numerous errors and to require long exposure durations on matching tasks in which strings of letters (Levine & Calvanio, 1978; Price & Humphreys, 1992) or numbers (Levine & Calvanio, 1978) were briefly presented and they were required to say whether the characters were all the same or whether one was different. It was also shown that most patients made errors on trials when the different character was visually similar to the others (e.g., COC, 966), but this was not invariably found (e.g., HT: Price & Humphreys, 1992). Similarly, Farah and Wallace (1991) showed that a LBL reader was impaired on a paper and pencil battery of rapid shape recognition, including a test of letter finding and matching tasks of number strings and geometric forms, and these results were replicated in five other LBL readers (Behrmann et al., 1998a; Sekuler & Behrmann, 1995). Moreover, several studies (Behrmann & Shallice, 1995; Kay & Hanley, 1991; Reuter-Lorenz & Brunn, 1990) have shown that LBL readers were significantly slowed on tasks in which pairs of letters had to be judged as same or different on the basis of their physical characteristics (e.g., AA vs. AB) and performance was found to be affected by the time interval between the two stimuli, consistent with findings obtained on identification tasks (Behrmann & Shallice, 1995; Kinsbourne & Warrington, 1962). When the two letters were presented sequentially, rather than simultaneously, their judgements were significantly faster, although only one of the three patients performed as well as controls (Kay & Hanley, 1991).

Since the original study by Kinsbourne and Warrington (1962), substantial evidence has accumulated supporting the notion that LBL readers have difficulty in the rapid processing of multiple stimuli. However, authors have often arrived at different conclusions regarding the specific deficit that underlies this problem, and its relation to LBL reading. Levine and Calvanio (1978) concluded that an insufficient capacity for feature discrimination underlies "alexia-simultanagnosia"; this perceptual capacity is adequate when only one stimulus has to be processed, but differentiation of multiple forms exceeds the available perceptual resources. Similarly, Price and Humphreys (1992) suggested that one of their patients (EW) had a deficit in parallel feature discrimination. They proposed that the strategy of attending sequentially to each item in an array enhanced processing sufficiently for discrimination to take place but resulted in a word length effect. However, Price and Humphreys concluded that a different impairment was responsible for the slow processing of multiple forms in their other patient (HT). They suggested that since HT was impaired on a dot detection task and had identification errors that were unrelated to visual similarity, a problem in attentional disengagement or orienting was most likely; LBL reading occurred because attention was not engaged at the appropriate point within words.

Farah (1990; 1991) has suggested that the inability to rapidly process multiple forms in LBL readers is a result of damage to a perceptual system specifically dedicated to this function. She proposed that two types of structural descriptions exist within the visual recognition system and that all recognition impairments can be explained by different degrees of damage to these two forms of representation. One type of structural description represents multiple simple components within objects, while the other form represents single complex "whole" objects. The former requires objects to be decomposed into simpler components before recognition can occur, while the latter requires little or no decomposition. Farah has postulated that LBL reading results from damage to the system that represents multiple parts of objects; the LBL reading strategy develops to compensate for the inability to automatically decompose words and recognize their multiple component letters as is thought to be required in normal word recognition (Carr & Pollatsek, 1985; Johnston & McClelland, 1980; McClelland, 1976). In contrast, damage to the system that represents "whole" objects affects recognition of faces and some objects that do not require decomposition but instead rely on the holistic relationship among parts.

According to Farah, dissociations between the abilities to recognize words, faces and objects do not result from an incapacity to process specific forms of visual material, but rather because the different stimuli place different demands on the two visual processing systems. In an extensive literature review (Farah, 1990), she demonstrated that prosopagnosia and LBL reading were dissociable disorders, but that object agnosia was always accompanied by prosopagnosia and/or LBL reading. Furthermore, prosopagnosia and LBL reading never co-occurred without some degree of object agnosia. These observations support the existence of two visual recognition systems: one that processes words and objects that require part decomposition, and another that processes faces and objects that are processed more holistically. This conceptualization though has been more recently challenged by reports of patients with object agnosia but no indication of prosopagnosia or LBL reading (Humphreys & Rumiati, 1998; Rumiati, Humphreys, Riddoch, & Bateman, 1994), as well as prosopagnosia and LBL reading without object agnosia (Buxbaum, Glosser, & Coslett, 1999; De Renzi & di Pellegrino, 1998).

The inability to rapidly recognize multiple visual forms in LBL reading also has been investigated in the spatial domain. Visual search tasks have been used in several studies to assess processing across a spatial array. These tasks require the subject to detect the presence or absence of a target from an array of distractor items. When the target has visual features that are not shared with the distractors, normal subjects typically show little effect of display size on RT, implying spatially parallel search processes. However, Rapp and Caramazza (1991) found that when their LBL reader was required to detect an X among an array of O's, RTs increased as the number of items increased. Similarly, when Humphreys and Price (1994) tested two simultanagnosic patients, one of whom (SA) was a LBL reader, on a task in which the presence of a C had to be detected among A's and H's, the LBL reader showed a clear effect of display size. These results suggest that the patients were unable to process multiple visual stimuli in parallel and instead relied on a serial search mechanism.

However, not all LBL readers have shown a display size effect in visual search tasks, suggesting that they were able to process items in parallel. Two studies found that RT did not increase with the number of distractors when patients were required to detect a filled circle among unfilled circles (Behrmann & Shallice, 1995) or a horizontal line among vertical lines (Arguin & Bub, 1993). Nevertheless, a partial explanation for the discrepant results may be found in Humphreys and Price (1994). They showed that when the target was made highly discriminable from the distractors (i.e., tilted line among vertical lines), their LBL reader was slower than normal but no longer showed a display size effect. The demands of this task and experimental findings are consistent with those in Behrmann and Shallice (1995) and therefore suggest that LBL readers may have a deficit in the parallel discrimination of form features but that this deficit may only be seen in some patients under stringent testing conditions when the target is not easily distinguished from the distractors. However, this account may not explain the lack of a display size effect in Arguin and Bub (1993) as the same results were obtained even when a degraded exposure condition was included as a stringent test of feature discrimination.

Rapp and Caramazza (1991) proposed a specific account of LBL reading in which the inability to process multiple visual forms across an array results from a left-right gradient in spatial attention. They suggested that their patient was unable to deploy attention evenly across a spatial array, and thus was forced to allocate their resources sequentially to each letter in a word in order to increase the discriminability. Evidence for this notion came from a series of experiments in which accuracy of letter recognition was shown to decrease from left to right across letter strings. These findings were also obtained with non-orthographic stimuli (i.e., horizontal and vertical bars), suggesting that the deficit affected the representation of spatially arrayed visual material more generally. Chialant and Caramazza (1998) later replicated these results in a different LBL reader.

Although Rapp and Caramazza presented ample evidence to support the presence of an attentional gradient in their patient, this account fails to explain the patient's pattern of LBL reading. Since letter recognition decreased across strings presented horizontally but not vertically (only horizontal strings were used in Chialant and Caramazza's study), it would follow that LBL reading should occur only when words were displayed horizontally. Their patient though showed clear word-length effects when reading words in both orientations. This finding suggests that the left-right gradient in spatial attention and the LBL reading may have been unrelated; the word-length effect may have resulted from an additional deficit that was not revealed in their investigation.

The spatial gradient account of LBL reading has also been challenged by evidence presented by Behrmann and Shallice (1995). They showed that report of letters in their patient was not affected by their relative position within the string, nor by the string orientation. When they compared the report of the first and last letters of letter strings with the report of letters in the first and second positions, the first letter was reported better than the second or last letters, but there was no difference between the latter two letters. In contrast, a comparison patient with visuospatial neglect was significantly better at reporting the second letter compared to the last letter, suggesting that the task was sensitive to a deficit in spatial processing, but that their LBL reader did not suffer from that impairment.

Many proponents of the perceptual hypothesis have suggested that patients have difficulty with rapid processing of multiple visual stimuli, although they differ in their view of whether the impairment is primarily spatial, or whether it also affects the processing of forms in rapid temporal sequence. According to this notion, the LBL reading strategy develops because patients are unable to process more than one letter at a time. The deficit is most apparent when patients attempt to read because this skill is strongly dependent on the perceptual process that is impaired. The obvious corollary of this account is that patients should also have difficulty when multiple non-orthographic stimuli must be rapidly processed. Unfortunately, several of the investigations that have attempted to assess this general perceptual skill have used letters as stimuli (e.g., Behrmann & Shallice, 1995; Levine & Calvanio, 1978; Price & Humphreys, 1992), but most studies that have used non-orthographic materials have found that patients were similarly impaired in this context (e.g., Farah & Wallace, 1991; Humphreys & Price, 1994; Kinsbourne & Warrington, 1962; Rapp & Caramazza, 1991).

However, Sekuler and Behrmann (1995) have more recently obtained evidence with non-orthographic materials that challenges the multiple forms hypothesis, at least as it was conceptualized by Farah (1990; 1991). They tested four LBL readers on an experiment in which they had to detect misoriented components of geometric shapes (e.g., square, hexagon) that were composed of a varying number of parts. If patients had difficulty representing multiple simultaneously presented parts of objects, it was expected that their target detection times would be significantly affected by an increasing number of components. Their performance though was found to be unaffected by the number of parts to be processed. Instead, Sekuler and Behrmann showed that patients were disproportionately slowed as the "figural goodness" of the stimuli was disrupted by eliminating good continuation of their parts, and a further experiment showed that performance was poor when symmetry was not available to assist with the integration of occluded object components. Based on these findings, Sekuler and Behrmann proposed that LBL readers did not have difficulty representing multiple parts of objects, but rather had a general perceptual deficit that surfaced when perceptual cues were unavailable to facilitate visual processing; their reading was particularly affected by this deficit because of the lack of perceptual cues in letters and words. However, as Farah (1999) has pointed out, normal subjects also were unaffected by the number of component parts to be processed, raising the possibility that "the visual system's parse of the stimuli differed from the experimenters' intended parse".

In summary, numerous authors have proposed that damage to low level perceptual processes is responsible for LBL reading. Support is derived from results which show that LBL reading co-occurs with object identification deficits, ventral simultanagnosia, difficulties processing multiple items across a spatial array and/or in rapid temporal sequence, and difficulties processing items that lack perceptual cues. However, an inherent weakness of almost all versions of the perceptual hypothesis is that they derive solely from an association between LBL reading and a perceptual impairment. That is, the relationship between these deficits is correlational and leaves open the possibility that the perceptual disturbance is not directly responsible for the reading disorder. That patients with severely impaired form perception may be able to read normally suggests that the two abilities may be dissociable (Warrington, 1985). Moreover, groups of patients with left posterior lesions have been shown to be impaired on tasks in which multiple simultaneously presented letters, numbers or line stimuli had to be reported (Warrington & Rabin, 1971), and also have been found to be significantly slowed on tasks of visual matching and identification of shapes, objects and faces (Zihl & Wohlfarth-Englert, 1986). Although these latter two reports do not specify which of their patients had reading disorders and their associated levels of performance on these tasks, they do suggest that such deficits may be more widespread and not reflective of an impairment specifically related to LBL reading.

The interpretation of perceptual deficits in LBL readers is further complicated by the fact that many studies use RT as their dependent measure and do not include brain-damaged control subjects. Slowed RTs are a very common symptom of brain damage (Lezak, 1995) and thus increased latencies on a particular task should not be assumed to be uniquely associated with LBL reading unless brain-damaged patients that are not reading-impaired are also tested as controls. Unfortunately, however, only one study has utilized a brain-damaged control group (Kinsbourne & Warrington, 1962) and most studies have tested only a few normal control subjects (e.g., Behrmann & Shallice, 1995; Farah & Wallace, 1991; Friedman & Alexander, 1984; Rapp & Caramazza, 1991) so variability amongst the normals on the experimental tasks has not even been well assessed.

Farah and Wallace (1991), however, attempted to show that a visual impairment may *cause* LBL reading. They reasoned, based on additive factors logic, that if LBL reading was produced by a visuoperceptual deficit then manipulation of the visual quality of the letters in word strings should exacerbate the word length effect. Accordingly, they found that while control subjects instructed to read LBL did not show an interaction between word length and visual quality, their patient was disproportionately affected by the visual manipulation. Thus, they concluded that an impairment in visuoperceptual encoding was directly responsible for the reading deficit in this patient.

Unfortunately, however, there are two major problems with Farah and Wallace's interpretation of their data. First, any deficit, perceptual or not, that forces the patient to access the word name by first encoding and naming each letter would predict an interaction between word length and visual quality. This is based on the assumption that the time to read a word via the LBL strategy is the sum of the time required to visually encode and name each letter, plus a constant time that is required to access the word name. Thus, visual masking, which affects the encoding of letters, would be expected to interact with word length. Second, the lack of an interaction in control subjects instructed to read LBL would be expected since, in spite of the specific instruction, the word stimuli were likely still processed as a unit (Reicher, 1969), with the individual letters named from a mental representation and not from the visual display. Thus, their interpretation that the lack of an interaction between word length and visual quality results from the intact perceptual ability of controls may not be warranted.

The Orthographic Hypothesis

An alternative view to the perceptual hypothesis is that LBL reading results from a more central disturbance specific to orthographic material and is not caused by any of the perceptual deficits that may accompany the disorder. The orthographic hypothesis includes theories that propose the damage is specific to letter representations, as well as those that propose the damage is specific to word representations.

Letter-Specific Deficits

A number of authors have suggested that LBL reading is the result of a deficit in identifying letters. The most thorough investigations of this theory were conducted by Arguin and Bub (1993; 1994a; 1994b). They first demonstrated that LBL reading dissociated from low level perceptual disorders, and then presented positive evidence for a deficit affecting the letter identification stage of word reading.

Arguin and Bub (1993; 1994a) demonstrated in a number of experimental tests that their LBL reader had good visuoperceptual abilities, ruling out a perceptual locus for the reading impairment. Their patient showed no effect of display size on a visual feature search task under normal and degraded exposure conditions, suggesting that parallel feature encoding processes were intact. On a conjunction search task in which combinations of visual features had to be integrated for correct performance (i.e., black X among white X's and black O's), their LBL reader showed an effect of the number of items and RTs that were within the normal range, implying that feature integration was not disturbed. Finally, the pattern of performance on full and partial report tasks also suggested that feature encoding was relatively preserved. In these tasks, two rows of three letters were briefly presented in a horizontal array. Subjects were required to either report all of the letters (full report) or one letter indicated by a post-stimulus cue (partial report). In the full report condition, performance of the LBL reader was poor and accuracy decreased from the left to right positions in the array. In contrast, accuracy did not vary as a function of the target location in the partial report task. Control subjects had high performance levels in both tasks with no effects of target location. Since the exposure conditions for the stimuli were identical in the full and partial report tasks, it was concluded that the discrepancy in performance between the two tasks in the LBL reader was not due to a deficit in feature encoding. Instead, it was suggested that the two tasks placed different demands on letter identification; performance was worse in the full-report task because six letters had to be identified, whereas only one letter had to be identified in the partial report task.

More conclusive evidence for a deficit affecting letter identification was obtained from a letter search task in which their LBL reader had to report whether an auditorily presented target letter was present in an array. Their patient showed a large display size effect suggesting that letter processing was slowed. Since low level perceptual abilities were intact, it was concluded that the deficit in this patient was in letter identification. Specifically, it was argued that the impairment occurred in a process where an intact description of letter shape was matched to its corresponding identity representation. This notion was then tested with a priming experiment in which subjects had to identify a single target letter that was preceded by a letter prime that was either identical (e.g., H – H), structurally similar (e.g., H – M), or structurally different from the target (e.g., H – Q). Control subjects had slower RTs with the two primes that differed from the target (i.e., structurally similar, different), relative to identical primes. In contrast, the LBL reader had comparable RTs for the identical and different primes, but was slower with structurally similar primes, and was much slower in all conditions relative to controls. It was suggested that performance in the LBL reader was inhibited by the similar prime because selection of letter identities was impaired. That is, exposure to structurally similar primes created noise amongst representations that were structural neighbours to the target, so that the time required for target identification was markedly increased.

Arguin and Bub (1994b), as well as a number of other investigators (Behrmann & Shallice, 1995; Hanley & Kay, 1996; Kay & Hanley, 1991; Miozzo & Caramazza, 1998; Reuter-Lorenz & Brunn, 1990), have obtained further evidence for a deficit affecting letter identification by using a letter matching paradigm. When normal subjects have to decide whether two letters have the same name, responses to physically identical (PI) pairs (e.g., A-A) tend to be about 70 to 100 ms faster than those to nominally identical (NI) pairs (e.g., A-a) (Posner & Mitchell, 1967). This finding was interpreted as evidence that subjects base their decisions on two different types of codes: the visual and name codes. Although Posner (1978; Posner & Mitchell, 1967) equated the name code with a phonological representation (i.e., subjects determine that "A" and "a" are the same because their names sound the same), it has become fairly clear that normals can perform NI matches without phonological coding, at least when the two letters are presented simultaneously (Boles & Eveland, 1983; Rynard & Besner, 1987). Instead, they seem to rely on abstract letter representations that are independent of visual and phonological information (Besner et al., 1984; Coltheart, 1981a; Mozer, 1989; Rynard & Besner, 1987).

A number of investigators have claimed that LBL readers are disproportionately impaired (i.e., increased RTs or decreased accuracy) at performing NI matches over PI matches, relative to normal controls (Arguin & Bub, 1994b; Behrmann & Shallice, 1995; Hanley & Kay, 1996; Kay & Hanley, 1991; Miozzo & Caramazza, 1998; Reuter-Lorenz & Brunn, 1990). In addition, this effect seemed to be exaggerated when the letters were presented simultaneously rather than sequentially (Behrmann & Shallice, 1995; Kay & Hanley, 1991; Reuter-Lorenz & Brunn, 1990). This has been interpreted as evidence that LBL readers have difficulty processing the abstract identities of letters.

Similar findings have been obtained in a letter priming paradigm (Arguin & Bub, 1994b). In this task, subjects had to identify a target letter that was preceded by a prime that was either PI (e.g., A-A), NI (e.g., A-a), or neutral (e.g., blank - A). Normal subjects showed equal RT benefits from NI and PI primes, relative to neutral primes (Arguin & Bub, 1995). However, in the LBL reader, PI primes resulted in a large reduction in identification times, relative to the neutral condition, but NI primes had no significant effect, suggesting abstract letter representations had not been activated normally.

Normal word recognition is thought to be based upon preliminary letter identification, with the letter identities represented in an abstract form which is independent of letter case. Evidence for this notion is derived from results that show the word superiority effect (i.e., better identification of letters in words over non-words) is maintained with alternated case stimuli (e.g., WoRd; Adams, 1979; McClelland, 1976), word recognition is primed by letter strings briefly presented in alternated case (Evett & Humphreys, 1981), and word reading is not affected by a change of letter case during a saccadic eye movement (Rayner, McConkie, & Zola, 1980). Thus, this version of the orthographic hypothesis that proposes LBL reading is a strategy adopted to compensate for a deficit in processing the abstract identities of letters is very consistent with, and provides additional support for, our conceptualization of the normal reading system.

Word-Specific Deficits

Other investigators have proposed that the damage underlying LBL reading is specific to word representations. This version of the orthographic hypothesis has been popularized and endorsed most strongly by Warrington and colleagues (Warrington & Langdon, 1994; Warrington & Shallice, 1980). Warrington and Shallice (1980) suggested that damage in their patients was to a specific stage in the reading process, termed the "visual word form system", that parses together letters into familiar orthographic units. This processing of word forms occurs after basic visual processing is complete but prior to phonological or semantic analysis. Thus, the word form system is roughly equivalent to the orthographic processing system that has been adopted in more recent models of the reading process (Coltheart et al., 1993; Plaut et al., 1996). In their account of LBL reading, automatic word recognition cannot occur in these patients because they do not have word-form representations that can be activated. Instead, reading must occur through an intact spelling system by identification of individual letters.

Warrington and Shallice (1980) presented two types of evidence for a damaged word form system in their patients. First, they attempted to rule out a general perceptual deficit by showing that their patients performed well on clinical tests involving picture interpretation and on three experimental tests of visuoperceptual function. These latter tasks examined the effects of visual angle, distracting characters, and tachistoscopic presentation on identification of alphanumeric characters. They argued that since the word length effect dissociated from visuoperceptual impairment their claim of damage to the word form system was strengthened. Second, they showed that their patients were impaired on script and tachistoscopic reading tasks that required whole word reading procedures.

The conclusion that the deficit responsible for LBL reading resides within the word form system was strongly criticized by Farah (1990; Farah & Wallace, 1991). She argued that the tests used by Warrington and Shallice did not assess the specific form of visual impairment that underlies LBL reading: the inability to rapidly process multiple visual forms. Since the picture interpretation tests that Warrington and Shallice selected (i.e., Picture Completion and Picture Arrangement subtests of the WAIS and Peabody Picture Vocabulary Test) did not assess this type of visual processing, it is not surprising that their patients performed in the normal range. Farah, in support of her hypothesis, showed that her LBL reader was impaired on tests designed specifically to test the rapid recognition of multiple visual stimuli but performed normally on the Picture Completion and Picture Arrangement subtests of the WAIS.

Similarly, the first two experimental tests used by Warrington and Shallice may not have been appropriate for detecting the relevant form of visuoperceptual impairment. Their patients showed no effect of visual angle and number of intervening letters when displays such as "6STOP4" were briefly presented and the digits in the first and last position had to be identified. They also made few errors in letter identification and displayed no effect of distracting characters when reading of single isolated letters was compared with reading of letters in an array. However, Farah maintained that since the first task did not require that the distractor letters be recognized, and the latter was completed without time constraints, they did not assess the critical ability to quickly recognize multiple visual forms.

In the third experimental test of visuoperceptual function presented by Warrington and Shallice, one patient performed several tachistoscopic tasks in which letter strings or numbers had to be reported. The patient exhibited only mild difficulties and performed at a level comparable to a group of patients with left hemisphere lesions that had been studied previously (Warrington & Rabin, 1971), even though rapid recognition of multiple stimuli was required. Farah, in support of the perceptual hypothesis, pointed out that the patient tested was an extremely mild LBL reader and would therefore be expected to have only mild visuoperceptual impairment. Moreover, comparing the performances of the LBL reader and the left hemisphere group may not have been appropriate since the left hemisphere group had viewed stimuli for a shorter duration which would have made their task more difficult.

The second type of evidence used by Warrington and Shallice to support a damaged word form system showed that patients were impaired on tasks that required whole word reading. They found that their patients had much more difficulty reading script compared to print and argued that since the individual letters in script are less distinctive its reading relies more on overall word form than print word reading. Farah noted, however, that the greater impairment with script is also consistent with the perceptual hypothesis because it is more difficult to visually differentiate letters in script. Warrington and Shallice also found that their patients were impaired on tachistoscopic reading tasks and suggested that this was because access to whole word forms was unavailable. However, all patients that used a LBL strategy in this task, regardless of the underlying impairment, would be predicted to perform poorly because sufficient time was not given to decipher the entire word.

Patterson and Kay (1982) revised the word form hypothesis and proposed that the word form system itself was intact but access to this system was restricted to individual letters. That is, the LBL strategy was thought to reflect a deficit in which letters were no longer able to be recognized in parallel. Patterson and Kay also observed that some patients appeared to have difficulties recognizing letters, even when they were presented in isolation. Although they did not specify the nature of this letter processing difficulty, they did report that visual similarity was strongly related to their misidentifications but, in accord with the orthographic view, they seem to have assumed that the deficit was limited to the processing of letters.

In their hypothesis, Patterson and Kay proposed that the disconnection between letter recognition units and the word form system was the critical deficit responsible for LBL reading, but they suggested that in a few patients there may be further difficulties within the word form system itself. This conceptualization was based primarily on the behavioural observation that in some LBL readers a sequence of correctly identified letters seemed to allow automatic recognition of the word, whereas in others, access to the lexical representations appeared difficult even after a correct sequence of letters was identified. These latter patients also made a significant number of reading errors, the majority of which were regularizations. Patterson and Kay (1982) labeled these different forms of dyslexics as type 1 and type 2 LBL readers. More recently, Friedman and Hadley (1992) referred to a type 2 LBL reader as a "LBL surface alexic", and in a somewhat similar account of the disorder, suggested that their patient had an acquired deficit that limited access to the orthographic system. This, together with a premorbid deficit in the orthographic system itself, which had manifested as poor premorbid spelling, resulted in the syndrome of LBL surface alexia.

Another orthographic theory proposes that LBL reading results from a deficit in accessing phonology, *after* orthographic processing has occurred (Arguin et al., 1998; Bowers et al., 1996a). This account was based on results from a series of priming studies conducted in a LBL reader. Word naming in this patient benefitted from briefly-presented orthographic primes, both when primes were in a different case than the target (e.g., prime: "gate"; target: "GATE") and when they were case-alternated (e.g., prime: "GaTe"; target: "GATE"). However, priming was not obtained with phonological primes (e.g., prime: "gait"; target: "GATE"). The difficulty in accessing phonology was proposed to result in the word length effect, although the details of this were not specified.

A number of LBL readers seem to have this ability to access some degree of word-related information without resorting to the LBL strategy. Several patients have been shown to perform above chance on lexical decisions about letter strings presented too quickly to have allowed for use of the LBL procedure. These patients were also able to make above chance judgements in certain categorization tasks, in which they had to decide whether a briefly presented word was associated with a particular semantic category or matched a picture (e.g., Coslett & Saffran, 1989; Coslett et al., 1993; Shallice & Saffran, 1986). Another patient was able to make quick and accurate lexical decisions to words presented with unlimited exposure durations, but had to rely on the slow, LBL decoding procedure to read words orally (Bub & Arguin, 1995). Other patients were found to perform better at identification of letters in briefly presented words as compared to non-words (e.g., Bowers et al., 1996b; Bub, Black, & Howell, 1989; Reuter-Lorenz & Brunn, 1990). This phenomenon, known as the word superiority effect, suggests that orthographic representations were available to provide top-down support to letter-level recognition units.

Some investigators have attributed these preserved abilities to residual functioning in the normal reading system that allows for partial word-level activation, but not normal word naming (Behrmann, Plaut, & Nelson, 1998b; Bub & Arguin, 1995). Others have suggested that these findings reflect the operation of a different system that does not play a major role in normal word reading, and that is likely based in the right-hemisphere (Buxbaum & Coslett, 1996; Coslett & Saffran, 1989; Coslett et al., 1993; Saffran & Coslett, 1998). It should be noted though that not all LBL readers have demonstrated access to lexical or semantic information for words that they are unable to read aloud (e.g., Behrmann & Shallice, 1995; Behrmann, Black, & Bub, 1990; Patterson & Kay, 1982). Whether this difference between patients reflects a fundamental difference in the nature of the impairment responsible for LBL reading (Behrmann et al., 1998b; Bub &

Arguin, 1995), or reflects a difference in the strategy that is applied to the task (Coslett et al., 1993; Saffran & Coslett, 1998) is a matter of debate.

In an interesting review paper, Behrmann, Plaut, and Nelson (1998b) suggested that these preserved word-level abilities do not necessarily indicate that the damage is to later stages of the word processing system (i.e., to phonological access), and that these abilities could also be preserved with an early deficit in perceptual or letter processing, as long as the deficit is not too severe. This is because processing does not have to be fully completed at the letter level before it can be started at the word level, according to models of normal reading (McClelland & Rumelhart, 1981; Rumelhart & McClelland, 1982). Thus, it is possible for LBL readers to have an underlying deficit in letter perception that still allows for word-level information to be activated.

To support their theory, Behrmann and colleagues first showed that deficits in perceptual or letter processing were evident in almost all published reports of LBL reading. A substantial number of cases, if tested, also showed evidence of word-level activation. These effects included lexical decisions and/or semantic categorizations under brief exposure durations, a word superiority effect, or effects of word frequency, imageability, regularity, or part-of-speech on word naming and/or lexical decision. Then, in an empirical analysis of seven LBL readers, all of whom had been previously found to have an impairment in perceptual or letter processing, they showed that lexical variables (word frequency and imageability) tended to interact with word length; the lexical effects (i.e., faster naming of words of high frequency and imageability) were more marked for long than short words. They argued that because of the increased time required to process longer words, there was more time for higher word-level activation to build-up and affect reading performance.

In an earlier report, Buxbaum and Coslett (1996) had also found this interaction between word length and imageability (in accuracy and RT), together with results indicative of a low level perceptual deficit in their LBL reader. In an interpretation similar to that of

Behrmann and colleagues, they had suggested that degraded visual information activated word-level representations, which then fed back to facilitate LBL-based word recognition (see also Saffran & Coslett, 1998). However, their account differed from that of Behrmann and colleagues in that the word-level activation was thought to be mediated by the right hemisphere, while the damaged left hemisphere was responsible for the LBL reading. Behrmann and colleagues had proposed that both hemispheres contributed to the word- and letter-based processes.

Scope of the Current Investigations

This thesis consists of a single-case study of a patient (GM) with acquired LBL surface alexia. The first set of investigations (Experiments 1 to 5) document the characteristics of his dyslexia. His ability to process words varying in length, regularity, and frequency, as well as non-words, is assessed in pronunciation and lexical decision tasks. Other tasks attempt to determine, more precisely, some of the strategies that he relies on to process words.

The second set of investigations (Experiments 6 to 9) addresses several hypotheses concerning the nature of the cognitive deficit that may underlie the LBL component of his reading disorder. The hypothesis that LBL reading results from difficulty in processing the abstract identities of letters is tested using a variant of the letter matching task of Posner (1967). This task requires letters to be matched on the basis of their physical and nominal identities; markedly slowed response latencies to NI matches, relative to PI matches, have been considered to indicate deficits in abstract letter processing in other LBL readers (Arguin & Bub, 1994b; Behrmann & Shallice, 1995; Hanley & Kay, 1996; Kay & Hanley, 1991; Reuter-Lorenz & Brunn, 1990). This investigation builds on those conducted previously in that it also attempts to determine the mechanism by which GM performs NI matches. That is, it evaluates whether he classifies the letters based on their abstract representations, or if he uses a process that is qualitatively different from that used in normal readers. Specifically, it examines whether he relies on the phonological representations of the letters to perform NI matches. This notion was of particular interest in the assessment of GM because of his accompanying surface dyslexia, which was taken as evidence that he depends to a large extent on the phonological pathway to name words. It was speculated that a reliance on phonology to process both letters and words could lead to the combination of his LBL reading and surface dyslexic symptoms.

The hypothesis that LBL reading results from difficulty in processing multiple letters in rapid temporal succession is tested using a RSVP paradigm. In this task, RSVP sequences of digits are presented successively in the same spatial location. Subjects are required to report the identities of two target letters embedded in the stream. Behrmann and Shallice (1995; see also Behrmann, 1999) found that their LBL reader was often able to report the identity of the first letter, but that they required more time than was normal to identify the second letter as well. The current investigation builds on this one in that it attempts to more precisely define the duration and characteristics of this temporal processing deficit.

The hypothesis that LBL reading results from a deficit in rapid processing of multiple visual forms that is *not* specific to orthographic material (i.e., letters) is tested using a variant of the RSVP procedure described above. In this investigation, the ability to temporally process letters is compared to that for numbers. Direct comparisons of this sort have not been conducted previously, despite their considerable relevance to the perceptual hypothesis. Possible differences between letter and number processing are also assessed using a matching task.

In the following investigations, GM's performance is compared to that of a group of brain-damaged individuals that are not reading impaired. This is one of the only studies (see also Kinsbourne & Warrington, 1962) that has utilized this type of control group. Thus, this study represents an important methodological improvement over previous investigations in that it allows for increased RTs and other measures of performance in the experimental tasks to be more confidently assumed to be uniquely associated with LBL reading, rather than due to general effects of brain damage.

General Methods

Subjects

Case Study Patient

GM presented at hospital with headache, confusion, blurred vision and dysphasia in June of 1992; he was 37 years old at the time. A CT scan revealed a 4 cm hyperdense lesion in the temporal-occipital region of the left cerebral hemisphere in keeping with a cerebral hemorrhage. Angiography found that the source of the bleeding was a ruptured arteriovenous malformation and incidentally revealed a left basilar tip aneurysm. He underwent neurosurgery for excision of the arteriovenous malformation in November of 1992, and for elective clipping of the basilar tip aneurysm in September of 1994.

Following his cerebral hemorrhage, GM had a moderate fluent aphasia for which he received speech-language therapy. He made a good recovery and returned to full-time work as a foreman at an industrial plant in the fall of 1993. Therapies to assist him with various aspects of verbal expression were administered intermittently for several years following his cerebral hemorrhage. GM reported that he was completely unable to recognize words or letters for several months after his brain injury. His ability to recognize letters gradually improved and he developed a LBL strategy (naming the letters aloud) to identify words. Over time, he became able to read words without explicitly naming each letter, although he reported that he continues to use this strategy silently. Even with the use of this strategy, he had difficulty naming some words accurately. GM received speech-language therapy to assist him with oral reading in the spring and summer of 1996, although the overall gains were apparently small. The primary exercise consisted of speeded naming of single words presented on flashcards (none of the practiced words were included in the following experiments). GM also had an upper-right quadrant visual field defect after his cerebral hemorrhage that had since resolved according to perimetry testing.

GM is right-handed and a native speaker of English. He has grade 10 education. Although he was not an avid reader premorbidly, he denied any difficulties with reading and had read newspapers and magazines regularly. He had mild difficulty with written spelling premorbidly, but according to GM and his wife, it worsened substantially after his cerebral hemorrhage. Unfortunately, samples of his premorbid written spelling were not available.

The following experiments were conducted between November, 1996 and March, 1997; GM was 42 years old at the time. His speech was fluent and he appeared to have no difficulty with oral comprehension. He displayed occasional word-finding problems in spontaneous speech, however. He took an anti-convulsant medication to control seizures which he experienced following his cerebral hemorrhage, but suffered no other physical health problems. He did not experience any seizures during the time period that he participated in the current study.

Several standardized neuropsychological tests were administered at the time of the current study. The Neurobehavioral Cognitive Status Examination (COGNISTAT) (Kiernan, Mueller, Langston, & Dyke, 1987) was administered to obtain a general indication of functioning in a number of cognitive domains. He obtained perfect scores on the subtests of orientation, attention, comprehension, repetition, construction, memory, calculation, and reasoning (similarities and judgement). His performance on the naming subtest fell in the impaired range.

GM's anomia was confirmed with the Boston Naming Test (Kaplan, Goodglass, & Weintraub, 1983) on which he correctly named only 34 of 60 objects without cueing, although he named an additional 16 items with phonetic cues (i.e., the first phoneme of object name). He was able to provide accurate verbal descriptions of all objects that he was unable to name (e.g., globe: "picture of world that spins around"; igloo: "made of snow, eskimo live in it"; abacus: "used for counting in ancient times"), indicating that he recognized the objects perceptually and had access to related semantic information.

GM performed well on the Visual Object and Space Perception Battery (Warrington & James, 1991), indicating that he did not have any obvious visuoperceptual impairments. He obtained perfect scores on the shape screening, incomplete letters, dot counting, position discrimination, and cube analysis subtests and his scores on the silhouette (18/30), object decision (18/20), progressive silhouette (11/20), and number location subtests (9/10) all fell above the 5th percentile cut-off scores for normal performance.

Accuracy of reading single words orally on the Wide Range Achievement Test – Revision 3 (WRAT-3) (Wilkinson, 1993) was impaired and his score was at the 3rd percentile, equivalent to a grade 5 reading level. Writing was assessed with subtest 35 from the Psycholinguistic Assessment for Language Processing in Aphasia (Kay, Lesser, & Coltheart, 1992). He spelled to dictation 20 of 30 regular words and 2 of 30 exception words correctly. The inferior performance with irregular words is characteristic of surface dysgraphia. His errors consisted primarily of regularizations (e.g., colonel: "curnel"), homophone confusions (e.g., quay: "key"), visually-similar letter substitutions (e.g., flannel: "blanel"), phonetically-inappropriate letter insertions, particularly with vowels (e.g., pump: "poump"), and phonetically-legitimate alternative spellings (e.g., effort: "efert") (see Appendix 1).

Control Subjects

Six individuals who had previously experienced a stroke (infarct or cerebral hemorrhage) served as controls in the following experiments. Demographic and neurological information is provided in Table 1. Subjects were approximately matched to GM in age and education. Only Subject 3 had returned to his premorbid occupation; the other control subjects had stroke-related disabilities that prevented them from working outside the home. Subjects varied considerably in the location of their brain lesions. All subjects had sufficient motor function in one hand to respond manually (with computer key presses) in the experimental tasks and had normal or corrected visual acuity. None of the subjects had visual field defects. All subjects were native speakers of English, with the exception of Subject 3 who was raised by french-speaking parents but was schooled entirely in English and spoke English exclusively outside his original family home. Control subjects were tested between December of 1997 and March of 1998. They were initially administered the COGNISTAT and reading subtest of the WRAT-3 in order to obtain an indication of their current levels of cognitive functioning and screen for reading difficulties. Results of these tests for control subjects, as well as for GM, are provided in Table 2. The domains of cognitive impairment varied across subjects but their scores on the WRAT-3 reading subtest all fell within the average range.

Procedure

Each test session lasted for no longer than 3 hours duration and frequent rest breaks were provided. All experiments, unless otherwise described, employed the following procedure. Experiments were run on a Macintosh Powerbook 180c computer using SuperLab software (version 1.68). Stimuli were presented in bold black Geneva 24-point font on a white background. Each trial started with a central black fixation point which remained on the screen for 1 second. Following a 500 ms delay, the stimulus appeared and remained on the screen until the subject made a response. A 2 second interval occurred between the trials. On tasks requiring an oral response, RTs were measured by an Apple microphone and voice key (in SuperLab) from the onset of each stimulus. Responses were hand-recorded by the experimenter during testing, but also tape-recorded for later verification. On tasks requiring a manual response, subjects used the index and middle finger of their right hand to press the "n" key for one response choice and the "m" key for the other response choice on an external keyboard ("x" and "z" were used for the left-handed subject). Accuracy and RT from the onset of each item were measured by the computer.

Statistical Analyses

The RT analyses excluded trials in which errors were made, the voice key was triggered erroneously (GM: < 1%; controls: < 3% in all studies), or the RT was greater than 2 standard deviations from the mean of a particular condition for a subject (GM: < 6%; controls: < 5% in all studies). The analyses of GM's RT data used individual items as independent samples. His accuracy data were analyzed with chi-square tests. Where appropriate, GM's results were directly compared to that of the controls by reporting whether or not his obtained values fell within the range of the individual control subjects. Analyses of variance (ANOVA) that used both subject (F_s, p_s) and item (F_i, p_i) means were conducted on the RT data from the control subjects. The factors were treated as within-subjects variables in the analyses by subjects and as between-items variables in the analyses by items. Accuracy data from the controls were analyzed only by subjects. Control group means presented in the figures are by subjects.

Experiment 1: Word Pronunciation

Background

The first purpose of this study was to obtain evidence for LBL reading in GM by evaluating the effect of word length on pronunciation. A dramatic increase in pronunciation latencies as length increases is considered to be diagnostic of LBL reading. The second purpose of this study was to examine for the presence of surface dyslexia by assessing the effects of regularity and frequency on oral reading. In surface dyslexia, words with irregular spelling-to-sound correspondences are pronounced with much less accuracy than words with regular spelling-to-sound correspondences. Reading irregular words of low frequency often seems to be particularly difficult for these patients, resulting in a frequency-by-regularity interaction in their accuracy (e.g., Behrmann & Bub, 1992; Patterson & Hodges, 1992).

Although the word list was not specifically generated for this purpose, this study also provided an opportunity to examine the effect of imageability, a semantic variable, on oral reading, as well as its interaction with the other variables manipulated in this list. In a small group of LBL readers, Behrmann and colleagues (1998b; see also Buxbaum & Coslett, 1996) recently found that the latency difference between high and low imageability words, and between high and low frequency words, tended to increase as word length increased. This was interpreted as evidence that word-level representations were activated in these patients, in spite of their demonstrated impairments in perceptual or letter processing; because of the increased time required to process longer words, there was more opportunity for word-level activation to build-up and influence reading performance.

Method

A set of 240 words was compiled (see Appendix 2), 120 of which were taken from other word lists (i.e., Behrmann & Bub, 1992; Coltheart & Rastle, 1994; Shallice, Warrington, & McCarthy, 1983; Strain, Patterson, & Seidenberg, 1995). The variables of word length (4-, 5-, 6-, and 7-letters), frequency (high: > 100; medium: 20 – 99; low: < 20; Kucera & Francis, 1967), and regularity (regular, irregular) were orthogonally crossed to create 24 conditions (each with 10 words). Specific frequency counts were matched across the conditions within each frequency band. Regularity was defined according to the spelling-to-sound correspondence rules of Venezky (1970).

Imageability ratings were available from the MRC Psycholinguistic database (Coltheart, 1981b) for 167 of the words. The imageability ratings in this database were derived from a merging of the Colorado norms (Toglia & Battig, 1978), the Paivio norms (unpublished; these are an expansion of the norms of Paivio, 1968), and the Gilhooley and Logie norms (1980). Imageability was treated as a categorical variable with items greater than 525 classified as high imageability, and items below 525 classified as low imageability. The words were presented in three blocks with each containing an approximately equal number of words from each condition. Words were presented in random order within each block.

Results

1. Effects of Word Length

Figure 2 shows mean pronunciation RTs for correct trials as a function of word length for GM and the control group, as well as for the control subject that displayed the largest effect of word length. The RT data were analyzed with three-way ANOVAs with length

(4-, 5-, 6-, and 7-letters), frequency (high, medium, low), and regularity (regular, irregular) as factors.

GM:

Accuracy

The number of pronunciation errors made did not vary by length (75 - 78% correct for the different lengths; $X^2(3) = .25, p = .97$).

RT

There was a main effect of length in that pronunciation latencies increased as word length increased ($F_i(3, 148) = 9.59, p_i < .001$). A regression line plotted with GM's reading latencies against word length revealed a linear fit ($r = 0.94, p < .06$) with a slope of 1230 ms/letter.

Controls:

Accuracy

Accuracy was greater than 96% in all word length conditions.

RT

There was a main effect of length ($F_i(3, 216) = 2.94, p_i = .03$) in the analysis by items, but the effect did not obtain statistical significance in the analysis by subjects ($F_s(3, 30) = 2.41, p_s = .11$). The slope of the word length function was 13 ms/letter with those for the individual subjects ranging from 8 to 23 ms/letter.

2. Effects of Regularity and Frequency

Figure 3a shows pronunciation accuracy as a function of regularity and frequency for GM, as well as for the least accurate control subject in each regularity condition (collapsed across frequency). Figure 3b shows mean pronunciation latencies for correct trials as a function of regularity and frequency for GM.

GM:

Accuracy

GM was more accurate in pronunciation of regular words (90% correct) than irregular words (62% correct; X^2 (1) = 25.06, $p < .001$). Frequency did not significantly affect the reading accuracy of either regular words (X^2 (2) = 1.67, $p = .44$) or irregular words (X^2 (2) = 2.56, $p = .28$), although his performance was worst with the low frequency irregular items (see Figure 3a). The difference in accuracy between regular and irregular words was larger for the low frequency words (33%) than for the medium frequency (25%) and high frequency (25%) words.

GM's pronunciation errors were classified into four main categories (c.f., Patterson, Suzuki, Wydell, & Sasanuma, 1995): 1) *Legitimate Alternative Reading of Components (LARC) errors* are those in which the pronunciation of the word is phonologically legal but inappropriate to the particular target word. This category includes pure regularizations (e.g., *racquet* = " rack-qu-et"), as well as alternative pronunciations appropriate to a different irregular word with the same spelling pattern (e.g., *through* = "throw", as in *though*), and pronunciations that split a monosyllabic word into two syllables (e.g., *view* = "vee-ew"). The majority of LARC errors were non-words (e.g., *fatigue* = "fa-tie-gue") but the error pronunciation of several target items formed a word (e.g., *sweat* = "sweet"); 2) *Visual-phonological word (VPW) errors* were those in which a different, visually- or phonetically-similar real word was named (e.g., *decade* = "decent"). The error word often shared the initial letters with the target word. In several of the VPW errors, a visually- or phonetically-similar real word was named but the irregular letter sequence was also regularized (e.g., *plaid* = "plate", *ai* regularized). In one of the VPW errors, the target and error pronunciation also had a semantic relationship (i.e., *push* = "punch"); 3) *Visual-phonological non-word (VPNW) errors* were those in which a visually- or phonetically-similar non-word was produced (e.g., *machine* = "mayhin"). VPW and VPNW errors included pronunciations in which a single letter in the target item appeared to have been perceptually misidentified in that the letter in the target item was visually-similar to that in the error pronunciation (e.g., *f* = "h" in *folk* =

"hulk"); and 4) *Other*, contained all other incorrect responses. Proportions of the different error types are shown in Table 3. Error responses are listed in Appendix 3.

RT

There was a main effect of regularity ($F_i(1, 148) = 17.44$, $p_i < .001$) in that GM was faster at naming regular words (4789 ms) than irregular words (7260 ms). Although the frequency main effect ($F_i(2, 148) = 1.0$, $p_i = .37$) and the regularity by frequency interaction ($F_i(2, 148) = .52$, $p_i = .59$) were non-significant, the pattern of results was somewhat meaningful. As can be seen in Figure 3b, the latency advantage for regular over irregular words was larger for the low frequency words (2658 ms) and medium frequency words (2816 ms) than for the high frequency words (2010 ms).

Controls:

Accuracy

Accuracy was greater than 93% in all regularity by frequency word groupings with the least accurate control subject obtaining greater than 92% correct (see Figure 3a).

RT

There was a main effect of regularity in the analysis by items ($F_i(1, 216) = 4.03$, $p_i = .05$), but the effect did not obtain statistical significance in the analysis by subjects ($F_s(1, 30) = 3.86$, $p_s = .11$). Regular words (749 ms) were pronounced more rapidly than irregular words (772 ms). There was also a main effect of frequency ($F_i(2, 216) = 34.21$, $p_i < .001$; $F_s(2, 30) = 5.90$, $p_s = .02$). High frequency words (726 ms) and medium frequency words (740 ms) were read more quickly than low frequency words (817 ms). The regularity by frequency interaction did not reach statistical significance ($F_s(2, 30) = 3.05$, $p_s = .09$; $F_i(2, 216) = 1.81$, $p_i = .17$), but the latency advantage for regular over irregular words tended to be larger for the low frequency words (52 ms) than for the medium frequency (14 ms) or high frequency (3 ms) words. Five of the 6 subjects displayed this interaction pattern to some extent.

3. Effects of Imageability, Frequency, and Length

Imageability analyses used only the subset of words for which imageability ratings were available (n = 167). Four-way ANOVAs with imageability (high, low), frequency (high, medium, low), regularity (regular, irregular), and length (4-, 5-, 6-, and 7-letters) were conducted on the RT data. The frequency by length interactions were assessed in the three-way ANOVAs conducted on the RT data from the full word set (n = 240, same analyses as 1. and 2. above).

GM:

Accuracy

There was no difference in accuracy between high imageability words (50/63, 79% correct) and low imageability words (81/104, 78% correct) collapsed across frequency and regularity. However, for the low frequency-irregular items, accuracy was greater for high imageability words (8/12, 67% correct) than for low imageability words (6/13, 46% correct), although the number of items was clearly too small to obtain statistical significance (X^2 (1) = 1.07, p = .30). There were no differences in accuracy between high and low imageability items in any of the other frequency by regularity word groupings.

RT

The imageability main effect was non-significant ($F_i(1, 79) = 1.32$, $p_i = .25$). However, for the low frequency-irregular items, pronunciation latencies were faster for high imageability words (5884 ms, n = 8) than for low imageability words (10711 ms, n = 6), but not for any of the other frequency by regularity groupings. The imageability by frequency by regularity interaction was not statistically significant though ($F_i(2, 79) = .85$, $p_i = .43$).

The imageability by length interaction was non-significant ($F_i(3, 79) = 2.01$, $p_i = .12$) and the RT differences between low and high imageability items did not appear to increase in any systematic fashion as word length increased; the RT differences between low and high imageability items were -234 ms, -594 ms, 3713 ms, and -727 ms for 4-, 5-, 6- and 7-letter words, respectively.

The frequency by length interaction ($F_i(6, 148) = 1.10$, $p_i = .36$) was statistically non-significant and the RT difference between low and high frequency words did not appear to increase in any systematic fashion as word length increased; the RT differences between low and high frequency items were 160 ms, 2195 ms, -104 ms, and 267 ms for 4-, 5-, 6- and 7-letter words, respectively.

Controls:

Accuracy

There was no difference in accuracy between high imageability words (99% correct) and low imageability words (98% correct) collapsed across frequency and regularity. However, for the low frequency-irregular items, accuracy was slightly greater for high imageability words (99% correct) than for low imageability words (92% correct), although this difference did not reach statistical significance ($F_s(1, 5) = 2.90$, $p_s = .15$). There were no differences in accuracy between high and low imageability items for the other frequency by regularity word groupings.

RT

Imageability did not appear to affect pronunciation latencies overall ($p_i = .68$, $p_s = .28$). However, for the low frequency-irregular items, pronunciation latencies were slightly faster for high imageability words (801 ms) than for low imageability words (832 ms), more so than in any of the other frequency by regularity groupings, but the imageability by frequency by regularity interaction did not obtain statistical significance ($p_i = .16$, $p_s = .34$). The imageability by length ($p_i = .89$, $p_s = .87$) and frequency by length ($p_i = .67$, $p_s = .82$) interactions were clearly non-significant.

Discussion

In this study, GM's reading latencies were very slow, and dramatically increased as word length increased. This word length effect is the defining characteristic of LBL reading. He required more than 1 second per letter on average to pronounce a word, which places him about in the middle of the latency range of previously studied LBL readers. Interestingly, the slope of the word length function levels off for 7-letter words (see Figure 2), suggesting that GM may have been able to guess their identities without processing the final letter (Farah, 1999). In contrast, the controls showed only minimal effects of word length with the slowest subject requiring less than 30 ms per letter on average to pronounce a word. The magnitude of this effect in the control subjects falls within the range found previously in normal readers (Butler & Hains, 1979; Henderson, 1982).

The accuracy of GM's reading was strongly affected by the regularity status of the words; he had much more difficulty naming irregular words than regular words. Although his accuracy for regular words fell only slightly below that of the least accurate control subject, his accuracy for irregular words was clearly impaired relative to controls. This impaired reading of irregular words is diagnostic of surface dyslexia. GM's advantage in accuracy for regular over irregular words was largest for the low frequency items. Although the magnitude of this regularity by frequency interaction is not as strong as that reported in some other surface dyslexics (e.g., Behrmann & Bub, 1992; Patterson & Hodges, 1992), the overall pattern is generally consistent with these cases.

The diminished magnitude of the regularity by frequency interaction may be due, in fact, to the characteristics of the word list itself, rather than to differences between GM and these other cases. High frequency words in the current study were considerably less familiar than those used in previous studies (Behrmann & Bub, 1992; Patterson & Hodges, 1992) and may not have been sufficient to facilitate GM's pronunciation of the irregular items; if higher frequency words had been employed, his accuracy for high-frequency irregular items may have been greater, and thus the strength of the interaction may have increased. Consistent with this explanation, Watt, Jokel, and Behrmann (1997) found that their surface dyslexic showed a clear regularity by frequency interaction on the word list used by Patterson and Hodges (1992), but not on a second list that had a mean high frequency count comparable to that in the present study.

GM's response latencies for the words that he pronounced correctly followed a pattern similar to that found in the accuracy data; he was considerably faster at naming regular words than irregular words. Although the frequency by regularity interaction was statistically non-significant, the latency advantage for regular over irregular words was largest for the low and medium frequency words. Five of 6 control subjects also showed this pattern to some extent.

The reduced magnitude of this interaction in GM and controls, relative to that found in other normal readers (e.g., Seidenberg, Waters, Barnes, & Tanenhaus, 1984), could be due to several different factors. First, as discussed above for the accuracy results, the relatively low familiarity of the high frequency words may have reduced the size of this effect. Second, when this interaction is found in normal readers, it is usually observed in group means derived from a larger sample size; only about half of individual normal readers display the characteristic form of the interaction (Bernstein & Carr, 1996). Thus, although GM was much less accurate and slower overall at naming words, those that he pronounced correctly seemed to be processed by a mechanism that was similar to that in normal readers.

Surface dyslexia is typically thought to result from damage to the semantic pathway with a subsequent reliance on the phonological pathway in reading words orally (Coltheart & Funnell, 1987; Patterson et al., 1996; Patterson et al., 1985). This phonologically-based reading could potentially lead to response latencies that correlated approximately with the number of letters in a word (Shallice & McCarthy, 1985). Although RTs in reading tasks have not typically been reported in previously studied surface dyslexics, speed of reading in at least one case was related to the number of syllables in a word (Shallice &

Warrington, 1980). Thus, it seemed possible that this phonological strategy, rather than a LBL strategy, could be responsible for the word length effect in GM. A post-hoc regression analysis including the number of letters, graphemes and syllables was attempted to determine which best predicted GM's reading latencies; however, the high intercorrelations (all r values > 0.65) between the variables did not allow these effects to be statistically disentangled.

In theories of surface dyslexia, reliance on the phonological pathway allows for accurate naming of regular words and non-words, but causes irregular words to be "regularized". The nature of GM's reading errors were generally consistent with this notion. About half of his error responses to irregular words were LARC errors; the vast majority of these were regularizations. However, GM made fewer LARC errors than many other surface dyslexics who have been reported to produce regularization errors almost exclusively (> 70% regularizations) (e.g., Behrmann & Bub, 1992; McCarthy & Warrington, 1986; Patterson & Hodges, 1992; Watt et al., 1997).

The other half of GM's error responses to irregular words and all of his error responses to regular words were VPW or VPNW errors; this classification scheme was adopted as it makes few assumptions regarding the origin of the errors. Some of these errors appear to be purely visually based in that letters were substituted for other visually similar letters (e.g., *f* = "h" in *folk* = "hulk"), but many of the errors bear phonological, as well as visual, similarities to the target words, often sharing the initial few letters.

At least some of GM's VPW and VPNW errors could have resulted from phonological approximations of the target words. Patterson and Kay (1982) first described the use of this strategy in two LBL surface alexics who appeared to be successively "trying out pronunciations" to identify words. GM also appeared to use this strategy and was frequently observed to silently "mouth out" several pronunciations before actually vocalizing a response. His subjective impression of how he reads also suggests the use of this strategy. GM claims that he first "looks at" the letters of words, sequentially from left to right, and then "sounds out" the word until he finds a pronunciation that "fits", which may take several attempts or more. The fact that many of his error responses were words (28/57, 49%), rather than non-words, is consistent with this notion if GM bases the "fit" of a response pronunciation on whether it is a word or not. Errors that were words were pronounced much faster (mean of 7665 ms) than errors that were non-words (mean of 21293 ms) which suggests that GM may stop "trying out pronunciations" after he generates a plausible word.

The use of a phonological approximation strategy may also explain why a smaller proportion of GM's errors were regularizations compared to other surface dyslexic cases. Since pure regularizations of irregular words usually form non-words, GM may have attempted to "edit" (c.f., Hanley & Kay, 1992) his responses somewhat to pronounce items which he recognized as words. Several previous cases have been reported to use this strategy (Coltheart & Funnell, 1987; Katz & Sevush, 1987). Coltheart and Funnel verified its use by administering a mixed list of words and non-words to read. In this task, where an "editing" strategy was no longer helpful, their patient made an increased number of regularization errors, whereas few errors of this type had been made in pure lists of words. Unfortunately, there was no opportunity to perform this experiment with GM.

This study also provided an opportunity to examine the effects of imageability on word pronunciation. Imageability effects are generally considered to reflect processing in the semantic pathway. Although the number of items with imageability ratings was too small to allow for definitive conclusions, both GM and controls tended to be faster and more accurate in naming high imageability words, compared to low imageability words, when the items were irregular and low in frequency. These findings are consistent with those of Strain, Patterson, and Seidenberg (1995) who obtained the same pattern of results in RTs and accuracy in normal readers. They concluded that imageability facilitates the naming of low frequency-irregular words because processing of these words is particularly dependent on the semantic pathway. Results from GM suggest that despite having a disorder that is considered to result from damage to the semantic route (i.e., surface dyslexia), he still may be able to utilize this route, at least to some extent, to read words.

However, the magnitude of the word length effect in GM did not appear to be affected by imageability or frequency, in contrast to the findings of Behrmann and colleagues (1998b; as well as the imageability results of Buxbaum & Coslett, 1996). These investigators had proposed that the longer LBL readers take to process words, the more time is available for lexical level variables, such as imageability or frequency, to influence performance. This inconsistency can be explained in a number of ways. First, it is again important to note that the current word list was not specifically designed to assess this issue; some of the word length – imageability conditions contained a relatively small number of items. Second, the frequency bands used in the current list were different than those used by Behrmann and colleagues; their cut-off for frequency was 20 per million, with items above that classed as high frequency, and items below that classed as low frequency. When GM's data were re-analyzed according to this frequency scheme, however, the difference between low- and high-frequency words still did not appear to increase as word length increased (i.e., RT differences were 396 ms, 1576 ms, 400 ms, and –702 ms for 4-, 5-, 6- and 7-letter words, respectively).

The final way to resolve the discrepancy between GM and the LBL readers studied by Behrmann and colleagues is to assume that there are individual differences between the cases in terms of their underlying cognitive deficits. These authors suggested that, in addition to a prelexical impairment, some LBL readers may have a deficit at a later stage of the reading system that determines the extent of the lexical level effects. This is an interesting issue to consider with respect to GM since his surface dyslexia suggests the presence of an impairment along the semantic pathway and none of the cases studied by Behrmann and colleagues were reported to have this additional deficit. However, the finding that GM's word naming appeared to be influenced by imageability and frequency, albeit non-significantly, suggests that access to later stages of the reading system may be at least partially intact. A further investigation using an appropriately designed word list is needed to establish whether the effects of these variables, and their interaction with word length, is different in GM relative to other LBL readers.

Experiment 2: Non-Word Pronunciation

Background

In the previous experiment, GM was slower and produced more errors in reading irregular words, relative to regular words, with a significant proportion of these errors taking the form of regularizations. These findings are indicative of surface dyslexia and suggest that GM relies primarily on the phonological pathway to read words orally. However, it was difficult to assess his ability to effectively use this process as his pronunciations also appeared to reflect the influence of an "editing" strategy in which he attempted to generate responses which he recognized as plausible words. Thus, the first purpose of this study was to assess GM's ability to use the phonological pathway to compute pronunciations when an "editing" strategy was no longer appropriate. This was investigated by the use of novel letter strings (i.e., non-words) whose pronunciation depends wholly on the operation of the phonological route. Accurate reading of non-words would suggest that the phonological pathway is relatively intact.

As was also demonstrated in the previous experiment, GM's pronunciation latencies increased markedly as the length of the words increased. Word length effects in LBL readers are generally assumed to arise from a strategy of identifying each letter sequentially. However, as mentioned previously, it also seemed plausible that phonologically-based reading could lead to word length effects (Shallice & McCarthy, 1985). In fact, non-words show much larger effects of length than do words in normal readers (Weekes, 1997). Thus, the second purpose of this study was to assess whether GM's use of the phonological route could account for his word length effect. Comparison of his non-word and word reading latencies with those of the control subjects should shed some light on this issue. If GM's word length effect is due to the process of computing pronunciations from orthography, and this component of his reading system is functioning normally, then the magnitude of his length effect with non-words and words should be comparable to that of the control subjects with non-words, since they both are unable to utilize lexical or semantic processes in this task.

Method

The stimuli consisted of 240 items that were 4-, 5-, 6- and 7-letters in length (see Appendix 4). Half of the items were words and half were pronounceable nonwords. Thus, there were 30 words and 30 non-words of each length. The words were medium-to-high in frequency (> 20 per million; Kucera & Francis, 1967) and had regular spelling-to-sound correspondences. Specific frequency counts were matched across the word-length conditions. Thirteen of the words had also been used in Experiment 1. The non-words were derived from the words by changing the first one or two letters, preserving the body of the word. Words and non-words were run in separate blocks (2 blocks per condition), with each block containing an equal number of items of each length. Items were presented in random order within each block. To minimize repetition effects, items that shared the word bodies were administered in different sessions at least one week apart. In scoring accuracy of the pronunciations, a non-word was accepted as correct if it was assigned a pronunciation that occurs in some real word with that same orthographic pattern.

Results

Figure 4 shows mean pronunciation latencies for correct trials as a function of item length and item type (words, non-words) for GM and the control group, as well as for the control subject that displayed the largest effect of length for non-words (the maximum length function for words overlay the group mean). The RT data were analyzed with two-way ANOVAs with length (4-, 5-, 6- and 7-letters) and item type (words, non-words) as factors.

GM:

Accuracy

GM made more pronunciation errors with non-words (13%) than with words (6%; X^2 (1) = 3.90, p = .05). Length did not significantly affect the pronunciation accuracy of either words (X^2 (3) = 2.88, p = .41) or non-words (X^2 (3) = 1.15, p = .76).

One of GM's non-word errors was of the VPW type (i.e., *touth* = "tough") and involved substituting a visually-similar irregular word for the non-word target. The remainder of his non-word errors were of the VPNW type and included responses in which a single letter appeared to have been deleted (e.g., *banager* = "banage") or substituted for another visually-similar letter (e.g., *sarm* = "sarn"; *yent* = "quint"). Other VPNW errors appeared to involve substituting a larger component of the target item for a visually- or phonetically-similar response (e.g., *chretch* = "ker-retch"; *flain* = "flean"). In 78% of his non-word responses, he assigned the regular pronunciation to the target item (i.e., his pronunciation followed spelling-to-sound rules and rhymed with the regular word from which it was derived). These responses were scored as correct. However, in 9% of his non-word responses, he assigned an irregular pronunciation to the target item (e.g., *plave* = "plahve" as in "have") or split a monosyllabic item into two syllables (e.g., *rait* = "ra-it"). These responses were also scored as correct. All of his word errors were of the VPW type. Word and non-word error responses are listed in Appendix 5.

RT

There were main effects of length (F_i(3, 197) = 25.94, p_i < .001) and item type (F_i(1,197) = 7.55, p_i = .007) but no interaction between the two factors (F_i(3, 197) = 1.12, p_i = .34). Slopes of the word and non-word functions were 794 ms/letter (r = 1.0, p = .002) and 593 ms/letter (r = .96, p = .04), respectively. Overall, he was faster at naming words (3574 ms) than non-words (4036 ms).

Controls:

Accuracy

Control subjects made more pronunciation errors with non-words (12%) than with words (O%) ($t_s(5) = 3.25$, $p_s = .02$).

The majority of errors were of the VPNW type (69% of errors) and included responses in which a single letter appeared to have been inserted (e.g., *tave* = "trave"), deleted (e.g., *flortly* = "florty"), substituted for another visually-similar letter (e.g., *nolid* = "nolit"), or transposed within the target item (e.g., *gilver* = "gliver"). Other VPNW errors appeared to involve substituting a larger component of the target item for a visually- or phonetically-similar response (e.g., *mectory* = "me-tree"). Thirty-one percent of the error responses were of the VPW type. That is, subjects pronounced a non-word as a visually- or phonetically-similar word, usually preserving the first few letters of the target non-word (e.g., *macket* = "market"; *rettle* = "riddle"; *brame* = "brain").

RT

There was an interaction between length and item type ($F_s(3, 15) = 3.24$, $p_s = .05$; $F_i(3, 232) = 7.22$, $p_i < .001$). Analyses of the simple effects showed that non-words took longer to pronounce than words at all lengths ($p_s < .003$, $p_i < .001$). As well, naming latencies significantly increased with length when the items were non-words ($p_s = .04$, $p_i < .001$) but not when they were words ($p_s = .38$, $p_i = .98$). The slope of the word function was 4 ms/letter. In contrast, the slope of the non-word function was 68 ms/letter ($r = 0.95$, $p = .05$). However, the slope of the non-word function for the control subject with the largest length effect (196 ms/letter) was still much smaller than that in GM (see Figure 4).

Discussion

GM's accuracy in pronouncing non-words (13% errors) was very similar to that of the control group (12% errors). Error rates for the control subjects varied considerably (1 to 26%), as in previous reports that showed normal readers to have markedly different skill levels in non-word reading (Masterson, 1985). GM's normal level of accuracy in non-word reading suggests that his phonological pathway is relatively intact, consistent with the typical conceptualization of surface dyslexia.

Almost all of GM's errors to non-words were of the VPNW type, and all of his errors to words were of the VPW type. Controls also made VPNW errors to non-words, but they produced a significant number of VPW errors as well. This implies that GM is quite skillful at manipulating his phonological output to suit the demands of the reading task. That is, he is able to vary his responses based on his knowledge of whether words or non-words are expected from him. This is consistent with the suggestion in the previous study that strategy is an important determinant of his reading responses.

In the majority of GM's correct responses to non-words, he utilized the regular spelling-to-sound correspondences. A number of his pronunciations, however, contained irregular correspondences. This suggests that GM is not bound to the use of a fixed set of spelling-to-sound rules, which is a characteristic of some reading models, most notably the traditional "dual-route" model (Coltheart, 1978; Coltheart, 1985). Rather, it implies that the spelling-to-sound computations occurring within the phonological route are influenced by other factors, including knowledge of less frequent correspondences that occur in other words (Plaut et al., 1996; Seidenberg, Plaut, Petersen, & McClelland, 1994).

GM took significantly longer to read items as the number of letters increased, regardless of whether the items were words or non-words; the magnitude of the length effect was comparable in the two item sets. This suggests that a similar factor was responsible for the length effect in both words and non-words, but does not determine whether the effect was due to phonologically-based reading. GM was faster overall at naming words, compared to non-words, which implies that some form of lexical or semantic information was available to facilitate his responses. Control subjects also showed a significant latency advantage for words. Interestingly, although the reading speed of the controls was not affected by length when the items were words, their responses did show a length effect when the items were non-words. This may reflect the operation of a serial mechanism that computes non-word pronunciations from orthography (Weekes, 1997). It is important to note, however, that the length effects in GM far exceeded those found in any of the control subjects (see Figure 4), indicating that GM's length effect in words is not due solely to the use of an *intact* phonological reading process. If use of the phonological pathway is responsible for his word length effect, then the rate at which it operates must be significantly slowed relative to controls, while the process must be sufficiently intact such that it generates accurate output.

Experiment 3: Pronunciation of Words Presented Letter-by-Letter

Background

In the previous two experiments, GM's pronunciation latencies dramatically increased as the length of the words increased. Based on observations of GM's reading, it appeared that at least part of the strategy that he used to pronounce words involved "trying out" different pronunciations until he found a word that "fit" (c.f., Patterson & Kay, 1982). Although GM claimed that he first identified the letters sequentially from left to right before using this pronunciation strategy, it seemed plausible that this phonological approximation strategy could result in the word length effect. That is, the time required to "try out pronunciations" may have increased as the number of letters in a word increased because longer items take longer to pronounce and/or because there may be more plausible pronunciations that can be applied to longer items. Thus, use of a phonological approximation strategy could lead to response latencies that were approximately in line with the number of letters in a word.

The purpose of the following experiment was to assess whether the word length effect in GM was due to identifying letters sequentially from left to right, or whether it was due to "trying out" different pronunciations based on whole-word representations. Words varying in length were presented one letter at a time, with the preceding letters remaining in view. GM was asked to pronounce each item after the final letter was presented.

Words were presented at a rate of 800 ms per letter since this was the average rate that GM required to pronounce regular, medium-to-high frequency words in the previous experiment. It was hypothesized that if the word length effect was due only to the use of a serial letter identification strategy, then presenting letters in a LBL fashion should make this strategy unnecessary, and thus a word length effect should not be present. However, if the word length effect, or a portion of it, resulted from a process that was applied to the entire word (i.e., attempting pronunciations of words), then the word length effect should still be present with the LBL presentation mode.

Method

The stimuli consisted of 80 medium-to-high frequency words (> 20 per million; Kucera & Francis, 1967) with regular spelling-to-sound correspondences that were 4-, 5-, 6-, and 7-letters in length (20 words of each) (see Appendix 6). Specific frequency counts were matched across the word-length conditions. Eighteen of the words had also been used in Experiments 1 or 2. The experiment was run in two blocks with an equal number of words of each length in each block. Each trial consisted of a horizontal sequential display of letters that formed a word. Each letter was presented for 800 ms before the next letter appeared. All letters stayed on the screen after they were presented. After the last letter of the word had been presented, the word was immediately masked with a row of upper case black X's, and this mask stayed on the screen until an oral response was made. The following is an example of a display sequence:

w   wo   wor   word XXXXXXX

GM was instructed to pronounce the word as quickly as possible after the mask was displayed. Vocal response latencies from the onset of the mask were measured. Control subjects were not tested in this experiment.

Results and Discussion

GM made more pronunciation errors in this study (14/80, 17% of trials) than in previous experiments that did not use a LBL display. This is likely due to the fact that the 800 ms/letter rate represents the average length of time that he required to pronounce similar words with unlimited exposure durations. Words that would have required a longer period of time to pronounce may not have had sufficient time to be processed in the LBL display mode, and thus generated errors. Errors were similar in type to previous experiments and included VPWs (7/14 errors) and VPNWs (3/14) errors, as well as "do not know" responses (4/14 errors) (error responses listed in Appendix 7). Pronunciation accuracy did not differ significantly across the lengths (X^2 (3) = 3.12, p = .37).

Figure 5 shows GM's RTs for correct trials (with percentage of correct responses) as a function of word length with the LBL display, as well as with the typical full display format for regular words from Experiment 2. The LBL latency data were analyzed with a one-way ANOVA with length (4-, 5-, 6-, and 7-letters) as a between-items factor. There was no effect of length ($F_i(3, 59) = 1.73$, $p_i = .17$). GM's increased error rate cannot account for the lack of a word length effect with the LBL display mode because accuracy did not differ with length. The lack of a word length effect with the LBL display mode suggests that the use of a serial, left-to-right processing strategy may account for the presence of the effect with the full word display format, and that the effect does not likely result from a process that is applied to the entire word (i.e., "trying out pronunciations"). However, as can be seen in Figure 5, his overall response latencies were slow (1479 ms averaged across lengths). That is, GM still seemed to require an abnormally long period of time to compute pronunciations *after* visual encoding of the letters had occurred. This increased time could reflect GM's use of the phonological approximation strategy. However, the important point here is that this process did not appear to be affected by the length of the word.

Experiment 4: Lexical Decision

Background

The first purpose of this experiment was to determine whether GM used a LBL strategy when word recognition, but not pronunciation, was required. Several patients have been able to distinguish words from non-words, known as lexical decision, too quickly to have allowed for use of the LBL procedure (e.g., Bub & Arguin, 1995; Coslett & Saffran, 1989; Coslett et al., 1993; Shallice & Saffran, 1986). Some investigators have attributed this preserved ability to residual functioning in the normal reading system that allows for partial word-level activation, but not normal word naming (Behrmann et al., 1998b; Bub & Arguin, 1995). Others have suggested that this finding reflects the operation of a different system that does not play a major role in normal word reading, and that is likely based in the right-hemisphere (Buxbaum & Coslett, 1996; Coslett & Saffran, 1989; Coslett et al., 1993; Saffran & Coslett, 1998). Not all LBL readers have displayed this preserved ability, however (e.g., Behrmann & Shallice, 1995; Howard, 1991).

The second purpose of this experiment was to help assess the underlying impairment that may have been responsible for GM's symptoms of surface dyslexia. Normal readers are generally thought to perform lexical decisions using the semantic pathway since their RTs are not affected by the regularity status of the words (Coltheart, Besner, Jonasson, & Davelaar, 1979; Seidenberg et al., 1984); their decisions may be based on either orthographic (Coltheart et al., 1979; Coltheart et al., 1993) or semantic (Plaut et al., 1996) information. Thus, if GM's surface dyslexia arises from damage to the semantic pathway (either in orthography or semantics), and he is forced to rely on the phonological pathway, then his performance in lexical decision should be affected by regularity in the same way as it is affected in pronunciation (i.e., irregular words less accurate than regular words). However, if his surface dyslexia results from damage further along the semantic pathway, such as in accessing phonology (e.g., Kay & Patterson, 1985), then his lexical decision performance should not be influenced by regularity, since his decisions can still be based on the orthographic and/or semantic information that is available.

Method

The stimuli consisted of 240 items. Half of the items were words and half were non-words. The words were taken from Experiment 1 (i.e., half of the words from each condition). Thus, half of the words were regular and half were irregular, and there were equal numbers of each of the four word lengths. A second list of words was matched to this list for length, regularity, and frequency and letters in these words were altered to create the non-words. One letter was changed in the 4- and 5-letter words and two letters were changed in the 6- and 7-letter words. The changes were made in the last three letter positions with the exception of some irregular words where the changes were made in earlier letter positions in order to preserve the orthographically irregular letter combinations. The items were presented in three blocks with each containing an equal number of words and non-words, and approximately equal numbers of items of each length. Items were presented in random order within each block. Subjects indicated whether items were words or non-words, as quickly as possible, by manual key presses. Items remained on the screen until a response was made. The stimuli are included in Appendix 8.

Results

Figure 6a shows lexical decision accuracy as a function of item length and item type (irregular words, regular words, non-words) for GM. Figure 6b shows mean lexical decision RTs for correct trials as a function of item length and item type for GM and the control group. The RT data were analyzed with two-way ANOVAs with length (4-, 5-, 6-, and 7-letters) and item type (words, non-words) as factors. Additional two-way ANOVAs with length (4-, 5-, 6-, and 7-letters) and regularity (regular, irregular) as factors were carried out on the RT data for the words only.

GM:

Accuracy

Overall, GM made more errors with words (33%) than with non-words (10%; X^2 (1) = 19.57, $p < .001$), and more errors with irregular words (43%) than with regular words

(24%; X^2 (1) = 19.57, $p < .001$) (see Figure 6a). The differences in accuracy between the item types varied as a function of length. At length 4, there were no differences between the item types (X^2 (2) = 1.15, $p = .56$). At length 5, irregular words were less accurate than regular words (X^2 (1) = 3.97, $p = .05$) and non-words (X^2 (1) = 7.78, $p = .005$). At length 6, irregular words were worse than non-words (X^2 (1) = 12.85, $p < .001$) but not significantly worse than regular words (X^2 (1) = 2.04, $p = .15$), and regular words were worse than non-words (X^2 (1) = 3.78, $p = .05$). At length 7, both regular words (X^2 (1) = 8.18, $p = .004$) and irregular words (X^2 (1) = 10.60, $p = .001$) were less accurate than non-words. To summarize, accuracy was high for all item types at length 4. As length increased, accuracy of regular and irregular words declined. The start of the accuracy decline was at length 5 for irregular words and at length 6 for regular words. Accuracy of non-words was consistently high across all lengths.

RT

In the analyses of the RT data, there were main effects of item type ($F_i(1, 172) = 11.39$, $p_i = .001$) and length ($F_i(3, 172) = 12.60$, $p < .001$) (see Figure 6b). Overall, he responded faster to words (4928 ms) than to non-words (6065 ms). Response latencies to 4- and 5-letter items were faster than to 6- and 7-letter items ($p_i < .008$ in all comparisons); however, there was no difference between 4- and 5-letter items ($p_i = .75$), and RTs to 7-letter items were faster than to 6-letter items ($p_i = .03$). Thus, the relation between RTs and item length was not strongly linear ($r = 0.69$, $p = .31$). The analysis conducted on the word data found a significant length effect ($F_i(3, 69) = 6.70$, $p_i < .001$) and marginal regularity effect ($F_i(1, 69) = 2.83$, $p_i = .09$). Overall, RTs were greater for irregular (5306 ms) than for regular (4644 ms) words.

To compare overall RTs in lexical decision (words only) and pronunciation (from Experiment 1), a three-way ANOVA with length (4-, 5-, 6-, and 7-letters) and regularity (regular, irregular) as between-items factors and with task (lexical decision, pronunciation) as a within-items factor was conducted. As in the previous analyses, there was a significant effect of word length ($F_i(3, 51) = 2.68$, $p_i = .05$). However, the regularity effect was not statistically significant ($F_i(1, 51) = 1.34$, $p_i = .25$), likely because of the fewer number of observations that were available for both tasks. The main effect of task ($p_i = .22$) and the interactions between task and length ($p_i = .50$), and between task and regularity ($p_i = .85$) were all non-significant.

Controls:

Control subjects made few errors (3% of trials). There were main effects of item type in the analyses by subject ($F_s(1, 5) = 10.78$, $p_s = .02$) and by item ($F_i(1, 232) = 64.54$, $p_i < .001$) with greater RTs for non-words (1007 ms) than words (822 ms) (see Figure 6b). There was also a main effect of length in the items analysis ($F_i(3, 232) = 2.82$, $p_i = .04$), although the slopes of the function were relatively small (group mean = 9.69 ms/letter; maximum individual slope = 38 ms/letter). There were no significant effects of length or regularity in the analyses carried out on the word data ($p > .20$).

Discussion

GM's response latencies in lexical decision were extremely slow and generally tended to increase as item length increased. In contrast, control subjects showed only minimal length effects that were in the range of those reported previously in normal readers (Henderson, 1982). A direct comparison of the lexical decision and pronunciation data from Experiment 1 showed that GM's overall response latencies and word length effects were roughly comparable in the two tasks. This suggests that GM employed the same LBL strategy to make lexical decisions as he did to pronounce words, consistent with findings from a number of LBL readers previously studied (e.g., Behrmann & Shallice, 1995; Howard, 1991). However, results from GM differ from those obtained in other patients who were able to rapidly perform lexical decisions without using the LBL procedure (e.g., Bub & Arguin, 1995; Coslett & Saffran, 1989; Coslett et al., 1993; Shallice & Saffran, 1986).

It is important to note, however, that the discrepancy between GM and the LBL readers who were able to perform lexical decisions rapidly may be attributable to differences in patient strategy rather than in the primary impairment. When administering lexical decision tasks, patients may need to be actively discouraged from using the LBL procedure that they typically rely on for explicit word identification, and instead prompted to adopt a more wholistic strategy that may be mediated by the right hemisphere (for a fuller description of this strategy see Coslett & Saffran, 1989; Coslett & Saffran, 1994; Coslett et al., 1993; Saffran & Coslett, 1998). The version of the lexical decision task administered to GM may not have been optimal for promoting the use of this wholistic strategy, in that the items were exposed for an unlimited duration; stimuli may need to be briefly-presented at durations that do not permit use of the LBL procedure. Assessment of GM's ability to rapidly access word-related information (lexical and semantic) with this type of task methodology would be an interesting line of future research.

Although GM's response latencies in lexical decision tended to increase as item length increased, the length functions were non-linear, and GM actually responded faster to 7-letter items than to 6-letter items. This result differed from the reasonably linear relationships between length and pronunciation latencies that were obtained in previous experiments (see Figures 2 and 4), and suggests that he may have guessed the lexical status of some items without fully processing all of their letters. That accuracy tended to decrease as word length increased (see Figure 6a) supports this proposal. The decline in accuracy with increasing length was greatest for irregular words, suggesting that GM had particular difficulty distinguishing them from non-words. In contrast, accuracy for non-words of all lengths was consistently high, likely reflecting a bias toward non-word decisions. Accuracy with words in lexical decision may have been reduced relative to that in pronunciation because in the latter task GM knew that he had to pronounce a word and thus would continue to "try out pronunciations" (c.f., Patterson & Kay, 1982) until he generated a plausible response (see Experiment 1). In lexical decision, however, this constraint was not present and if he was not able to produce a suitable word, he classified it as a non-word.

Overall, GM was faster and more accurate at lexical decisions for regular words, relative to irregular words, consistent with his pronunciation data in Experiment 1. Control subjects, by contrast, did not show a regularity effect in their RTs in lexical decision but did in pronunciation, in keeping with results from other normal readers (Coltheart et al., 1979; Seidenberg et al., 1984). These findings suggest that GM relied on the phonological pathway to perform both tasks, whereas controls made lexical decisions via the semantic pathway using either orthographic (Coltheart et al., 1979; Coltheart et al., 1993) or semantic (Plaut et al., 1996) information. It seems most likely that GM used this different strategy because he had sustained damage to the semantic route, in either orthographic or semantic systems.

Experiment 5: Lexical Decision with Pseudohomophones

Background

To further confirm that GM relied on the phonological pathway to perform lexical decisions because of damage to the semantic pathway, a lexical decision task with pseudohomophones was administered. Because these stimuli sound like real words (e.g., "brane"), subjects are required to use the semantic route to make correct decisions. If only the phonological route is employed, they would be falsely accepted as words, and the error rate for pseudohomophones would be considerably greater than that for non-words or words.

Method

The list consisted of 160 items that were 4- or 5-letters in length. Forty of the items were pseudohomophones (i.e., non-words constructed to be homophonic with a word). The pseudohomophone base words were medium-to-high frequency (> 17 per million). Forty of the items were pronounceable non-words which were constructed by substituting the first grapheme of each pseudohomophone with another grapheme. Eighty of the items were regular words that were matched to the pseudohomophone base words in frequency and number of letters. Pseudohomophones and non-words were taken from other sources (Mayall & Humphreys, 1996; McCann & Besner, 1987). Items were presented in random order. Subjects indicated whether items were words or non-words by manual key presses. Items remained on the screen until a response was made. This experiment was self-paced and only accuracy data were collected since the primary hypothesis related to this dependent variable. The stimuli are included in Appendix 9.

Results and Discussion

Table 4 contains the percentage of correct items for each condition for GM and the control group, as well as the range in accuracy for control subjects. Accuracy in the control group was analyzed with a one-way repeated measures ANOVA. Accuracy was consistently high for controls in all conditions and there was no significant difference between the conditions ($F_s(2,10) = 2.02$, $p_s = .18$). For GM, accuracy was lower in the non-word condition compared to the word condition ($X^2\ (1) = 4.87$, $p = .03$), and in the pseudohomophone condition compared to the non-word condition ($X^2\ (1) = 26.87$, $p < .001$). His performance was the worst in the pseudohomophone condition. GM's accuracy in all conditions fell below the range of the control subjects, particularly in the pseudohomophone condition. His strong tendency to accept pseudohomophones as words suggests that he relied on the phonological pathway to perform lexical decisions because of damage to the semantic pathway.

Summary of Experiments 1 to 5

The previous set of investigations documented the characteristics of GM's acquired dyslexia. The results of the pronunciation (Experiments 1 and 2) and lexical decision (Experiment 4) tasks indicated that his response latencies increased as item length increased. The presence of this word length effect is considered to be diagnostic of LBL reading. Unlike some other LBL readers (e.g., Bub & Arguin, 1995; Coslett & Saffran, 1989; Coslett et al., 1993; Shallice & Saffran, 1986), GM relied on the same laborious decoding strategy in making lexical decisions as he did in pronouncing words. However, this discrepancy may be attributable to differences in patient strategy rather than in the primary impairment.

GM's accuracy in these tasks was also strongly affected by the regularity status of the words. He had great difficulty naming and making lexical decisions about irregular words, and many of his pronunciation errors were regularizations. His naming accuracy was worst with irregular words of low frequency, whereas with regular words and non-words he was about as accurate as the control subjects. In making lexical decisions, he tended to accept pseudohomophones as words (Experiment 5). This pattern of results is indicative of surface dyslexia, and is consistent with the notion that the disorder is due to damage along the semantic pathway. Thus, GM appears to suffer from a disorder that has been termed LBL surface alexia (Friedman & Hadley, 1992) or type 2 LBL reading (Patterson & Kay, 1982). Although precise neuroanatomical data were not available, GM's large left temporal-occipital lesion likely included the areas deemed to be critical for LBL reading (i.e., left inferior occipital lobe) and surface dyslexia (i.e., left superior and middle temporal gyri) (Black & Behrmann, 1994), accounting for the co-occurrence of these two syndromes.

Word length effects in LBL readers are widely assumed to arise from a serial letter identification strategy. However, given GM's accompanying surface dyslexia and likely reliance on a phonologically-based reading strategy, it seemed possible that this process in itself could be responsible for the word length effect. GM's length effect with non-words, however, far exceeded that found in any of the control subjects (Experiment 2). Therefore, it was concluded that if a phonologically-based process was responsible for his word length effect, then the rate at which it operated must be significantly slowed relative to controls. It was also suggested that GM's apparent strategy of "trying out pronunciations" (c.f., Patterson & Kay, 1982) could have resulted in the word length effect. However, the lack of a length effect with the LBL display mode (Experiment 3) implied that the presence of the effect with the typical display format did not likely result from "trying out pronunciations", since this strategy would have been applied to the entire word after all of the letters had been presented. Taken together, these results are most consistent with the notion that GM's word length effect was due to the use of a serial letter identification process, in keeping with the typical conceptualization of this disorder, as well as GM's own subjective reports. It remains unclear though what premorbid mechanism(s) necessary for reading were damaged in GM and therefore why he was required to use this LBL procedure. The next set of investigations address several hypotheses concerning the cognitive deficit that may have caused him to rely on this reading strategy.

Experiment 6: Letter Matching

Background

One version of the orthographic hypothesis proposes that LBL reading is a strategy adopted to compensate for a deficit in processing the abstract identities of letters. The letter matching task of Posner (1967) has been frequently used to assess this ability, as the nominal match component (NI, e.g., Aa) is considered to reflect abstract letter processing (Besner et al., 1984; Coltheart, 1981a; Mozer, 1989; Rynard & Besner, 1987). A number of investigators have claimed that LBL readers are disproportionately impaired at NI matching, over physical matching (PI, e.g., AA), relative to normal control subjects (Arguin & Bub, 1994b; Behrmann & Shallice, 1995; Hanley & Kay, 1996; Kay & Hanley, 1991; Reuter-Lorenz & Brunn, 1990). The difficulty that arises in this interpretation, however, is that most of these patients also performed PI matches markedly slower than control subjects. Thus, it seemed possible that the smaller differences between the PI and NI conditions in the controls may have been due to floor effects in their RTs.

Furthermore, the strategy by which LBL readers perform NI matches has not yet been determined. It is not clear if they classify the letters, albeit slowly, based on their abstract representations, or if they have a deficit that completely precludes this type of processing. It could be the case that LBL readers can only accomplish the NI matching task by mapping the letters onto their corresponding pronunciations. That is, they may determine that "A" and "a" are the same because they sound the same. It is fairly clear that normals can perform NI matches without phonological coding, at least when the two letters are presented simultaneously (Boles & Eveland, 1983), although this strategy may be used when the two letters are presented sequentially (Dainoff, 1970; Dainoff & Haber, 1970; Thorson, Hochhaus, & Stanners, 1976). These studies determined whether a phonological code was in use by manipulating the phonetic confusability of the different letter pairs (e.g., "Aj" is more confusable than "Ac"); the assumption was that if letters were coded into their phonological forms, then the presence of phonetically confusable pairs should disrupt or slow the matching process.

The purpose of the following experiment was to examine whether GM has a deficit in abstract letter processing that causes him to rely on the phonetic codes of letters. This notion was tested using a variant of the letter matching task of Posner (1967) with a phonetic confusability manipulation. To minimize scaling artifact in the RT data, his results were compared to those from a group of brain-damaged control subjects, who were expected to perform the task slower than normal controls. It was hypothesized that if GM was unable to perform simultaneous NI matches based on the abstract identities of the letters, and instead relied on the phonological representations of the letters, then phonetic confusability should disrupt his performance. The possibility that LBL readers may rely on phonetic codes to perform NI matches was of particular interest in the assessment of GM because of his accompanying surface dyslexia. It was speculated that a reliance on phonology to process both letters and words could lead to the combination of his LBL reading and surface dyslexic symptoms. This type of evidence would have interesting implications for our conceptualization of the normal reading system as it would suggest that letters and words are represented in similar ways.

Method

The stimuli and method were adapted from Boles and Eveland (1983). In each trial, two horizontally adjacent letters were simultaneously presented. Upper- and lower-case versions of 10 letters were used (A, B, C, F, I, J, Q, S, U, and Y). They were combined to form 120 letter pairs as follows: (1) 20 PI pairs (e.g., AA, aa); (2) 20 NI pairs (e.g., Aa); (3) 40 phonetically confusable differents (i.e., AJ, BC, FS, IY, QU); and (4) 40 phonetically nonconfusable differents (i.e., AC, BS, FY, IU, QJ). Phonetic confusability was determined according to Conrad (1964). In the two types of different pairs, each pair member could be in 1 of 2 cases, and the members could be in 1 of 2 orders, resulting in 40 pairs for each type (5 pairings x 2 cases of first member x 2 cases of the second member x 2 orders). Each subject received 4 blocks of 80 trials. Each block consisted of 20 PI, 20 NI, and 40 different trials. The first two blocks used phonetically nonconfusable differents and the second two blocks used phonetically confusable differents. The first two blocks of each type were preceded by 40 practice trials (1/2 of the experimental items). Stimuli were presented in random order within each block. Subjects indicated whether items were the same or different, as quickly as possible, by manual key presses. Stimuli remained on the screen until a response was made. Subjects were instructed to respond "same" for PI and NI letter pairs.

Results

Figure 7 shows mean RTs for correct trials for the PI (e.g., AA) and NI (e.g., Aa) same matches and for the physical (e.g., AB) and nominal (e.g., Ab) different matches collapsed across confusability block for GM and the control group (bars on control data represent RTs for the slowest control subject in each condition). The RT data were analyzed with three-way ANOVAs with match type (physical, nominal), decision type (same, different), and confusability block (confusable, nonconfusable differents) as factors.

GM:

GM made few errors (1% of trials). In the RT analysis, there was an interaction between match type and decision type ($F_i(1, 297) = 27.67$, $p_i < .001$) with longer RTs for nominal than physical matches when the correct decision type was "same". There was no effect of confusability block ($F_i(1, 297) = .05$, $p_i = .83$), nor any interactions between confusability block and the other factors ($p_i > .30$).

Controls:

Controls made few errors (2% of trials). In the RT analysis, there was an interaction between match type and decision type ($F_s(1,5) = 11.09$, $p_s = .02$; $F_i(1, 312) = 36.81$, $p_i < .001$) with longer RTs for nominal than physical matches when the correct decision type was "same". There was no effect of confusability block ($F_s(1,5) = .81$, $p_s = .41$; $F_i(1, 312) = 3.56$, $p_i = .06$), nor any interactions between confusability block and the other factors ($p > .4$).

Discussion

GM and the control subjects displayed the same qualitative pattern in their matching RTs. Both showed a relative advantage for PI over NI same matches and both types of different matches. This general pattern is consistent with results reported previously in normals (Posner & Mitchell, 1967) and has been interpreted as evidence that PI and NI match decisions are based on different types of codes. However, as can be seen in Figure 7, the difference between NI and PI same matches for GM (501 ms) far exceeded the difference score for the controls (mean = 153 ms, maximum individual difference score = 297 ms). Nevertheless, since GM took considerably longer than even the slowest control subject (see bars on control data in Figure 7) to match all item types, including PI same matches, it seemed possible that the smaller difference score in controls may have been due to a floor effect in their RTs. That is, the difference between NI and PI same matches may have been reduced in controls because PI matches were performed as fast as was possible.

To assess this possibility, the RTs for the PI and NI same matches for GM and the individual control subjects were plotted in Figure 8. This figure clearly shows that as PI match latencies increased so did the NI match latencies. A regression line plotted with NI match latencies against PI match latencies revealed a strong linear relationship between the two variables ($r = 0.96$, $p < .002$). The value of the residuals (i.e., the difference between the observed NI match latency and that predicted by the regression equation) was then used to assess whether GM's NI match latency was substantially greater than the value predicted from his PI match latency. As can be seen in this figure, GM's NI match latency was slightly greater than the predicted value (i.e., his observed value was 53 ms more than the value on the regression line). However, one control subject (Subject 1) showed an even greater discrepancy between their observed and predicted NI match latencies (i.e., value of the residual was 152 ms). This suggests that although GM was substantially slower than all control subjects in performing this task, his ability to perform NI matches was *not* disproportionately impaired relative to his ability to perform PI matches.

These results have important implications for how performance on this type of task has been interpreted in other LBL readers. Figure 9a shows PI and NI same match RTs for GM and all of the LBL readers from the published literature that have been tested previously on this type of letter matching paradigm with RT as the dependent variable (DS: Behrmann & Shallice, 1995; Behrmann, 1999; WL: Reuter-Lorenz & Brunn, 1990; PD and DC: Hanley & Kay, 1996; Kay & Hanley, 1991; DM: Arguin & Bub, 1994b). Since neurologically-intact individuals with considerably faster RTs were used as controls in these previous studies and variability amongst the subjects was not reported (two studies, in fact, had only one control subject: Behrmann & Shallice, 1995; Kay & Hanley, 1991), the data from the LBL readers are compared to that from the brain-damaged controls of the current study (see Figure 9b). Regression lines plotted with NI match latencies against PI match latencies revealed a strong linear relationship between the two variables in both the LBL readers ($r = 0.96$, $p < .002$) and controls ($r = 0.89$, $p < .02$). Importantly, however, the slope of the regression line was *less* in the LBL readers (0.79) than in the controls (1.53). That is, as PI match latencies increased, NI match latencies increased *more* for the control subjects than for the LBL readers. These results contradict previous claims that LBL readers were disproportionately impaired at NI matching over PI matching, relative to normal controls (Arguin & Bub, 1994b; Behrmann & Shallice, 1995; Hanley & Kay, 1996; Kay & Hanley, 1991; Reuter-Lorenz & Brunn, 1990). In fact, these results suggest that the non-dyslexic, brain-damaged controls in the current study were disproportionately impaired at NI matching over PI matching, relative to the LBL readers.

It should be noted that patient DC (Hanley & Kay, 1996) was *not* claimed to be disproportionately impaired at NI matching over PI matching, and like GM, performance in both conditions was considered impaired. However, even if DC and GM are removed from the regression equation, the slope of the line from the remaining LBL readers that *were* claimed by their respective authors to be disproportionately impaired at NI matching was still considerably less (0.88) than that of the brain-damaged controls (1.53).

Although GM's NI matches did not appear to be disproportionately slowed relative to his PI matches, it was still possible that he performed NI matches using a strategy that was qualitatively different than that in control subjects. To help determine the strategy by which GM performed NI matches, the phonological confusability of the different matches was manipulated. The hypothesis was that if GM performed NI matches by coding the letters into their phonological forms, then the presence of phonetically confusable pairs should disrupt or slow the matching process. However, neither GM, nor control subjects, showed an effect of phonetic confusability (in accuracy or RT). This finding is consistent with that reported previously in normals: they do not appear to use a phonological code to match letters that are simultaneously presented (Boles & Eveland, 1983), although they may use this code to match letters that are sequentially-presented (Dainoff, 1970; Dainoff & Haber, 1970; Thorson et al., 1976). If GM did not use a phonological code to perform letter matches, then it could be argued that, by default, he must have relied on some type of stored information about the abstract identity of letters to perform NI matches. Unfortunately, however, this conclusion cannot be made with complete certainty as neither GM nor control subjects were tested with sequentially-presented letters, and thus the effectiveness of phonetic confusability as a manipulation of phonological letter coding was not verified. It does imply though that the type of deficit that causes words to be processed phonologically (i.e., surface dyslexia) does not necessarily affect letters.

It could be argued though that the nature of the letter pairs in this study allowed GM to perform some of the NI matches on the basis of a visual code, rather than an abstract code. That is, since a number of the letters had a similar visual appearance for the upper and lower case forms (Cc, Ss, Uu, Yy), it is possible that he performed NI matches of these letters on the basis of their physical characteristics. According to this account, the increased latencies that he required to perform NI matches relative to PI matches would be due to size differences between the upper and lower case letters in the NI match pair. It has been demonstrated in normals that the time to judge two simultaneously presented forms as identical in shape increases as their size difference increases (Bundesen & Larsen, 1975). Thus, it is possible that a deficit in abstract letter processing, indicated by disproportionately greater RTs to NI matches than PI matches, relative to controls, might have been obscured in the data analyses because some of the NI matches did not require abstract codes. This explanation did not seem likely, however, because even when the data were re-analyzed with those from the visually-similar letter pairs removed (i.e., Cc, Ss, Uu, Yy), the RT difference between NI and PI same matches for GM (619 ms for this data subset vs. 501 ms for complete set) was increased in approximate proportion to that of the control subjects (222 ms for this data subset vs. 153 ms for complete set). However, both GM and controls showed a larger RT difference between NI and PI matches when the upper and lower case forms of the letters were visually dissimilar, suggesting that visual similarity can facilitate the matching of NI letter pairs.

Thus, to conclude, GM appears to have a letter processing deficit that affects his ability to match letters. However, he was not disproportionately impaired at NI matching, over PI matching, relative to the brain-damaged controls. Moreover, the lack of an effect of phonetic confusability suggests that he performed NI matches on the basis of abstract letter codes. It is important to note that his slowness on the letter matching task is entirely consistent with a general visual processing deficit and does not necessarily reflect a specific letter processing deficit. This notion is explored in later studies (see Experiments 8 and 9).

Experiment 7: Identification of Letters in Rapid Serial Visual Presentation

Background

Another prominent account of LBL reading proposes that the disorder results from difficulty in processing letters simultaneously, and thus letters have to be identified one at a time for word recognition to occur. Moreover, the deficit seems to extend not only to letters that are presented simultaneously, but also to those presented in rapid temporal succession (Behrmann & Shallice, 1995; Kinsbourne & Warrington, 1962). Behrmann and Shallice (1995; see also Behrmann, 1999) based this conclusion on results from a RSVP paradigm in which items were displayed individually in rapid succession all in the same spatial location. Two letters were embedded at varying positions in a stream of digits. After each item stream was presented, subjects were required to report the identities of the two letters. Behrmann and Shallice found that their LBL reader was often able to report the identity of the first letter, but that they required more time than was normal to identify the second letter as well. Specifically, when the SOA between the two letters was 100 ms or 400 ms, the LBL reader was worse than a control subject at reporting the second item; however, when the SOA was increased to 800 ms, their performances did not differ.

RSVP paradigms have proved to be a useful tool for studying the temporal characteristics of the normal visual system. Individuals without neurological damage also show a transitory processing deficit, known as the "attentional blink", in which identification of the second of two targets is impaired if it is presented within about 400 ms of the first (e.g., Duncan, Ward, & Shapiro, 1994; Raymond, Shapiro, & Arnell, 1992). Given that the version of the task used by Behrmann and Shallice included only three, widely-spaced SOA conditions and only one control subject was tested, their conclusion that the LBL reader was uniquely impaired on this task may not be fully warranted; a deficit up to the 400 ms SOA would be expected based on results in the normal literature. Thus, the following study attempted to more precisely define the duration and characteristics of this possible temporal processing deficit by including a wider range of SOA conditions in a similar RSVP task and by comparing GM's results to those from a larger group of brain-damaged control subjects. That GM took substantially longer than controls to match two letters that were simultaneously presented (in Experiment 6) suggests that he may also be impaired in the temporal processing of letters.

Method

This experiment was run with custom software (Raymond et al., 1992). Each trial consisted of a series of successively presented digits in which two upper case letters were embedded as targets. The stimuli that were presented on a given trial were randomly selected from sets of 8 single digits (0 and 1 excluded) and 24 letters (O and I excluded). The number of digits presented before the first target letter (T1) varied randomly between 7 and 15. T1 was always followed by a sequence of 10 items and the second target letter (T2) appeared an equal number of times in each of these 10 serial positions. Each item was presented for 100 ms with an interstimulus interval of 67 ms. Thus, the SOA between T1 and T2 ranged between 167 and 1670 ms. Subjects initiated a trial by pressing a computer mouse button. This caused a central fixation point to disappear and the stream of stimuli to be displayed. Subjects were instructed to report the two letters aloud at the end of the trial. After the experimenter entered the responses into the computer, the fixation point returned and subjects could initiate the next trial when ready. GM completed 30 trials at each of the 10 intervals between T1 and T2 (for a total of 300 trials). Since the controls were available for a limited time for testing, only 20 trials at each of the 10 intervals were administered (for a total of 200 trials). The trials were presented in random order.

Results

Column 2 in Table 5 shows, for each SOA, the overall percentage of letters correctly identified by GM and the control group. The percentage of trials in which T1 and T2 were correctly reported are displayed in columns 3 and 4, respectively. The range in mean accuracy for control subjects is also included. Figure 10 shows, for GM and controls, the percent of trials in which T2 was correctly reported given that T1 was reported (T2IT1) as a function of SOA (arrows indicate where functions reach maximal asymptotes based on statistical comparison with 1670 ms SOA). These conditional percentages were used to assess the extent of the temporal processing deficit as is customary in the RSVP literature in normals. Trials in which the two target letters were the same were excluded from the analyses.

GM:

A chi-square analysis showed that the accuracy of T2IT1 was not independent of SOA (X^2 (9) = 85.67, $p < .001$). Pairwise comparisons between the 1670 ms SOA and each of the other nine SOA conditions revealed that accuracy with the 1670 ms SOA was significantly greater than accuracy with all conditions from 167 ms to 668 ms ($p < .003$ for all comparisons). However, performance with the 835 ms SOA and greater did not differ significantly from performance with the 1670 ms condition ($p > .2$ for all comparisons). Although this statistical method suggests that the function reached a maximum asymptote at the 835 ms SOA, it is important to observe visually that the function does not appear to asymptote until the 1169 ms SOA (see Figure 10).

Controls:

A one-way repeated measures ANOVA on the conditional report of T2IT1 showed a significant effect of SOA ($F_s(9, 45) = 21.32$, $p_s < .001$). Pairwise comparisons between the 1670 ms SOA and each of the other nine SOA conditions showed that the T2IT1 percentages were significantly lower from 167 ms to 501 ms but that by the 668 ms SOA the function had increased to reach an asymptote (see Figure 10). The controls were better able to identify T2 when it immediately followed T1 (167 ms SOA) compared to when there was an intervening digit between the target letters (334 ms SOA, $p < .01$). It is important to note that the performance of every individual in the control group conformed to the pattern of results described above (i.e., the function had reached an asymptote by 668 ms and T2IT1 accuracy was greater in the 334 ms SOA than in the 167 ms SOA).

Discussion

Both GM and the control subjects had difficulty reporting the identity of T2 when it was presented in close temporal proximity to T1. GM's performance improved progressively as the interval between T1 and T2 increased until it reached a maximal level of accuracy at 835 ms. It is important to observe visually, however, that the function does not appear to fully asymptote until the 1169 ms SOA (see Figure 10). In contrast, the control subjects' report of T2 reached a maximal asymptote at the 668 ms condition. This indicates that GM required an extended period of time (at least up to 835 ms) *after* he had encoded the first letter before he was able to reliably identify the second letter, relative to the control group, as well as to normal subjects previously tested on this type of RSVP task (Chun & Potter, 1995).

The LBL reader studied by Behrmann and Shallice (1995; Behrmann, 1999) required between 400 ms and 800 ms after T1 was presented, before they were able to identify T2 accurately. Given that brain-damaged control subjects in the current study required 668 ms to reach a maximal level of accuracy for T2, it is not clear that the increased T1-T2 interval required by their patient did, in fact, constitute a reading-related impairment. However, the wider range of SOAs and comparison to an appropriate control group in the current study allows for the conclusion that LBL reading is uniquely associated with a temporal processing deficit for letters, at least in this case.

One feature of the method used in the current study was that the T1-T2 interval was confounded with the position of T2 in the digit stream. That is, as the T1-T2 interval increased, T2 moved closer towards the end of the stream. The results were not likely attributable to the T2 position, however, because accuracy was consistently high from 1169 to 1670 ms in GM and from 668 ms to 1670 ms in controls and did not appear to increase across this range.

The second aspect of the results which is important to note is that GM was most likely to miss T2 when it immediately followed T1 (167 ms SOA), whereas the performance of the controls was improved when T1 and T2 were temporally adjacent relative to when T1 was followed by a distractor digit. In the normal literature, this U-shaped trend has been referred to as "Lag-1 sparing" (with *lag-1* meaning that T2 is the *first* item after T1) (Visser, Bischof, & Di Lollo, 1999). This effect is thought to occur when temporally-contiguous items (i.e., T1 and T2) with similar processing requirements (i.e., determination of letter identity) enter the visual short-term memory system together, prior to the closing of an attentional gate (Visser et al., 1999). This is an interesting notion to consider with respect to GM. It suggests that GM is only able to process one item at a time in visual short-term memory.

The final aspect of the results to note is that GM's ability to identify rapidly-presented letters, regardless of the interval between them, was worse than the controls. The percentage of letters overall, and in the T1 position, that he correctly reported collapsed across SOA fell well below that of the least accurate control subject (see Table 5). This suggests that his ability to visually encode even single letters is impaired.

Experiment 8: Identification of Letters and Numbers in Rapid Serial Visual Presentation

Background

The previous experiment showed that GM required an extended period of time after he had visually encoded one letter before he was able to reliably process a second letter. He was also much less accurate than control subjects at visually encoding even single letters. As was reviewed in the Introduction, one of the controversial issues in the literature is the extent to which the cognitive deficits in LBL readers are restricted to orthographic material, or involve other visuoperceptual material as well. Although Behrmann and Shallice (1995) only tested their case on temporal processing of letters, they noted that a letter identification deficit could arise from a more general underlying perceptual problem. Much earlier, Kinsbourne and Warrington (1962) had showed that tachistoscopic recognition thresholds in their patients were elevated for multiple geometrical forms and silhouette drawings, as well as for letters. Similarly, GM's slowed letter matching (Experiment 6) and difficulty processing letters in the RSVP task (Experiment 7) could reflect a more widespread visual processing deficit.

The processing of numbers in LBL readers has been studied relatively infrequently. Kinsbourne and Warrington (1962) had noted that identification of numbers appeared to be as impaired as letters. Several studies have also observed that reading single-digit numbers was better than multi-digit numbers (e.g., Cohen & Dehaene, 1995; Dejerine, 1892; Holender & Peereman, 1987; McNeil & Warrington, 1994), much like the superior reading of single letters relative to multi-letter words. Direct comparisons of number and letter processing have not been conducted, however. As was noted by Farah (1999), the lack of attention that has been paid to the differences between letter and number recognition is surprising given its considerable relevance to the perceptual hypothesis.

The purpose of the following experiment was to evaluate the generality of GM's visuoperceptual deficit by comparing the processing of letters and numbers in a RSVP task. This task did not contain a stream of distractors between the target items, unlike the RSVP paradigm employed in the previous study (referred to as a "stream" task). Instead, two target items were presented, each followed by a pattern mask, and the interval between the targets was varied (referred to as a "target mask – target mask" (TM-TM) paradigm). The previous stream task had confounded the time interval between the two targets with the number of digit distractors that had to be processed between them. Thus, the TM-TM task assessed whether GM still required an extended period of time between the two targets (either letters or numbers) when the task no longer required him to process the intervening items (i.e., when he no longer had to select the letters to be identified from amongst the digit distractors). Studies in the normal literature have shown that the "attentional blink" is also produced in TM-TM tasks (Duncan et al., 1994; McLaughlin, Shore, & Klein, in press; Ward, Duncan, & Shapiro, 1997) and that it likely assesses the same underlying function as the more popular stream tasks (McLaughlin et al., in press).

Method

This experiment was run with custom software (Raymond et al., 1992). Each trial consisted of two successively presented target items (T1, T2) each of which was followed by a pattern mask. T1 was presented for 100 ms, followed by a 100 ms pattern mask. For GM, T2 was then presented randomly at one of the 10 SOAs that followed T1 (200 to 1100 ms) and was also followed by a 100 ms pattern mask. For controls, only 7 SOAs followed T1 (200 to 800 ms). In one condition, the two targets presented on a given trial were randomly selected from a set of 8 upper-case letters (Z, B, A, R, G, L, S, P). In a second condition, the two target items were randomly selected from a set of 8 single digits (0 and 1 excluded). The letters were selected to match the physical attributes of the numbers as closely as possible. The letter and number conditions were alternated in their order of administration (i.e., ABAB design). GM completed 20 trials at each of the 10 SOAs in each of the letter and number blocks (400 trials per condition). The controls completed 15 trials at each of the 7 SOAs in each of the letter and number blocks (210 trials per condition). Subjects initiated a trial by pressing a computer mouse button. This caused a central fixation point to disappear and the stream of stimuli to be displayed. Subjects were instructed to report the two items aloud at the end of the trial. After the experimenter entered the responses into the computer, the fixation point returned and subjects could initiate the next trial when ready. The trials in each block were presented in random order. One control subject (Subject 6) did not participate in this experiment.

Results

Table 6 shows the percentage of items overall and in the T1 and T2 positions that were correctly identified by GM and the control group in the letter and number conditions. The range in mean accuracy for control subjects is also included. The mean percentage of items that GM correctly reported was averaged across the 200 to 800 ms SOA conditions to allow for comparison with controls. Figure 11 shows, for GM and controls, the conditional percentages (T2IT1) as a function of SOA for letters and numbers (arrows indicate where functions reach maximal asymptotes based on statistical comparison with

1100 ms SOA in GM and 800 ms SOA in controls). Trials in which the two targets were the same were excluded from the analyses.

GM:

A chi-square analysis showed that the accuracy of T2IT1 was not independent of SOA for letters (X^2 (9) = 88.0, $p < .001$) or numbers (X^2 (9) = 145.34, $p < .001$) (see Figure 11). For both the letter and number conditions, pairwise comparisons between the 1100 ms SOA and each of the other 9 SOA conditions revealed that accuracy with the 1100 ms SOA was significantly greater than accuracy with the 200, 300, and 400 ms SOAs ($p < .03$ for all comparisons). However, performance with the 500 to 1000 ms SOA conditions did not differ significantly from performance with the 1100 ms conditions ($p > .09$ for all comparisons) indicating that the letter and number functions reached a maximum asymptote at the same SOA. However, the percentage of correct items in the T1 position collapsed across the 200 to 800 ms SOA conditions was greater for numbers (99%) than for letters (87%; X^2 (1) = 7.34, $p = .007$) (see Table 6).

Controls:

A two-way repeated measures ANOVA on the conditional report of T2IT1 with SOA (200 to 800 ms) and item type (letters, numbers) as factors was conducted. There was an interaction between SOA and item type ($F_s(6, 24) = 3.82$, $p_s = .008$) (see Figure 11). For letters, pairwise comparisons between the 800 ms SOA and each of the other SOAs showed that the T2IT1 percentages were significantly lower for the 200 ms SOA ($p_s = .02$) and marginally lower for the 300 ms SOA ($p_s = .06$) but that by the 400 ms SOA the function had increased to reach an asymptote ($p_s > .19$). For numbers, pairwise comparisons between the 800 ms SOA and each of the other SOAs showed that the T2IT1 percentages were marginally lower for the 200 ms SOA ($p_s = .06$) but that by the 300 ms SOA the function had increased to reach an asymptote ($p_s > .17$). There was no difference in T1 accuracy between the letter (100%) and number (98%) conditions.

In three of the five control subjects, the asymptote point for numbers was reached at a smaller SOA than for letters, consistent with the group results described above. In two control subjects, however, the asymptote point was the same for numbers and letters. The control subject with the asymptote points at the largest SOAs required 500 ms in the letter condition and 400 ms in the number condition to reach maximal levels of accuracy (i.e., 100 ms more than the group mean in both letter and number conditions).

Discussion

As in the previous RSVP study, GM had more difficulty reporting the identity of T2 when it was presented in close temporal proximity to T1. For both the letter and the number conditions, GM's performance improved progressively as the interval between T1 and T2 increased until it reached a maximal level of accuracy at the 500 ms SOA. This suggests that the amount of time that GM required *after* he encoded the first item before he could process the second item was similar for letters and numbers.

In contrast, the control group's report of T2 reached a maximal asymptote at 400 ms for the letter condition and at 300 ms for the number condition. Although these group data indicate that less processing time was required for numbers than for letters, two individual subjects required equivalent processing times in the two conditions, consistent with results in GM. GM's T2IT1 asymptote point in the letter condition falls at the upper end of the performance range in the controls (i.e., 500 ms for both GM and the slowest control subject), and his asymptote point in the number condition was 100 ms greater than the slowest control subject (i.e., 500 ms for GM vs. 400 ms for slowest control). Thus, his ability to process both letters and numbers in rapid temporal succession was still somewhat reduced relative to most of the control subjects, in that he required an extended period of time after he had encoded the first item before he was able to reliably identify the second item, although the difference in their performances was not as clear as in the previous RSVP stream task.

The finding that GM was relatively more impaired than controls in the stream task than in the TM-TM task suggests that processing the number distractors and selecting which amongst them were the letter targets was particularly challenging for GM, and may account, to a considerable extent, for the increased T1-T2 interval that he required in the previous stream task. Thus, this pattern of results is very consistent with the hypothesis that GM has difficulty processing multiple items in rapid temporal succession; his performance is worse in the stream task than in the TM-TM task because more items need to be processed. Moreover, it is important to note that the distractor items to be processed in the stream task were non-orthographic stimuli (i.e., numbers), suggesting that this deficit is not specific to letters.

Unlike the pattern of results in the stream task, neither GM nor control subjects displayed lag-1 sparing in the TM-TM task, consistent with normal studies that have utilized this type of paradigm (Duncan et al., 1994; McLaughlin et al., in press; Ward et al., 1997). It has been suggested that this is because the lag-1 position in this task is always occupied by the mask, whereas in the stream paradigm, T2 can be presented in the lag-1 position (McLaughlin et al., in press).

The final aspect of the results to observe is that GM's ability to identify single items in the T1 position was worse for letters than for numbers. There was no difference in T1 accuracy between letters and numbers in controls. His T1 accuracy for numbers fell inside the range of the controls, whereas his T1 accuracy for letters fell below this range (see Table 6). Similarly, T2 accuracy in the asymptotic portion of the functions was worse for letters than for numbers in GM, while there was no difference between the two item types in controls (see Figure 11). These results could suggest that GM's ability to visually *encode* letters, over numbers, was disproportionately impaired relative to control subjects. However, this type of interpretation is complicated by the fact that T1 accuracy and asymptotic T2 accuracy for controls for both item types was at ceiling. This implies that the relative encoding benefit for numbers over letters may not represent a pattern unique to GM, but rather that it is more apparent in his data than in controls because his overall levels of accuracy were lower.

Experiment 9: Physical Identity Matching of Letters and Numbers

Background

In the previous RSVP study, the finding that T2IT1 accuracy in the letter and number conditions reached a maximal asymptote at the same SOA indicates that GM required a similar amount of time to process numbers and letters *after* the items had been visually encoded. However, the finding that T1 accuracy collapsed across SOA, as well as T2 accuracy in the asymptotic portion of the functions, were higher for numbers than letters implies that his visual *encoding* of numbers may be better than letters. It was suggested though that this may have been because accuracy in controls was close to ceiling levels in both conditions, and that letters were not necessarily disproportionately impaired in GM relative to numbers.

The following experiment attempted to confirm whether the visual encoding benefit for numbers over letters was unique to GM, or was also present to a similar extent in control subjects. A physical identity matching task with letters and numbers as stimuli was selected for this purpose. Since performance differences between letters and numbers could also result from greater uncertainty associated with a potentially larger stimulus set (Farah, 1999), the letters and numbers were intermixed. This task required items to be matched strictly on the basis of their physical characteristics and identification was not required. Response latencies, which may be a more sensitive measure than accuracy, were recorded. It was expected that if his visual encoding deficit was greater for letters than numbers, his RTs for letter matches would be slower than for number matches, whereas controls would show no RT differences in their matches of the two item types.

Method

In each trial, two horizontally adjacent items appeared simultaneously and remained on the screen until a response was made. Items were either two upper-case letters (from a set of 8) or two numbers (from a set of 8) and were the same as in the previous RSVP study. They were combined to form 64 letter pairs and 64 number pairs. Half of the pairs were "same" pairs and were composed of four pairings of each item within the letter set (e.g., AA) and the number set (e.g., 22). Half of the pairs were "different" pairs and were composed of all possible pairings of the items within the letter set (e.g., AB) and the number set (e.g., 24) for a total of 28 pairings per set, plus an additional four pairings in each set that were repeated to make an equivalent number of trials as in the "same" condition. Thus, 128 trials were administered (i.e., 32 "same" matches and 32 "different" matches in the letter and number set). The items were presented in two blocks with each containing an equal number of letter/number matches and same/different trials. Items were presented in random order within each block. Subjects indicated whether the items were the same or different, as quickly as possible, by manual key presses.

Results

Figure 12 shows the mean response latencies for correct trials for same and different matches in letter and number conditions for both GM and the control group (bars on control data represent RTs for the slowest control subject in each condition). The RT data were analyzed with two-way ANOVAs with item type (letter, number) and match type (same, different) as factors.

GM:

GM made few errors (<1% of trials). There was a main effect of item type ($F_i(1,115) = 6.07$, $p_i = .02$) in that he was slower at matching letters (1080 ms) than numbers (974 ms). Analyses of match type were non-significant ($p_i = .97$).

Controls:

Controls made few errors (<1% of trials). There was a main effect of match type ($F_s(1,5) = 20.74$, $p_s = .006$; $F_i(1, 124) = 62.34$, $p_i < .001$) with longer RTs to the different trials (777 ms) than to the same trials (702 ms). Analyses of item type were non-significant ($p_s = .18$, $p_i = .17$).

Discussion

In this experiment GM took longer to match letters than numbers on the basis of their physical characteristics. Since letters and numbers were intermixed and identification of items was not required in this task, this result suggests that GM was better able to visually encode numbers compared to letters. The control subjects, by contrast, showed no overall difference in their response latencies to match the two types of items. For both GM and controls, the letter match RTs were comparable to those in the previous letter matching study (Experiment 6, PI matches), indicating that the findings were reliable. Although the increased match latencies for letters relative to numbers seemingly would suggest that GM has a visual encoding impairment that particularly affects orthographic material, it is important to note that he took considerably longer to match both letters and numbers than all of the control subjects (see bars on control subject data in Figure 12). Therefore, the lack of an overall difference in the match speeds for numbers and letters in the controls may have been due to a floor effect in their response latencies, rather than to a fundamental difference in the way GM and the controls processed these two types of items.

This type of scaling problem was discussed in the previous letter matching study (Experiment 6), and the same approach for data examination was used here. The response latencies for the number and letter conditions (collapsed across match type) for the individual subjects were plotted (see Figure 13). A regression line with letter match latencies against number match latencies revealed a strong linear relationship between the two variables ($r = 0.99$, $p < .001$), indicating that as number match latencies increased so did the letter match latencies. The value of the residuals (i.e., the difference between the observed letter match latency and that predicted by the regression equation) was then used to assess whether GM's letter match latency was substantially greater than the value predicted from his number match latency. As can be seen in Figure 13, GM's letter match latency was slightly greater than the predicted value (i.e., his observed value was 26 ms more than the value on the regression line). However, two control subjects (Subjects 5 and 2) also showed small discrepancies in that direction between their observed and predicted letter match latencies (i.e., values of the residuals were 27 ms and 14 ms, respectively). This suggests that GM did not perform letter matches substantially slower than what would be predicted from his number match latencies. His latency advantage for numbers occurs because he is much slower overall, relative to the control subjects, in performing this task. The three control subjects that had the slowest number match latencies (Subjects 2, 3 and 6) also matched numbers faster than letters (latency advantages of 27 ms, 36 ms, and 16 ms, respectively; see differences between data points and unit slope function (i.e., function resulting if RTs for letters were equivalent to those for numbers) in Figure 13), whereas the three subjects that had the fastest number match latencies (Subjects 5, 4 and 1) did not show positive latency advantages for their number matches (latency advantages of – 4 ms, - 22 ms, and – 29 ms, respectively; see differences between data points and unit slope function). Thus, the difference between the letter and number matching latencies for GM (106 ms) is approximately what would be predicted given the overall slowness of his match latencies.

These results suggest that numbers may be encoded better than letters in all subjects. However, this difference is only apparent in the data when subjects are sufficiently slowed so that there are not floor effects in their response latencies. An account of why numbers may be encoded better than letters is reviewed in the General Discussion section. Importantly, however, the results of this experiment demonstrate that GM's difficulty in visual matching is not orthographic-specific and applies equally to both letters and numbers. It also suggests that his slowed letter matching (Experiment 6) and difficulty processing letters in the RSVP task (Experiment 7) were due to a general visual processing deficit, rather than to a specific letter processing deficit.

General Discussion

This research investigated the cognitive mechanisms responsible for LBL reading in a single patient, GM, who demonstrated a form of this disorder known as LBL surface alexia or type 2 LBL reading. The first set of investigations (Experiments 1-5) confirmed the diagnosis of his dyslexia and documented some of the strategies that he relied on to process words. The LBL component of his syndrome was established by the results of the pronunciation (Experiments 1 and 2) and lexical decision (Experiment 4) tasks: the increase in his response latencies as item length increased, a finding known as the word length effect, is considered to be the hallmark of LBL reading. The surface dyslexia component of his syndrome was established by his decreased accuracy with irregular words, relative to regular words, in these tasks.

To ensure that GM's word length effect resulted from identification of letters in a serial, left-to-right fashion, in keeping with the typical conceptualization of LBL reading, tasks of non-word pronunciation (Experiment 2) and pronunciation of words presented LBL (Experiments 3) were administered. Given GM's accompanying surface dyslexia and likely reliance on a phonologically-based reading strategy, it seemed possible that this process in itself could be responsible for the word length effect. However, GM's length effect with non-words far exceeded that found in any of the control subjects (Experiment 2), suggesting that if a phonologically-based process was responsible for his word length effect, then the rate at which it operated must be significantly slowed relative to controls. It was also suggested that GM's apparent strategy of "trying out pronunciations" (c.f., Patterson & Kay, 1982) could have resulted in the word length effect. However, the lack of a length effect with the LBL display mode (Experiment 3) implied that the presence of the effect with the typical display format did not likely result from "trying out pronunciations", since this strategy would have been applied to the entire word after all of the letters had been presented. Taken together, these results were considered to be most consistent with the notion that GM's word length effect was due to the use of a serial LBL process.

The second set of investigations (Experiments 6-9) tested three specific hypotheses concerning the cognitive deficit that may have caused GM to rely on the LBL strategy.

The Role of Abstract Letter Identities

The hypothesis that LBL reading results from difficulty processing abstract letter identities with a reliance on phonetic codes was tested using a letter matching task with a phonetic confusability manipulation. Although GM was much slower at NI matching, relative to PI matching, comparison with individual control subjects suggested that this was a result of scaling artifact. That is, the RT difference between NI and PI matches was increased because his overall matching speed was markedly slowed. Moreover, the lack of a phonetic confusability effect suggested that GM was able to perform NI matches on the basis of abstract letter codes.

These findings have important implications for the abstract letter theory of LBL reading. As with GM, in most of the previous cases in which NI matches were claimed to be disproportionately impaired relative to PI matches, PI matches were conducted significantly slower than control subjects (Behrmann & Shallice, 1995; Hanley & Kay, 1996; Kay & Hanley, 1991; Reuter-Lorenz & Brunn, 1990; except for Arguin & Bub, 1994b, see DM in Figure 9a), suggesting that their results may also have been due to scaling artifact. Moreover, comparison of the data from these LBL readers with those from the non-dyslexic, brain-damaged controls of the current study indicated, in fact, that the controls were disproportionately impaired at NI matching over PI matching, relative to the LBL readers (see difference in regression line slopes in Figure 9). This study is also the first to investigate the mechanism by which LBL readers perform NI matches, and results implied that abstract letter codes were accessible, at least in this case. Thus, the evidence for impaired abstract letter processing in LBL readers using this letter matching task may be substantially weaker than has been considered previously in the literature.

Deficits in abstract letter codes may need to be examined using a different technique. In the patient (DM) studied by Arguin and Bub (1994b), abstract letter processing was also assessed using a letter priming paradigm. The finding that letter identification in DM was facilitated by PI primes but not by NI primes, in contrast to normals who benefitted from both prime types (Arguin & Bub, 1995), implied that abstract letter representations had not been activated normally. Furthermore, results of a rehabilitation study (Arguin & Bub, 1994b) suggested that the type of representation assessed by NI priming may be more closely related to actual reading skill than that assessed by NI matching, at least in this patient.

In this rehabilitation study, Arguin and Bub (1994b) attempted to re-establish abstract letter coding in DM through practice of a speeded NI matching task. After training, DM was faster than all normal controls in performing PI and NI letter matches, but he continued to display a significant word length effect in reading. In addition to the lack of change in the word length effect, his performance in the letter priming task remained qualitatively unchanged. It was suggested that DM's improvement in NI letter matching may have resulted from use of a phonetic mapping procedure, whereas the letter priming task continued to reveal his deficit in abstract letter processing. Although the lack of a phonetic confusability effect in GM implied that phonetic processing was not an important factor in his NI matching performance, it clearly should be assessed if the letter matching task is used for the purpose of assessing abstract letter coding in other cases. Investigations with other LBL readers that focus on the relations between NI matching, NI priming, and reading skill are still needed to determine if an abstract letter deficit is a common contributor to this disorder. However, the current results suggest that this type of deficit is not responsible for GM's LBL reading, and is certainly not as frequent as has been claimed by other studies in the literature that have employed letter matching tasks (Behrmann & Shallice, 1995; Hanley & Kay, 1996; Kay & Hanley, 1991; Reuter-Lorenz & Brunn, 1990).

The Role of Temporal Letter Processing

The hypothesis that LBL reading results from difficulty in rapid processing of multiple letters was tested using an RSVP task. GM was found to require an extended period of time (at least up to 835 ms) *after* he had encoded one letter before he was able to reliably process a second letter. This finding provides good support for the temporal processing theory of LBL reading and confirms that the deficit can extend beyond simultaneity per se to the processing of forms in rapid temporal succession (Behrmann & Shallice, 1995; Kinsbourne & Warrington, 1962). Although Behrmann and Shallice had tested their patient on a similar RSVP task, they used only three widely-spaced SOA conditions and tested only one neurologically-intact individual as a control. Given that brain-damaged subjects in the current study required 668 ms to reach a maximal level of accuracy for the second letter, it is not clear that the 400 to 800 ms interval required by their LBL reader did, in fact, constitute a reading-related impairment. However, the results obtained in GM allow for the conclusion that LBL reading is uniquely associated with a temporal processing deficit for letters, at least in this case.

The original evidence for this theory presented by Kinsbourne and Warrington (1962) had suggested that although LBL readers were not abie to rapidly *recognize* multiple objects, they were able to *see* multiple items at a time. Tachistoscopic recognition thresholds for multiple forms were elevated in their patients, but they had no difficulty counting the number of dots briefly presented in an irregularly distributed array. RSVP paradigms provide a unique way to distinguish between these two aspects of visual processing. Because the target items are embedded in a stream of distractors which eliminate them from view, the time required *after* the first target has been encoded before a second target can be processed is precisely determined. Accuracy for the first target item collapsed across the SOA conditions can be considered to reflect visual encoding ability. By this account, GM not only had difficulty in rapid post-sensory letter processing, but was also impaired at visual encoding of single letters. Furthermore, an interesting and unique result in the stream task had been the lack of lag-1 sparing in GM, which could be interpreted as an inability to process more than one item at a time in visual short-term memory (c.f., Visser et al., 1999).

Individuals without neurological damage also show a transitory processing deficit in RSVP tasks that persists for about 400 ms after the first target has been processed. This phenomenon, known as the "attentional blink" (Raymond et al., 1992), has been investigated extensively in recent years. Does the temporal processing deficit obtained in GM reflect an increased attentional blink? The attentional blink in the normal literature appears to be a very robust finding, occurring in a wide range of RSVP paradigms. It has been shown that *detection* of any masked item produces this temporary deficit in the processing of a second item, and that *identification* of the first item is not required (Shapiro, Raymond, & Arnell, 1994). Since the task employed with GM required identification of the letters, it is possible that his deficit may have been restricted to this level of processing and was not generalized to the extent that is found in the normal literature.

Normal studies have also shown that the attentional blink is produced in TM-TM tasks (Duncan et al., 1994; McLaughlin et al., in press; Ward et al., 1997) and that performance in this version of the task is correlated with that in the more popular stream tasks (McLaughlin et al., in press). The finding that GM was considerably more impaired in the stream task than in the TM-TM task, relative to controls, suggests that his difficulty in the stream task was a result of having to process an increased number of items (i.e., targets and distractors), and not exclusively due to limitations in processing the two target items, as is assumed to underlie the attentional blink in normals.

The attentional blink in normals has been shown to occur using a wide range of target stimuli, including letters, digits, words, and pictures. The temporal processing theory of LBL reading also presumes that the deficit affects processing of all types of visual forms, not just letters. Consistent with both of these notions, results of the TM-TM task suggested that any temporal processing deficit that was present in GM affected letters and numbers equally.

If the temporal processing deficit obtained in GM reflects an increased attentional blink, then theories developed to account for this phenomenon may provide insights into what causes LBL reading. Two broad classes of models have been used to explain the underlying mechanism of the attentional blink in normal individuals. According to one class, both target items can immediately enter visual short-term memory, but at short intertarget intervals, there is interference or competition between the items when they need to be retrieved (e.g., Raymond, Shapiro, & Arnell, 1995; Shapiro & Raymond, 1994; Shapiro et al., 1994). Alternatively, the second class of model proposes that the attentional blink results because of a processing bottleneck (e.g., Chun & Potter, 1995; Giesbrecht & Di Lollo, 1998; Seiffert & Di Lollo, 1997). That is, the visual system takes time to process the first item and thus is otherwise occupied when the second target occurs after a short interval.

It seems reasonable to assume that a deficit in either type of attentional mechanism could potentially lead to LBL reading. If the retrieval or initial processing of letters is especially temporally-limited, then reading, which is known to rely on simultaneous letter processing, could be restricted to a LBL procedure. Results obtained in GM do not adjudicate between these two options. Interestingly though, Kinsbourne and Warrington (1962) had much earlier conceptualized the deficit in LBL reading along the lines of the bottleneck models. They wrote that "if 'filter theory' is substantiated for the visual system, then it may be that in the patients with disordered simultaneous form perception there is relative block at the filter, slowing up the passage of the percept through it...The proof must await further experiment". The results of the current study suggest that the use of RSVP paradigms may be a fruitful way to explore these different hypotheses and to determine if the generalities of the attentional blink apply to the temporal processing deficit obtained in LBL readers.

Is the Deficit Specific to Orthography ?: A Comparison of Letter and Number Processing

The hypothesis that LBL reading results from an impairment that is *not* specific to letters was tested using a TM-TM RSVP task in which processing of letters was compared to that of numbers, as well as a matching task with the two types of stimuli intermixed. Numbers were selected as the non-orthographic stimuli because they have similar visual characteristics to letters and are also visually-arbitrary, symbolic forms. As was discussed above, there was no difference between letters and numbers in terms of the temporal interval that GM required between the RSVP targets to achieve maximal levels of accuracy. Although the reduction in his performance relative to control subjects was not as clear as in the stream task, the results did suggest that any temporal processing deficit that was present affected letters and numbers equally. His difficulty in identifying letters that were presented amongst numbers in the RSVP stream task is also consistent with the notion that he suffers from a general visual processing deficit.

Although GM's accuracy for the first target item collapsed across the SOA conditions, and T2 accuracy in the asymptotic portion of the functions (see Figure 11), considered to reflect visual encoding ability, were greater for letters than numbers, interpretation of this data was complicated by the fact that accuracy for controls for both item types was at ceiling. Thus, possible encoding differences between the stimulus types were followed up in the matching task. Results showed that GM was slower at physical matching of letters than numbers, but comparison of letter/number performance with individual control subjects suggested that this was due to scaling artifact. That is, the RT difference between letter and number matches was increased because his overall matching speed was markedly slowed. These findings suggest that numbers may be encoded better than letters in all subjects, but this difference is only apparent in the data when they are sufficiently slowed so that there are not floor effects in their response latencies.

Why might numbers be encoded better than letters? The most obvious reason is that numbers may be seen and processed more often as single units, whereas letters are usually grouped in words. Polk and Farah (1995; 1998) have proposed, and implemented in a neural network model, a mechanism by which the visual region of the brain could "self-organize" to create functionally-specialized and spatially-segregated subareas for letter and number processing. In this model, the statistical frequencies in the environment (i.e., that letters usually occur with other letters, and digits with other digits) interact with the Hebbian learning mechanisms in the brain to lead to segregated areas that differ in their optimal processing capabilities. Based on this type of mechanism, it seems plausible that an area that encodes numbers may respond best to single digits, whereas an area that encodes letters may respond best to multiple letters, reflecting the statistical regularities in the visual environment.

Evidence for spatially-segregated letter and number areas was also found in a neuroimaging study (Polk & Farah, 1998). Areas of the left extrastriate visual cortex responded differentially to strings of letters and digits in functional MRI. The authors noted that there may also have been additional right-hemisphere differences in activation, but the use of a surface coil over the left-hemisphere disrupted these signals. Other investigators though have found a greater right-hemisphere contribution to the naming of numbers, compared to letters (e.g., Chochon, Cohen, van de Moortele, & Dehaene, 1999).

What are the implications of spatially-segregated letter and number areas for theories of LBL reading? Farah (1999) suggested that, in principle, brain-damage in a particular case could be localized to the letter area of the brain leading to especially poor performance on orthographic tasks, but since this region developed out of a general perceptual area, performance on other non-orthographic tasks would be expected to be reduced to some extent as well. Since GM's performance on letter and number tasks did not differ significantly more than was predicted from the control subjects, his brain lesion would be expected to have affected both subareas. Although precise neuroanatomical data were not available, GM's large temporal-occipital lesion would be consistent with this notion.

Conclusions

These studies have revealed several cognitive deficits in GM that potentially could underlie his LBL reading. First, an impairment that affects encoding of visual features was suggested by his slowed letter and number matching, his reduced accuracy for letter and number RSVP targets collapsed across the SOA conditions, as well as his letter misidentification errors made in reading. Second, an impairment in rapid temporal processing of multiple letters and numbers was found in the RSVP tasks, particularly in the stream task where an increased number of items had to be processed (i.e., targets and distractors). The lack of lag-1 sparing in the stream task was also compatible with the view that GM had difficulty processing more than one item at a time. Importantly, none of these deficits were shown to be restricted to orthographic material, providing good support for perceptual theories of LBL reading.

Given these different areas of impairment, however, it becomes difficult to determine which are responsible for his LBL reading. This strategy of focusing sequentially on each individual letter of a word could be adopted to compensate for any one of these deficits. In fact, it may be misleading to assume that one critical deficit must underlie this disorder; the effects of several types of impairment could summate to restrict normal word recognition. Consistent with this notion, children learning to read also show significant word length effects, suggesting that a serial processing strategy may be a fairly general phenomenon used to facilitate automaticity in word recognition (LaBerge & Samuals, 1974; Seymour & Porpodas, 1980). Unfortunately, there is no good evidence yet to suggest that LBL reading can spontaneously recover (Behrmann et al., 1990) or be significantly remediated (Arguin & Bub, 1994b; Behrmann, 1999).

The notion that a variety of types of deficit may lead to LBL reading is certainly supported by other findings in the literature. Almost every patient studied has been claimed to have a unique type of deficit that is critical to the disorder. It is difficult to determine how heterogeneous the underlying deficit may be since single case accounts each with different testing techniques predominate in the field. Undoubtedly, the lack of appropriate control subjects contributes to this heterogeneity. When only normal subjects are employed as controls, as is the case in almost all of the relevant studies, it is impossible to determine which behaviours are uniquely associated with the LBL reading, and are not a general result of brain-damage.

Results of the current studies highlight the importance of comparing data from single cases to that of a group of brain-damaged patients. The analysis of the variability between individual control subjects, rather than group means or single-case data, that was conducted in these studies (particularly in the two matching tasks, Experiments 6 and 9) represents a simple and novel way of determining whether a particular pattern of results is meaningful. The conclusions derived from these data would have been radically different if this method had not been employed. Previous claims that NI letter matching was disproportionately impaired relative to PI matching is a case in point.

Although considerable heterogeneity in the specific deficit underlying LBL reading may exist, Behrmann and colleagues (1998b), in a recent literature review, found that a perceptual or letter processing impairment was common to almost all patients. Thus, the prelexical deficits found in GM are in good agreement with this notion. This type of theory contrasts with those that suggest the disorder is due to a lexical level deficit, such as in the word-form system (Warrington & Langdon, 1994; Warrington & Shallice, 1980) or in accessing phonological codes (Arguin et al., 1998; Bowers et al., 1996a). However, Hanley and Kay (1996) found that the variation in letter processing abilities in LBL readers did not explain the variation in reading speed, suggesting that deficient letter processing is not a complete explanation of the disorder. In studying two LBL readers, they found that the faster LBL reader (DC) was substantially slower at PI and NI letter matching than the slower LBL reader (PD). Since PD also read somewhat inaccurately, they suggested that he had an additional lexical level deficit.

GM was also shown to have a lexical level deficit, in that he had symptoms of surface dyslexia and appeared to use a strategy of "trying out pronunciations" (c.f., Patterson &

Kay, 1982) after he had identified the individual letters. Although this deficit did not seem to contribute to his word length effect, it likely increased his overall pronunciation latencies, and may have resulted in the abnormally long period of time that he required to compute pronunciations after words had been displayed in the letter-by-letter presentation mode (see Figure 5). Although determining the mechanisms that gave rise to GM's surface dyslexia was not a major objective of this research, aspects of his performance did provide some relevant information in this regard. That GM had difficulty making lexical decisions to irregular words and tended to accept pseudohomophones as words suggested that the locus of the impairment was at a stage of reading prior to phonological output. That his word pronunciation appeared to have been influenced by imageability and that he was able to accurately describe items on the Boston Naming Test, as well as perform well on the Similarities and Reasoning subtests of the COGNISTAT (see *Subjects* section), implied that his semantic system was relatively preserved. Thus, the deficit that underlies GM's surface dyslexia could tentatively be placed either within the orthographic system itself or in access to the semantic system, consistent with accounts of the syndrome in several previous cases (Behrmann & Bub, 1992; Coltheart & Byng, 1989).

Although it is generally assumed that acquired reading deficits are due solely to effects of the brain damage, Friedman and Hadley (1992) suggested that the combination of an acquired prelexical deficit and a premorbid lexical deficit, which had manifested as poor premorbid spelling, resulted in the syndrome of LBL surface alexia in their patient (BL). In the case of GM, his premorbid ability also likely influenced the extent of his acquired reading impairment, but it probably is not a complete explanation of the surface dyslexic component of his disorder. GM's surface dyslexia was considerably worse than that in BL (i.e., based on accuracy of irregular word reading), and his spelling ability was reported to decline markedly after his brain-injury.

Future Directions

Detailed single-case studies that consider the role of premorbid abilities, compare results to those from non-dyslexic, brain-damaged controls, and attempt to find similarities amongst many different patients are clearly needed for the cognitive mechanisms underlying LBL reading to be better understood. Development of a common set of baseline assessment tools to be administered to all relevant cases would likely be valuable in this endeavor. Results from such studies may also prove to be beneficial in the design of appropriate rehabilitation strategies for this disorder, and will continue to provide important insights into how the skill of reading is performed in the brain.

Table 1: Characteristics of control subjects.

Subject	Age	Education	Gender	Premorbid Handedness	Premorbid Occupation	Etiology	CT or MRI Scan Results	Time Post-Stroke
1	58	Grade 11	M	R	School Custodian	Infarction	Right internal capsule lesion, extending into basal ganglia	9 months
2	51	Grade 11	M	R	Insurance Underwriter	Infarction	Right medial frontal cortex lesion, as well as old ischemic changes in left frontal cortex	1 year, 7 months
3	50	Grade 11	M	R	Hair Dresser	Infarction	Left putamen and external capsule lesion	9 months
4	37	Grade 12	M	R *	Office Clerk	Infarction	Left frontal-temporal lesion, as well as old ischemic lesions in right subcortical areas	2 years, 4 months
5	48	Grade 12	M	R	Mechanic	Infarction	Left medulla infarct	11 months
6	42	Grade 10	F	R	Postal Clerk	Hemorrhage and aneurysm clipping	Right frontal-parietal lesion	5 years, 2 months

* Left hand used for experimental tasks due to right hemiplegia

Table 2: Performance on cognitive screening measures for GM and control subjects.

		COGNISTAT				
Subject	**WRAT-3 (%ile, Gr Level)**	**Orientation**	**Attention**	**Comprehension**	**Repetition**	**Naming**
GM	3, Gr 5	Average	Average	Average	Average	Mild
1	34, HS*	Average	Average	Average	Average	Average
2	63, Post-HS	Average	Moderate-Severe	Average	Average	Average
3	32, HS	Average	Average	Average	Moderate	Mild
4	55, Post-HS	Average	Average	Average	Average	Average
5	45, Post-HS	Average	Average	Average	Average	Average
6	32, HS	Average	Average	Average	Average	Average

* High School

Table 2 continued.

	COGNISTAT				
Subject	**Construction**	**Memory**	**Calculation**	**Similarities**	**Judgement**
GM	Average	Average	Average	Average	Average
1	Average	Average	Mild	Average	Average
2	Average	Severe	Average	Average	Average
3	Average	Average	Average	Average	Average
4	Average	Severe	Average	Average	Average
5	Average	Average	Average	Average	Average
6	Average	Average	Average	Average	Average

Table 3: Number (%) of different error types made by GM in pronouncing irregular and regular words.

Error Types	**Irregular**	**Regular**
LARCs		
Regularizations	18 (40)	
Alt. Irr. Prons.	1 (2)	
Splittings	1 (2)	
VPWs	16 (36)	7 (58)
VPNWs	8 (18)	5 (42)
Other	1 (2)	
Total	45	12

Table 4: Percentage of correct items for each condition in pseudohomophone lexical decision task for GM and control subjects.

Subject	**Words**	**NonWords**	**Pseudohomophones**
GM	96	85	28
Control Group	99	97	94
Range in Controls	99 - 100	90 - 100	78 - 100

Table 5: Percentage of letters correctly reported in RSVP task as a function of increasing SOA between letters for GM and control subjects.

GM

SOA (ms)	Overall	T1	T2
167	44.83	65.52	24.14
334	46.43	75.00	17.86
501	57.14	89.29	25.00
668	68.97	89.66	48.28
835	76.67	80.00	73.33
1002	80.36	89.29	71.43
1169	77.78	77.78	77.78
1336	79.31	68.97	89.66
1503	81.48	81.48	81.48
1670	80.36	75.00	85.71
Mean	69.33	79.20	59.47

Controls

SOA (ms)	Overall	T1	T2
167	75.48	79.32	71.65
334	65.38	94.82	35.94
501	74.32	94.69	53.95
668	89.42	88.83	90.02
835	95.75	96.62	94.87
1002	94.47	94.81	94.12
1169	96.48	96.39	96.57
1336	95.39	94.96	95.83
1503	95.35	94.91	95.79
1670	96.11	94.86	97.35
Mean	87.82	93.02	82.61
Range in Mean	83 - 93	90 - 96	72 - 91

Table 6: Percentage of letters and numbers correctly reported in RSVP task as a function of increasing SOA between items for GM and control subjects.

	Letters			**Numbers**		
GM						
SOA (ms)	**Overall**	**T1**	**T2**	**Overall**	**T1**	**T2**
200	43.75	81.25	6.25	55.71	97.14	14.29
300	57.89	89.47	26.32	72.06	100.00	44.12
400	67.11	86.84	47.37	85.94	100.00	71.88
500	89.71	91.18	88.24	91.89	94.59	89.19
600	79.73	86.49	72.97	95.59	100.00	91.18
700	76.47	79.41	73.53	94.44	100.00	88.89
800	85.71	91.43	80.00	98.61	100.00	97.22
900	87.88	87.88	87.88	100.00	100.00	100.00
1000	86.84	92.11	81.58	94.29	94.29	94.29
1100	79.41	85.29	73.53	93.24	91.89	94.59
Mean*	71.48	86.58	56.38	84.89	98.82	70.97
Controls						
SOA (ms)	**Overall**	**T1**	**T2**	**Overall**	**T1**	**T2**
200	66.73	97.02	36.43	79.74	100.00	59.47
300	84.37	98.43	70.31	93.50	98.46	88.55
400	91.47	99.23	83.71	98.17	99.26	97.09
500	97.3	98.43	96.18	100.00	100.00	100.00
600	97.36	97.04	97.69	99.26	99.20	99.31
700	98.36	99.13	97.59	97.58	100.00	95.17
800	99.31	99.31	99.31	99.23	100.00	98.46
Mean	90.70	98.37	83.03	95.36	99.56	91.15
Range in Mean	82 - 97	96 - 99	66 – 95	89 - 99	99 - 100	78 - 99

* Averaged across the 200 to 800 ms SOA conditions to allow for comparison with controls.

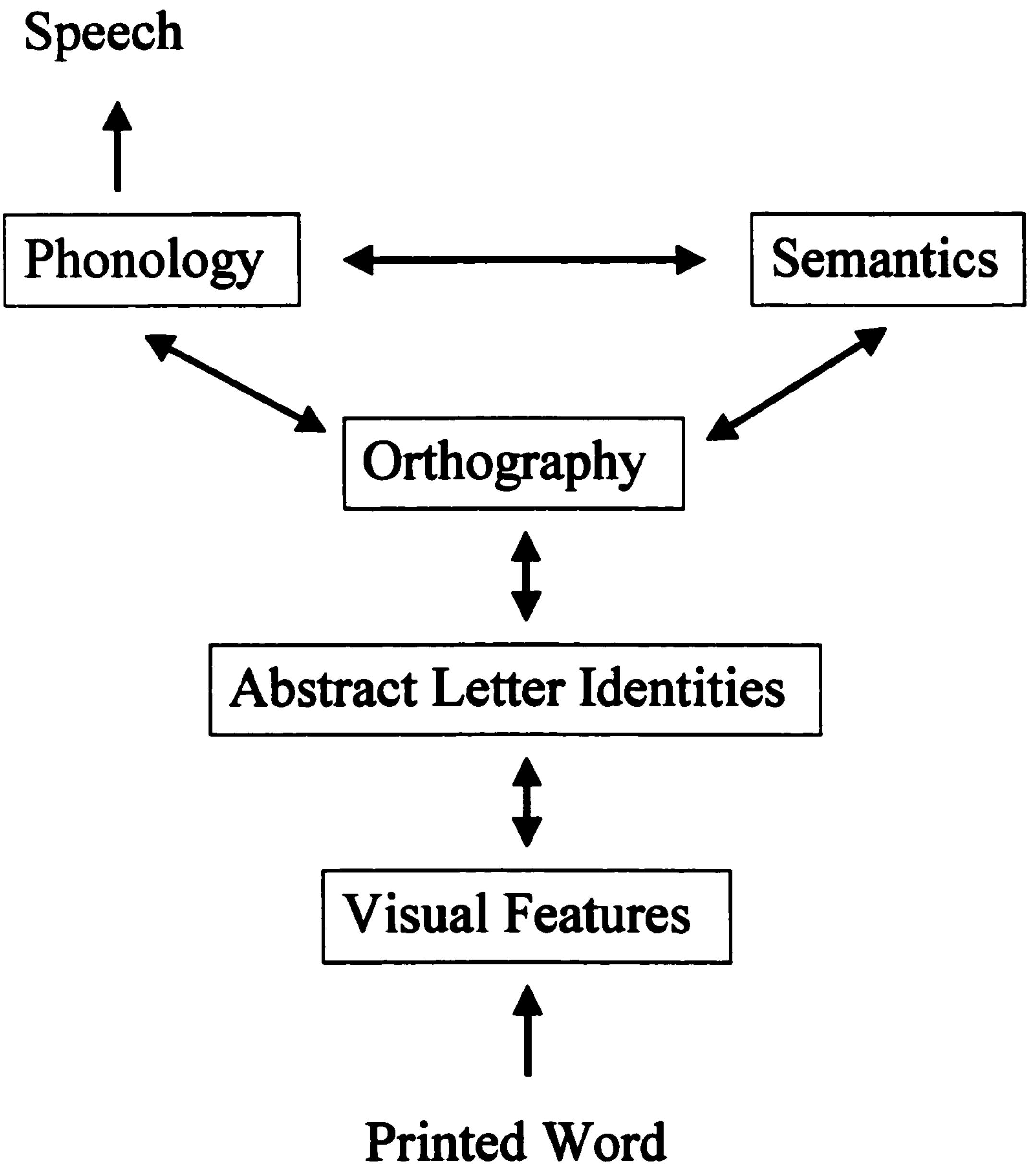

Figure 1: A model of single-word reading.

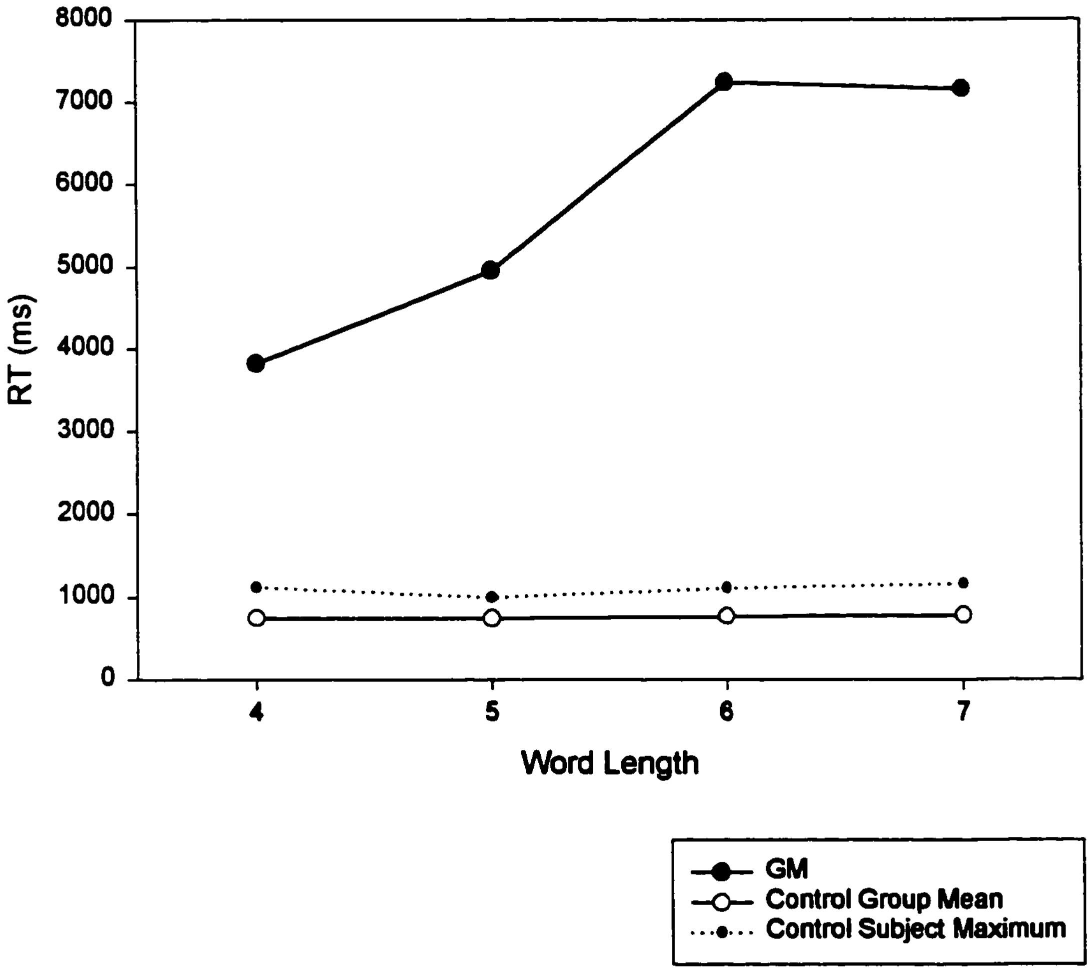

Figure 2: Mean pronunciation RTs for correct trials as a function of word length for GM, the control group, and control subject that displayed the largest word length effect (Experiment 1).

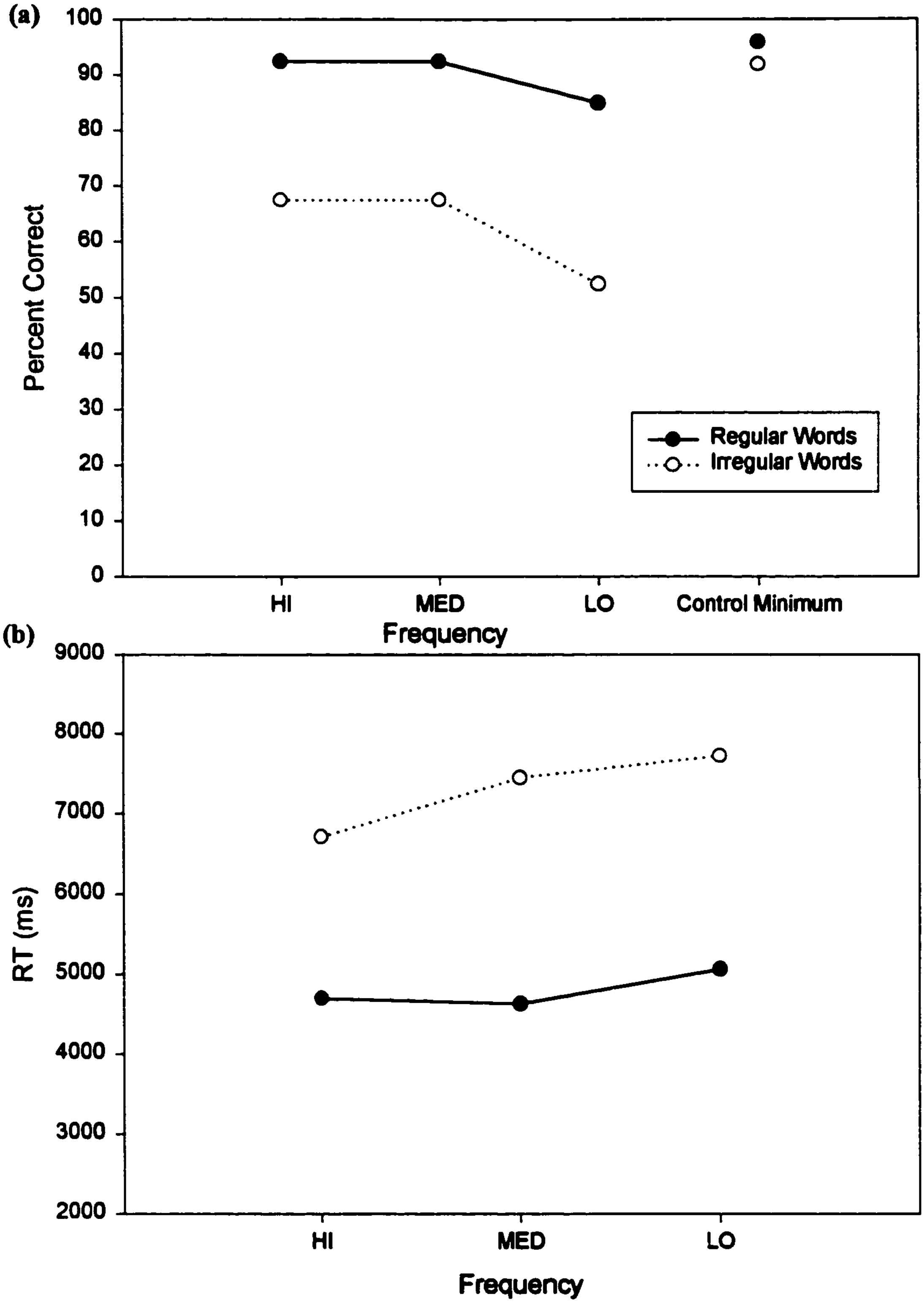

Figure 3: (a) GM's pronunciation accuracy as a function of regularity and frequency, as well as that for the least accurate control subject. Mean accuracy for the control group was greater than 93% in all conditions with the least accurate control subject obtaining greater than 92% correct; (b) GM's mean pronunciation RTs for correct trials (Experiment 1).

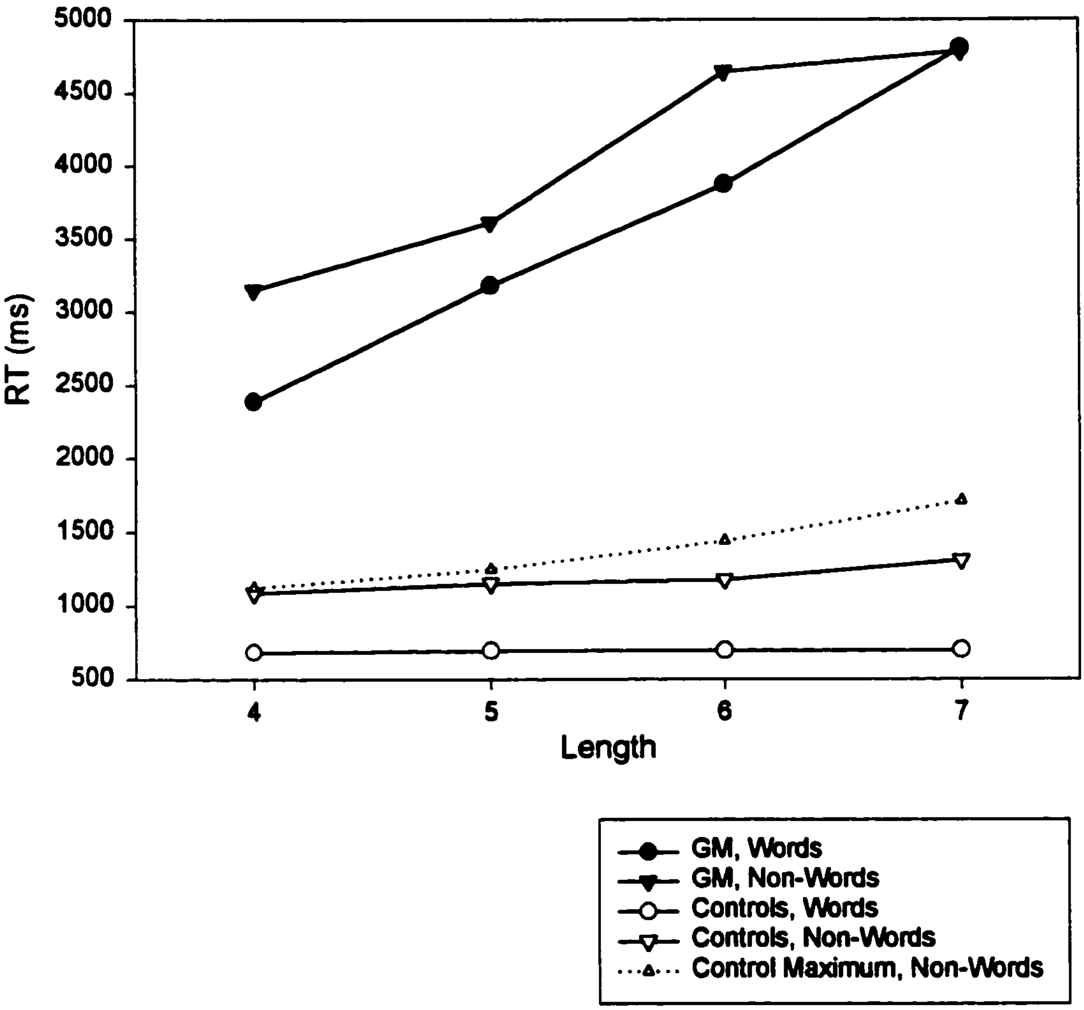

Figure 4: Mean pronunciation RTs for correct trials for words and non-words as a function of item length for GM, control group, and control subject that displayed the largest non-word length effect (Experiment 2).

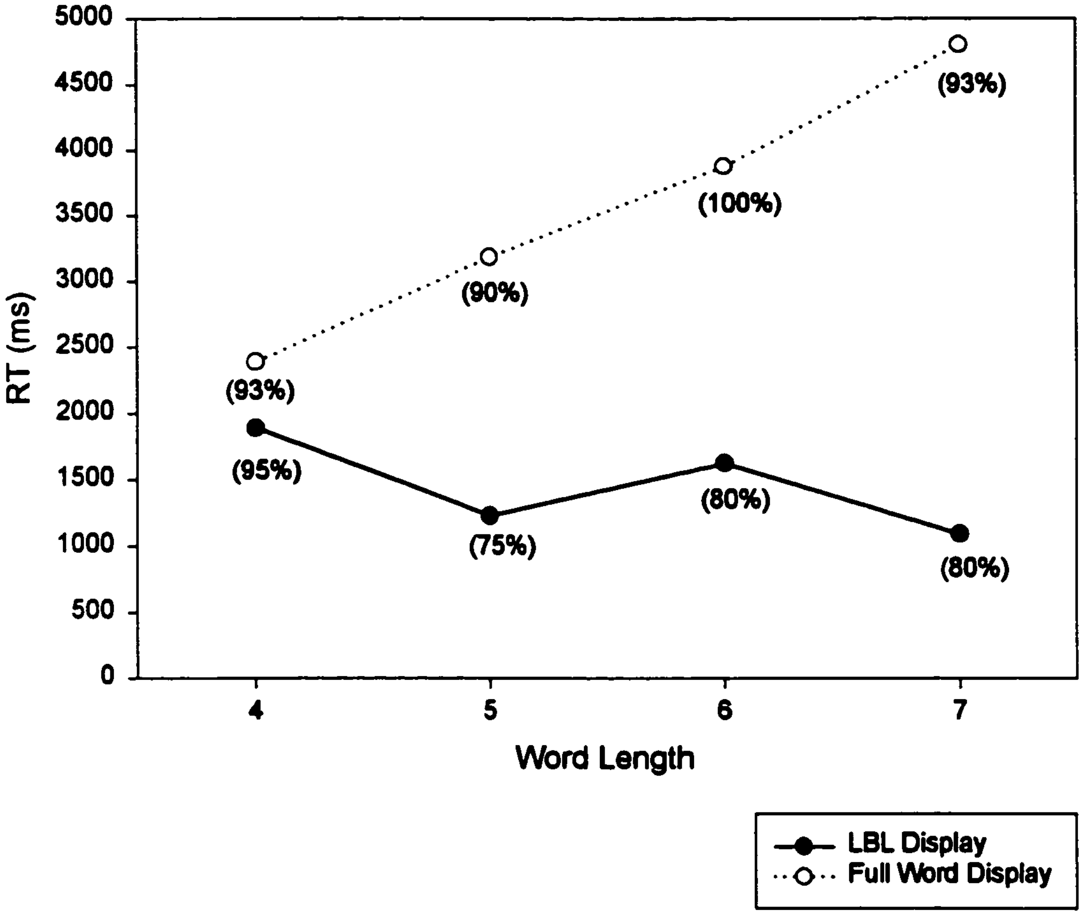

Figure 5: GM's mean pronunciation RTs for correct trials (with % correct) as a function of word length with letter-by-letter display (Experiment 3) and full word display (Experiment 2).

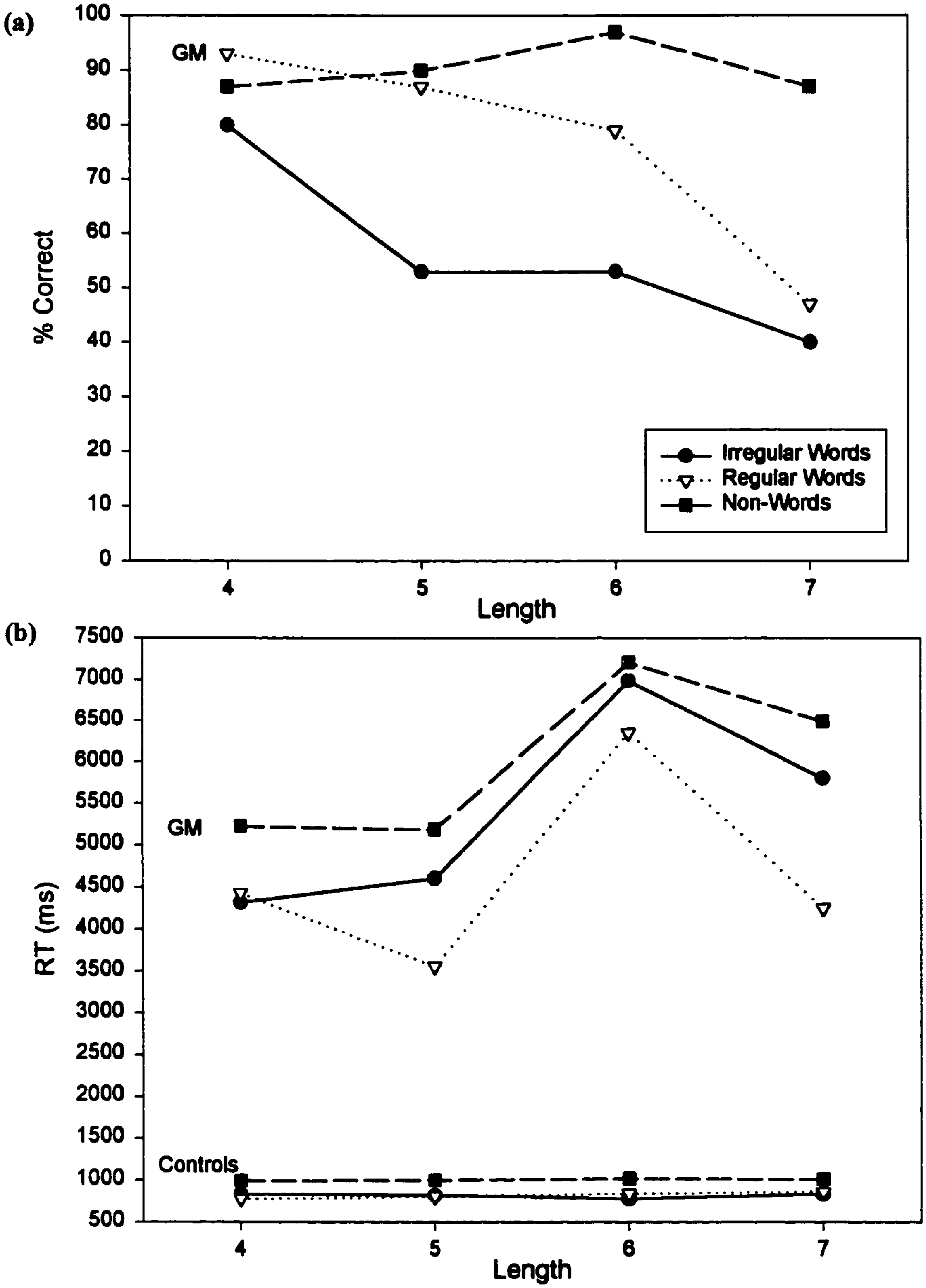

Figure 6: (a) GM's lexical decision accuracy for irregular words, regular words, and non-words as a function of item length. Control subjects were highly accurate in all conditions (97% correct overall); (b) Mean RTs for correct trials for GM and controls (Experiment 4).

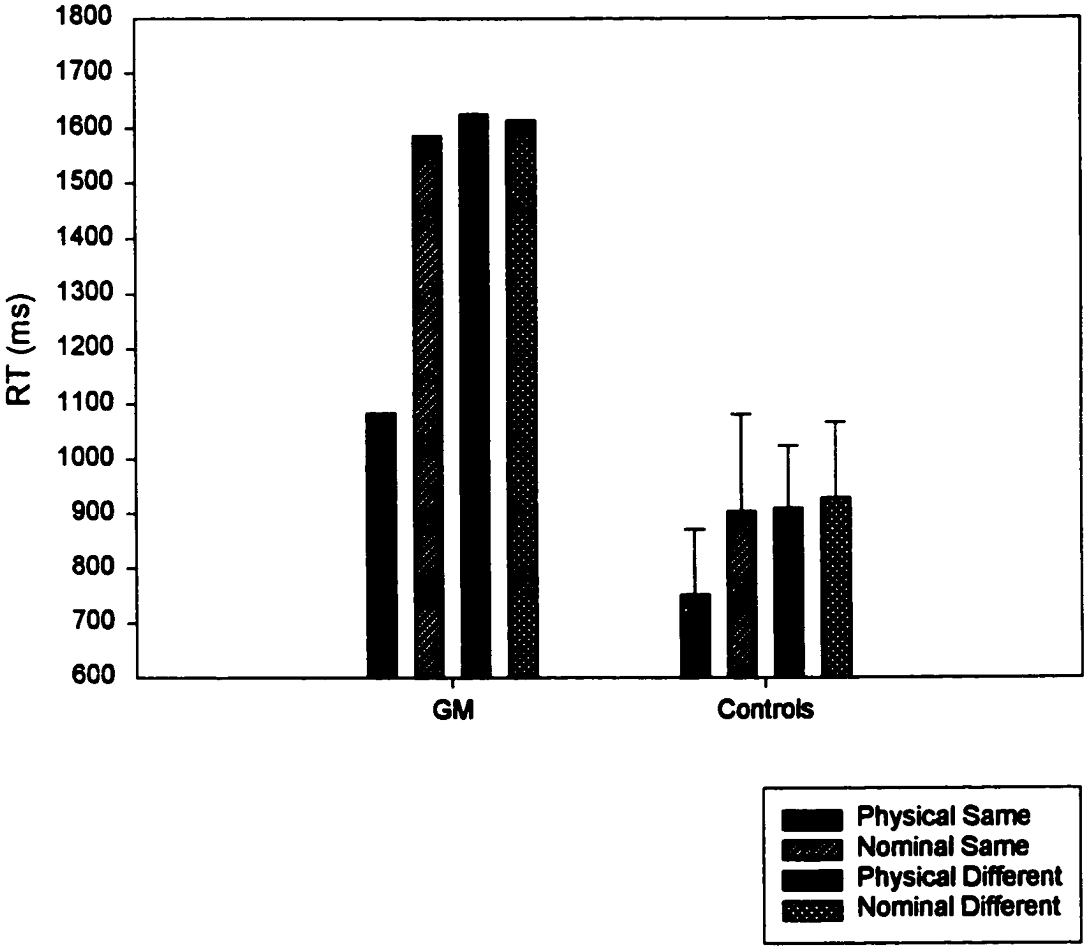

Figure 7: Mean RTs for correct trials for PI and NI same and different letter matches collapsed across confusability block for GM and control group (bars on control data represent RTs for slowest subject in each condition) (Experiment 6).

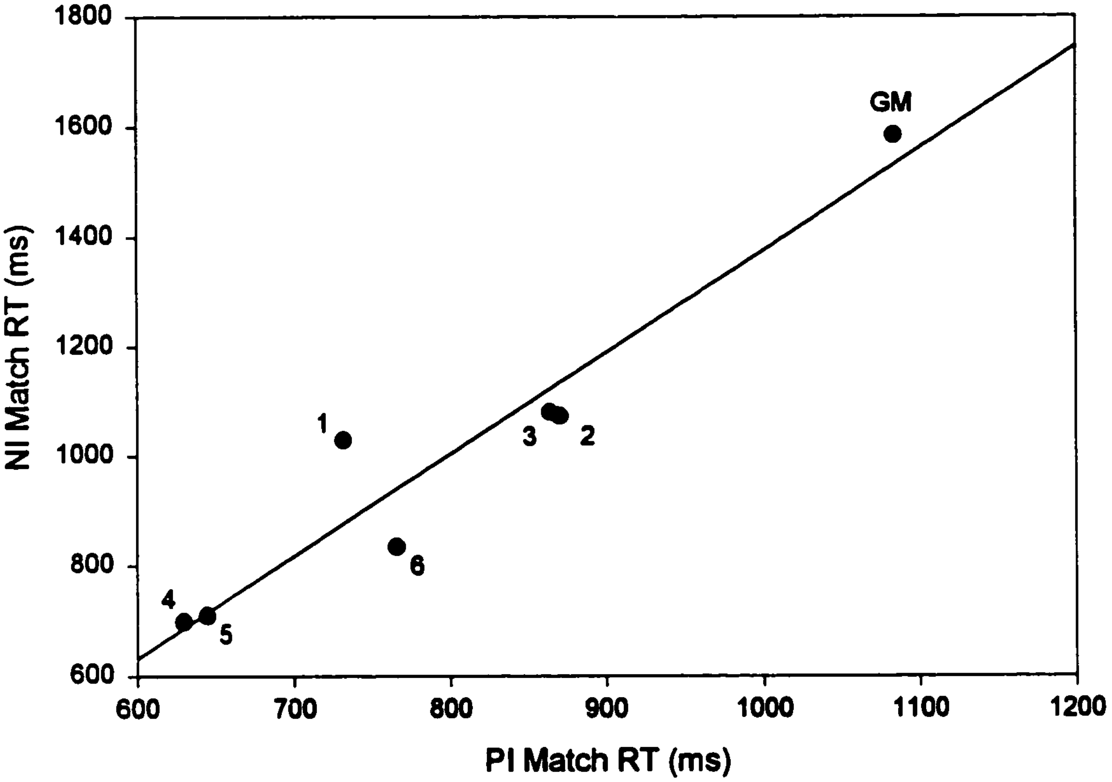

Figure 8: RTs for PI and NI same letter matches for GM and individual control subjects, with the line of best fit (Experiment 6).

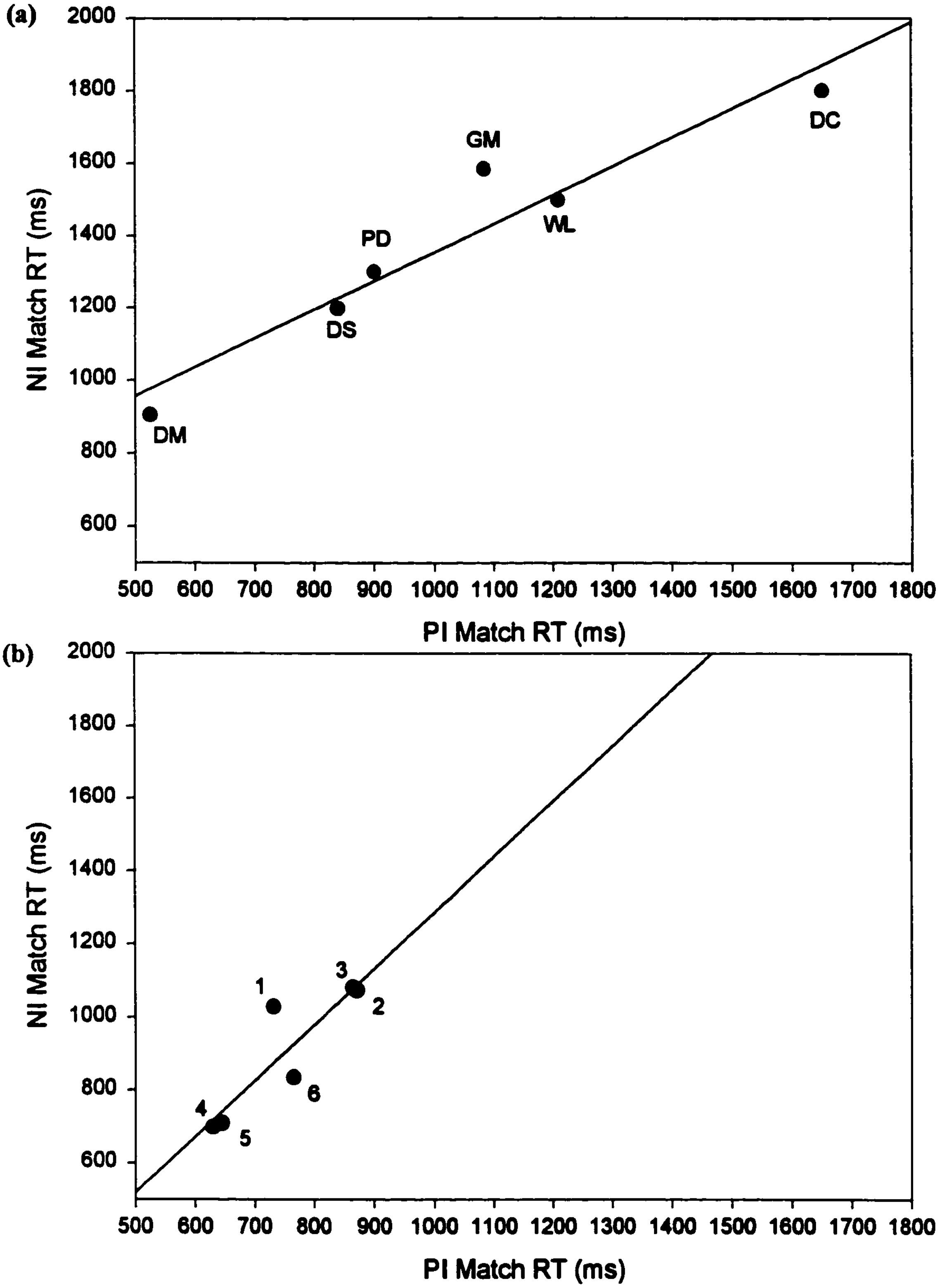

Figure 9: RTs for PI and NI same letter matches for (a) GM and other LBL readers in literature and (b) individual control subjects, with lines of best fit in both groups (Experiment 6).

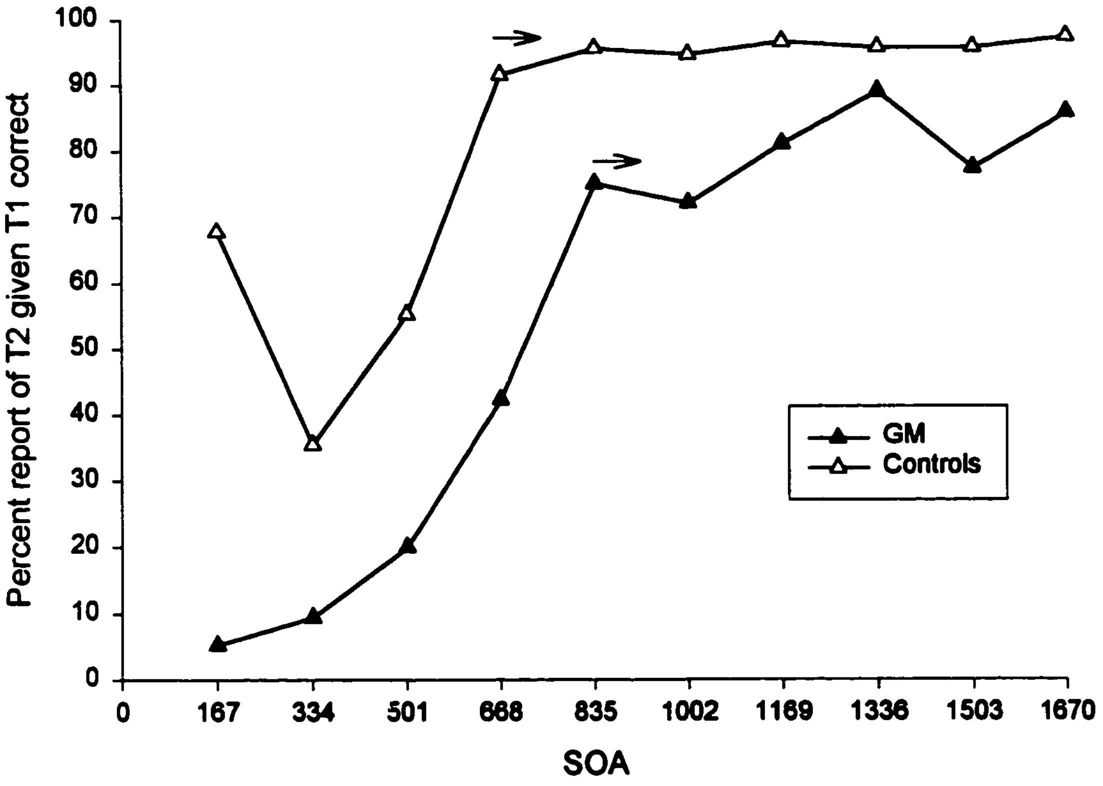

Figure 10: Percent of RSVP trials in which second letter was correctly reported given that first letter was correctly reported as a function of increasing SOA for GM and controls. Arrows indicate where functions reach maximal asymptotes based on statistical comparisons with 1670 ms SOA (Experiment 7).

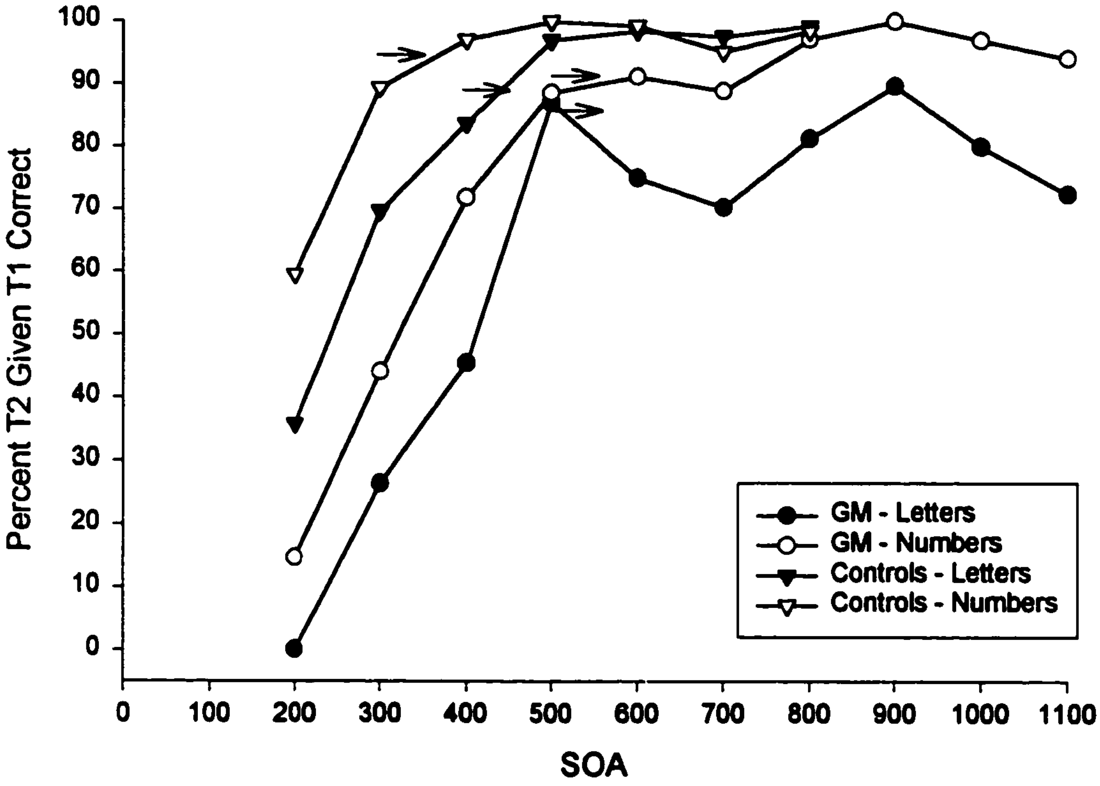

Figure 11: Percent of RSVP trials in which T2 was correctly reported given that T1 was correctly reported as a function of increasing SOA for letters and numbers for GM and controls (Experiment 8).

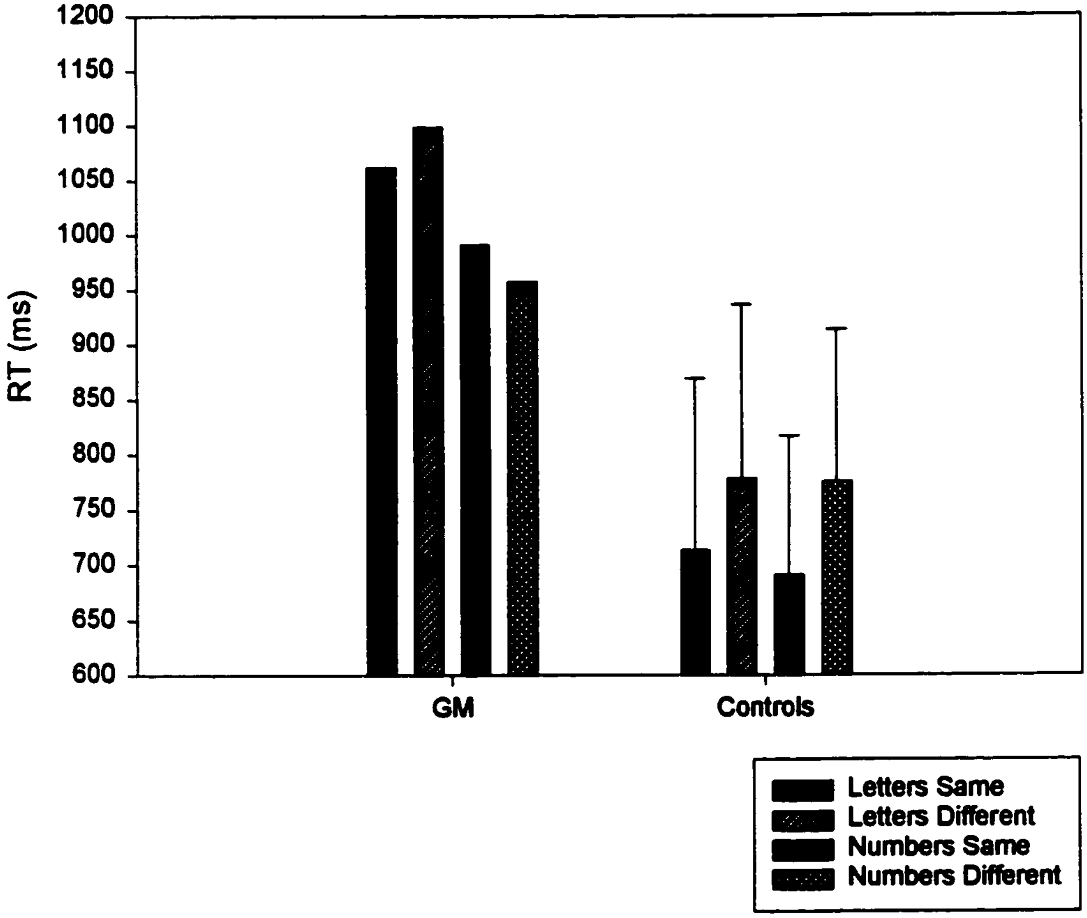

Figure 12: Mean RTs for correct trials for same and different matches in letter and number conditions for GM and control group (bars on control data represent RTs for slowest subject in each condition) (Experiment 9).

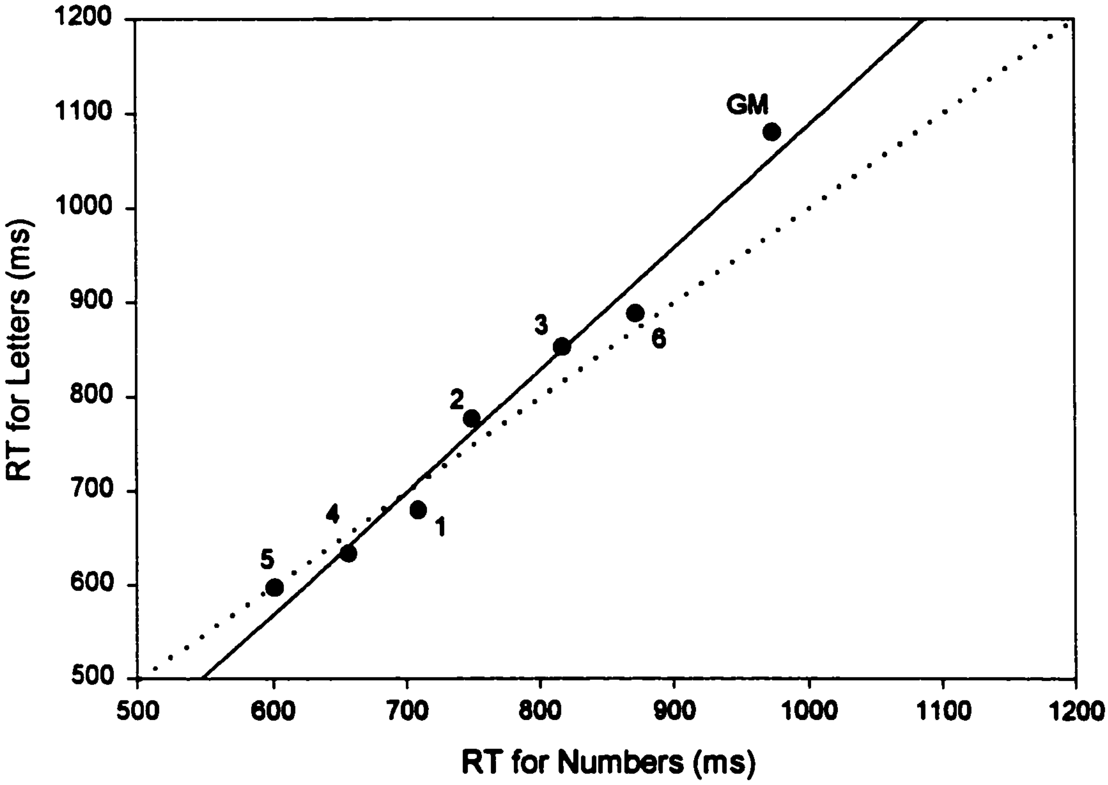

Figure 13: RTs for number and letter same matches for GM and individual control subjects. The line of best fit (solid line) and unit slope function (dotted line) are included (Experiment 9).

Appendix 1: GM's error responses in writing to dictation.

Irregular Word	**Response**	**Regular Word**	**Response**
pretty	prity	effort	efert
break	brake	rub	roub
blood	bloud	flannel	blanel
bowl	boul	wedding	weading
ceiling	cealing	smog	smoug
iron	iran	nerve	nerye
cough	couf	peril	purl
routine	routean	cult	coult
bury	barry	free	bree
yacht	yout	pump	poump
island	iland		
colonel	curnel		
sew	sow		
sword	sord		
shoe	show		
bouquet	becay		
castle	casel		
pint	piant		
tomb	toom		
choir	quier		
gauge	gouge		
sure	shure		
debt	dete		
brooch	brouch		
mortgage	morage		
answer	ancer		
soul	soal		
quay	key		

Appendix 2: Word stimuli used in Experiment 1.

Low Frequency Regular	**Low Frequency Irregular**	**Medium Frequency Regular**	**Medium Frequency Irregular**	**High Frequency Regular**	**High Frequency Irregular**
clog	comb	fill	aunt	clay	ball
coil	deaf	flat	bomb	firm	full
duel	isle	gate	deny	hand	good
fowl	knob	ring	flow	hear	head
hike	mild	soap	folk	help	move
leaf	soup	song	foot	kept	none
pine	stow	team	post	lost	talk
rust	wand	tied	pull	make	view
sank	wool	wait	push	seem	walk
weed	worm	yard	sign	wish	want
boost	debut	baker	allow	bring	child
braid	fever	bride	blind	force	court
ditch	ghost	broke	build	mouth	final
ethic	grind	dream	guest	never	great
glide	guise	grant	owner	order	group
rebel	juror	shape	prove	party	heavy
seize	plaid	sheep	ratio	point	meant
shaft	siren	spend	rifle	press	month
skate	tread	spoke	sweat	speak	often
steal	weird	stick	touch	wrong	truth
button	allege	bench	breath	before	couple
candle	burial	bitter	dollar	center	enough
custom	fasten	decade	master	charge	father
dismay	honour	empire	motive	county	friend
morbid	malign	remain	notice	doctor	future
outlaw	morale	smooth	scheme	ground	health
rabbit	rating	soiled	source	public	income
staple	remind	struck	spread	season	police
strewn	scarce	tragic	steady	second	should
tactic	shovel	winter	tongue	summer	toward
blemish	biscuit	captain	chamber	between	country
calorie	boulder	concert	circuit	changes	foreign
episode	conjure	cooking	courage	despite	machine
fertile	cottage	manager	library	federal	nothing
foolish	fatigue	payment	measure	husband	private
founder	feather	promise	patient	meeting	society
rampage	racquet	protest	soldier	members	station
sandals	receipt	release	stomach	officer	student
torment	salvage	shelter	version	process	through
verdict	sweater	tuesday	village	program	trouble

Appendix 3: Phonetic transcriptions of GM's pronunciation errors in Experiment 1.

Word	Response
	Regularizations
allege	al-leg
burial	bur-ral
chamber	chamber (*cham* as in *champion*)
fasten	fast-ten
fatigue	fa-tie-gue
future	fu-tur (*fu* as in fun)
guise	gizz
none	none (as in *known*)
patient	patent
racquet	rack-qu-et
receipt	recept (as in *receptor*)
society	sock-ity
station	sta-tun
sweat	sweet
version	verson
walk	walk (*alk* as in *balk*)
wand	wand (*and* as in *band*)
move	mauve
	Alternative Irregular Pronunciations
through	throw
	Splittings
view	vee-ew
	VPWs
court	sort
debut	debit
foreign	forage
group	grump
guest	gust
knob	nub
morale	moral
tread	trade
county	country
decade	decent
hear	her
mouth	moth
release	realize
blind	blend
ball	bail

boost	**boast**
folk	**hulk**
flow	**flew**
rebel	**riddle**
worm	**warn**
comb	**calm**
plaid	**plate**
push	**punch**
	VPNWs
biscuit	**biscot**
circuit	**cirsis**
isle	**isen**
machine	**mayhin**
ratio	**rate-too**
stomach	**stumush**
tongue	**tung-edge**
outlaw	**ought-lay-oh**
strewn	**strean**
tragic	**tregas**
malign	**nel-ledge**
ethic	**ethis**
tactic	**tastic**
	Other
stow	**true**

Appendix 4: Word and non-word stimuli used in Experiment 2.

4-Letter Words	4-Letter Nonwords	5-Letter Words	5-Letter Nonwords	6-Letter Words	6-Letter Nonwords
bank	mank	blame	glame	assume	essume
beat	deat	block	glock	battle	mattle
beef	neef	catch	satch	bigger	ligger
core	nore	crack	drack	bitter	mitter
deep	feep	draft	braft	cattle	wattle
farm	sarm	drawn	grawn	charge	blarge
hide	jide	drive	frive	corner	norner
list	hist	faith	laith	demand	gemand
main	dain	fence	bence	detail	setail
page	nage	frame	brame	device	revice
pass	fass	glass	blass	direct	hirect
path	gath	green	treen	factor	dactor
pick	fick	motor	botor	follow	jollow
plus	glus	mouth	touth	forest	korest
rent	yent	noise	doise	glance	slance
rise	dise	plain	flain	jacket	macket
rock	vock	plane	klane	leader	teader
roof	soof	plant	clant	manner	panner
save	tave	quick	quisk	mantle	nantle
seed	yeed	sharp	slarp	pocket	tocket
send	kend	sheet	gheet	repair	fepair
shut	sput	shore	brore	sample	gample
sick	gick	slave	plave	season	geason
stem	glem	solid	nolid	settle	rettle
step	brep	speed	kleed	silver	gilver
thin	clin	spend	glend	sister	dister
wait	rait	teeth	weeth	stress	shress
wine	bine	train	prain	struck	chruck
wish	mish	trust	drust	twenty	swenty
yard	vard	visit	disit	winter	binter

7-Letter Words	7-Letter Nonwords
advance	alvance
blanket	slanket
chapter	shapter
comment	romment
content	pontent
correct	torrect
current	murrent
despite	vespite
failure	kailure
herself	perself
kitchen	fitchen
landing	randing
manager	banager
mistake	listake
officer	efficer
operate	eberate
painter	bainter
pattern	dattern
perfect	serfect
pointed	rointed
project	troject
reading	yeading
request	fequest
setting	vetting
shortly	flortly
stretch	chretch
subject	rubject
teacher	weacher
traffic	craffic
victory	mectory

Appendix 5: Phonetic transcriptions of GM's pronunciation errors to words and non-words in Experiment 2.

Word	Response	Non-Word	Response
farm	form	banager	banage
rise	rice	chretch	kur-retch
solid	sold	chruck	chur-ruck
teeth	teach	dain	doin
train	strain	flain	flean
comment	commend	geason	cheason
mistake	mystic	hirect	her-rick
		quisk	qu-ick
		rointed	ronted
		sarm	sarn
		shress	shur-ress
		slance	slank
		touth	tough
		troject	tro-jet
		yent	quint

Appendix 6: Word stimuli used in Experiment 3.

4-Letters	5-Letters	6-Letters	7-Letters
hill	press	struck	operate
feed	plate	define	plastic
camp	stick	lumber	advance
horn	sleep	finger	furnish
code	horse	dinner	maximum
park	agree	beside	address
fail	enter	remain	despite
rose	claim	coffee	respond
mine	drill	select	pattern
flat	stone	screen	attempt
test	dance	sample	officer
mail	beach	regard	teacher
date	clean	middle	failure
sand	check	energy	balance
file	brush	bottle	victory
bend	shape	branch	subject
nose	ranch	degree	protect
heat	faith	bridge	beneath
lake	broke	thirty	correct
firm	serve	impact	current

Appendix 7: **Phonetic transcriptions of GM's pronunciation errors in Experiment 3.**

Word	**Response**
firm	fern
shape	sheep
ranch	wrench
faith	fish
broke	break
serve	service
degree	degreem
bridge	dk*
thirty	throw
impact	impast
protect	dk
beneath	dk
correct	correst
current	dk

* do not know

Appendix 8: Stimuli used in Experiment 4.

Regular Words	Irregular Words	Nonwords	
clay	ball	suin	volase
hand	full	cose	friant
lost	head	acho	fabren
seem	move	pify	securd
wish	walk	slup	thythm
clog	isle	nome	dellet
duel	knob	wace	menkow
fowl	mild	bolf	losign
pine	stow	pnaw	laight
rust	wool	soct	tanign
flat	aunt	tolt	maites
ring	bomb	wibe	orique
soap	deny	tulk	laursh
team	flow	doof	shafew
yard	post	goaf	mannin
bring	court	pala	mothun
force	final	fich	infarb
mouth	group	nive	tomege
point	meant	shob	drinur
press	truth	tood	joctep
boost	debut	beff	chaspe
braid	grind	pape	mardle
ditch	plaid	wign	sampun
glide	tread	deab	pesiob
steal	weird	freb	leffet
baker	build	cood	deauty
bench	ratio	gron	twerly
dream	rifle	raze	behent
shape	sweat	hend	tryany
sheep	couple	toun	threel
center	enough	worf	memlirs
charge	future	grore	trushen
county	health	anion	kitcler
doctor	police	cught	blunkes
public	allege	swean	deether
button	honour	kough	chutreg
custom	rating	clore	lerough
dismay	remind	fakle	scholin
morbid	shovel	tulig	nojoure
outlaw	dollar	gilot	despule
decade	motive	fearn	senafon
empire	notice	basle	brothac

struck	spread	houbt	colloye
winter	tongue	rerch	mornisp
federal	foreign	coman	capsete
husband	machine	basoc	currask
meeting	nothing	rhaki	privele
officer	society	leart	teackem
program	student	salen	compich
blemish	biscuit	goung	folstir
calorie	boulder	steck	protair
fertile	conjure	noine	tuoyant
founder	salvage	jupil	teright
verdict	sweater	thirk	stufion
captain	chamber	meady	ercient
promise	circuit	sholl	prowiss
protest	library	chule	froudle
release	patient	purch	weathun
tuesday	stomach	shome	curiars
smooth	allow	plaic	sountey

Appendix 9: Stimuli used in Experiment 5.

Pseudohomophones	Nonwords	Words	
bawx	vawx	camp	moon
berd	perd	bath	golf
bern	pern	tray	kick
bild	sild	wait	term
blud	clud	clay	king
boan	poan	meal	tube
bote	wote	neck	wine
brite	crite	fresh	dance
burth	turth	frame	store
cheef	bleef	plane	glass
dait	yait	heat	deep
durt	jurt	gift	mail
ferm	serm	wish	role
flore	glore	space	black
furst	gurst	there	where
gerl	verl	land	wife
gess	dess	join	seek
gide	pide	crew	rice
grait	brait	while	still
grean	drean	plant	horse
groe	broe	beat	task
hoal	joal	suit	wind
hoap	goap	hold	live
kair	gair	fine	rest
nerse	merse	clock	flame
nues	fues	mass	thin
peece	deece	range	trade
raize	kaize	taste	spite
rong	mong	main	stay
slite	clite	trust	quick
sune	hune	rate	kept
taip	baip	root	coal
taks	caks	hard	mean
thret	shret	grade	pride
wawl	vawl	bill	club
wirth	hirth	claim	forth
wunce	tunce	place	since
wurld	murld	state	three
yeer	keer	life	left
yung	nung	face	form

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